

NAUTILUS

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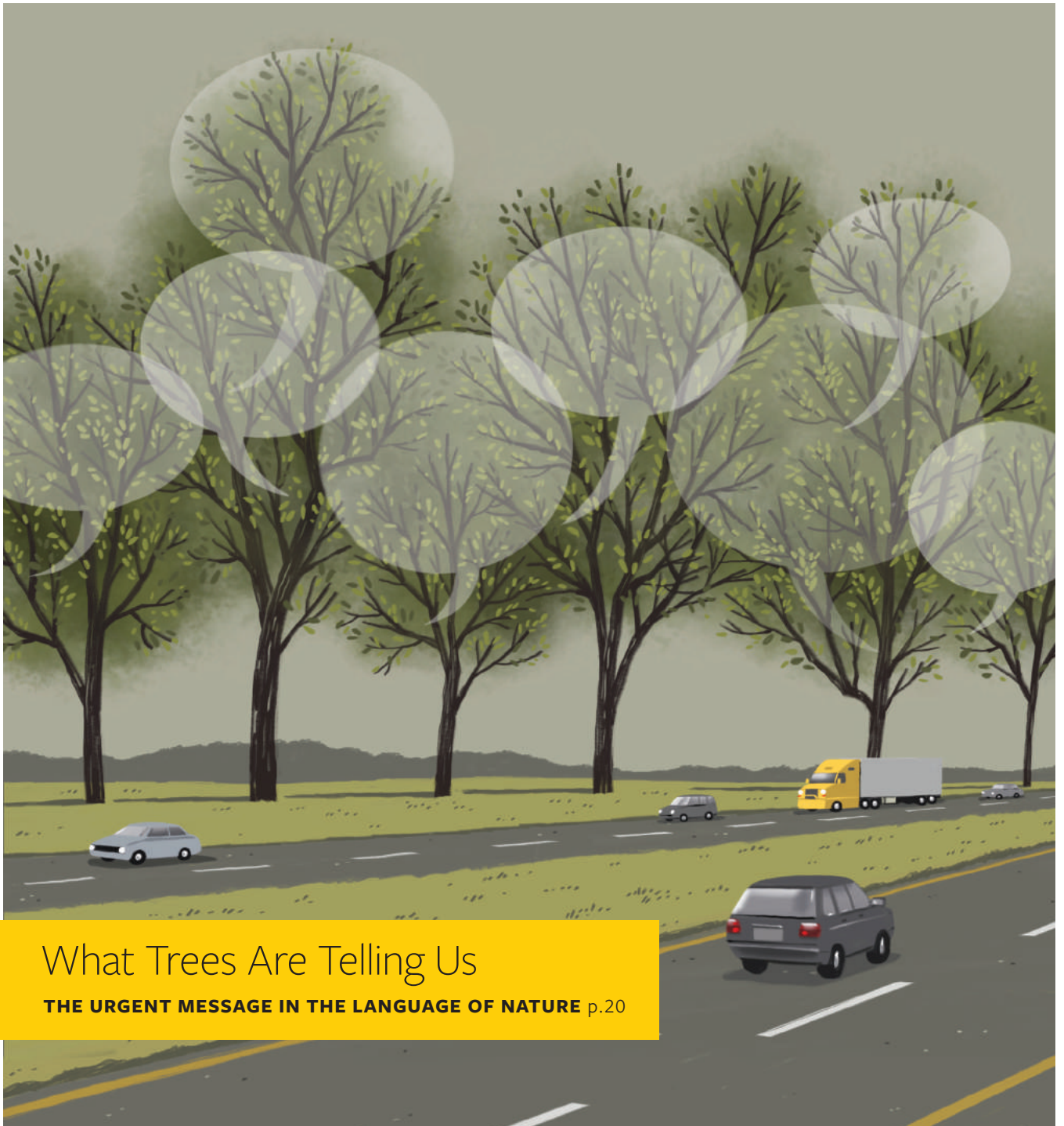
Brain scientists strike gold

AI FAILS PHYSICS

Machine learning needs more schooling

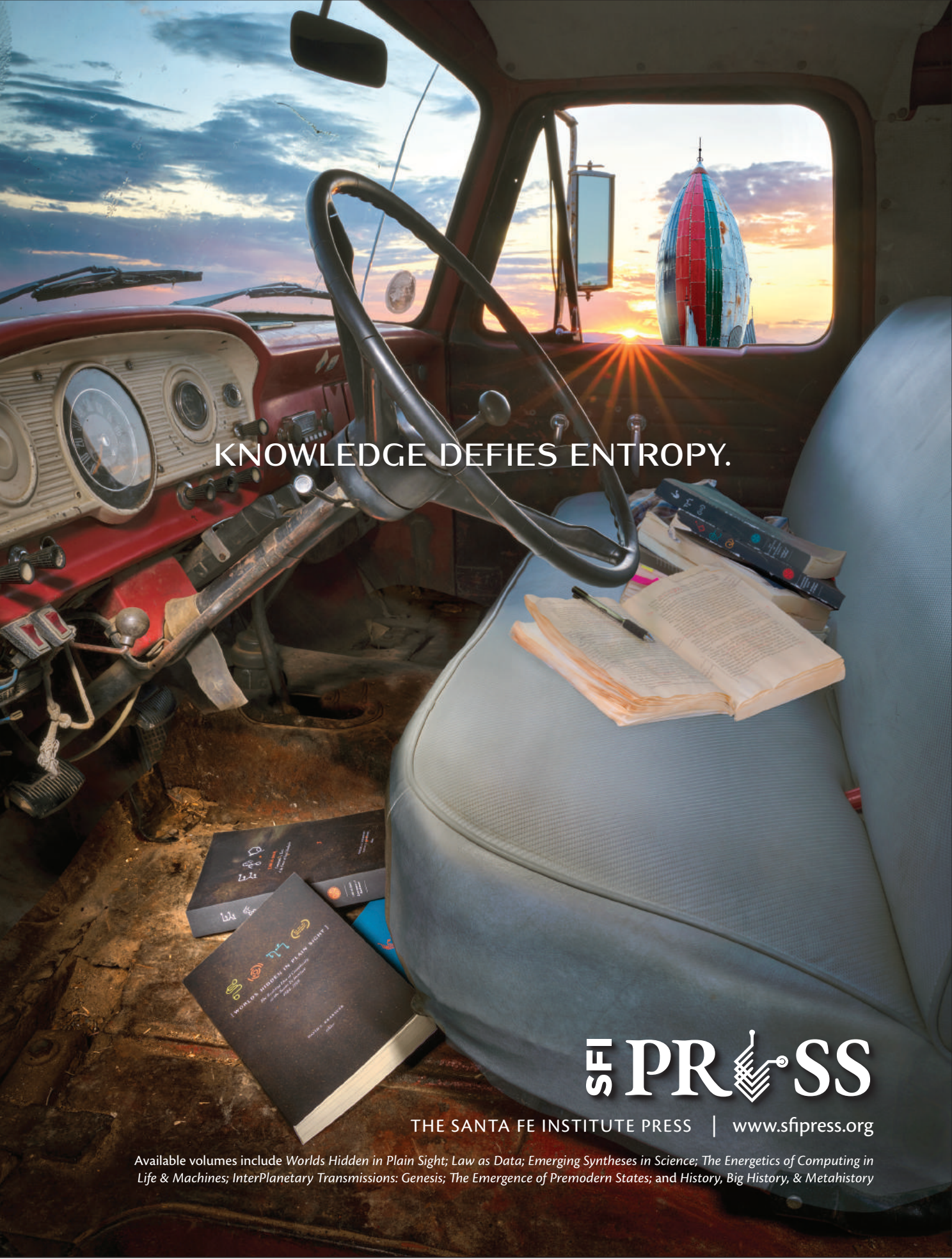
THE THINGS WE BURY

Awe and terror in the underworld



What Trees Are Telling Us

THE URGENT MESSAGE IN THE LANGUAGE OF NATURE p.20



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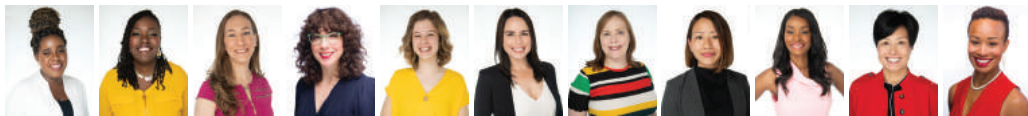
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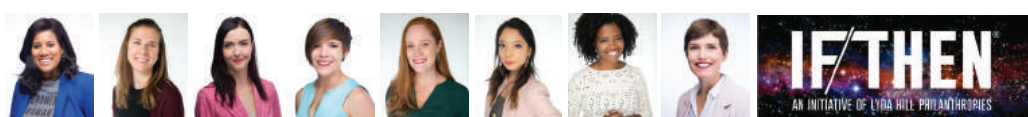
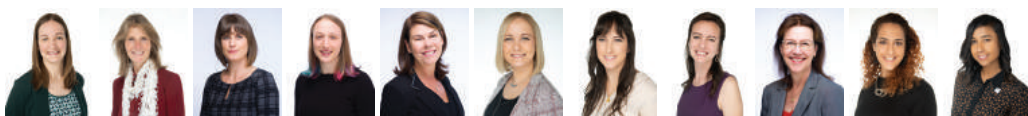
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These are the faces of our future



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NAUTILUS *Next*

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Back to Nature

BY KEVIN BERGER

LOVE THE CARS in this issue's cover illustration. Artist Jorge Colombo has them cruising along a highway under a grove of chatty trees. I hate to sound like one of those people in an art museum *explaining* a work to a friend, reducing it to one interpretation, but Jorge has me thinking about how easily we tune out the environment that envelops us.

This issue can be seen as science putting us back in touch with nature. That sounds New Age-y, I know, but feeling connected to nature runs deep in biology. In "Never Underestimate the Intelligence of Trees," Suzanne Simard, a professor in the Department of Forest & Conservation at the University of British Columbia, admits to *Nautilus*' Brandon Keim that saying trees have emotions sounds like an anthropomorphic stretch.

"That said, let's say you have a group of plants and stress one out, it will have a big response," Simard says. "Botanists can measure their serotonin responses. They have serotonin. They also have glutamate, which is one of our own neurotransmitters. There's a ton of it in plants. They have these responses immediately. If we clip their leaves or put a bunch of bugs on them, all that neurochemistry changes. They start sending messages really fast to their neighbors. Is that an *emotional* response? I guess it is."

Psychologists have long told us perceiving the emotions of others moves us to share their joys and pains. Neuroscientists have stepped in to explain that feeling is generated by brain cells called "mirror neurons." Further research has stretched that connection to nonhuman life. However, it's not quite clear what plants and animals get out of the bond, other than, and it's not incidental, our experiences of them can inspire us to protect them. It would be hard to find an environmentalist who hasn't felt awe in the embrace of a forest. It's easy to find politicians who haven't.

The emotional impact of wrenching nature into industry is a theme that runs through this issue. On our warming planet, Bernd Brunner writes, snow packs are receding, shortening our winters, lengthening our discontent. Sidney Perkowitz laments that a pioneering insight about global warming by a 19th-century woman scientist was ignored. Importantly, though, *Nautilus* contributors John Baez and Aubrey Clayton, both mathematicians, and paleoclimatologist Summer Praetorius, calculate solutions to climate change, where the future looks, if not bright, at least not underwater.

Science, devoted to solutions, is by nature optimistic. But thinking about the problems it's trying to solve can sink us into heaps of stress. In that case, this issue has just the cure, an article that underscores how feeling connected to nature transforms us. Its advice? Run with the wind.

Every extinction is a tragedy.



PROTECT BIODIVERSITY

Readers Respond

Comments and letters about stories from print issue 28.

“WHEN WORDS FAIL”

My primary complaint with Mr. Kosik’s article is the failure to address a primary feature of all language, the one which repudiates the very concept of solipsism. Language in its origins and function is social. Vocalizations and gestures by a lone individual of any species have to be given meaning and shaped into language through repeated social interactions with others. The most abstract philosophical pronouncements are ultimately rooted in the human social interactions from which language emerges.

—George Gantz

“HUMANS ARE WIRED FOR GOODNESS”

The argument that humanity’s reign is a result of sociability, rather than selfishness, is compelling. Thank you for correcting the popular lopsided narrative about people’s propensity to be immoral. In my view, E.O. Wilson sums it up best: To thrive within groups, we must compete selfishly. To thrive as a community surrounded by a challenging environment, we must cooperate with other group members (i.e., be moral). Optimizing the trade-off between cooperation and competition is what E.O. Wilson calls the fundamental problem of social life. Long story short, it is not an either/or, it is both. The question is: How do we create an environment that fosters a healthy balance between the two.

—Carsten Tams

“THE GREAT SILENCE”

Humans are arrogant. Many of us actually believe we are created in the image of god(s) who made an entire universe just for us. We even used to believe that the sun, moon, and stars all revolved around earth, i.e., we were at the center of everything, apparently because we’re so darn wonderful. We also used to believe we’re the only animals on earth possessing consciousness and feelings, and that all other animals are just bundles of dumb instincts, thus justifying our cold-hearted cruelty to them. We’ve even treated other humans who don’t look like us as though they’re animals without feelings, justifying their enslavement or even genocide.

We humans think pretty highly of ourselves, but if there are intelligent civilizations out there, they may not share our high opinion of ourselves. If there’s a universal word for ‘jerks’, it may be how they refer to us.

—Commenter Bob

You be good. I love you. If only humans could put that into practice. I guess we think we’re too smart for that.

—mykelde

“HUMAN EMOTIONS ARE PERSONAL NARRATIVES”

I’m concerned that LeDoux may be overlooking evidence of complex cognition in other great apes, like the gorilla Koko, who was taught sign language and independently

produced unique utterances, not just rote responses. When asked about the death of her pet cat she self-reported being “sad” about the experience (in sign language). In general it seems necessary to refine the distinction between “verbal” and “nonverbal” responses and to use a different framing to account for conscious behaviors, including (for example) sign language, gesture, and body language as mediated forms of communication, and not just as “automatic” non-conscious reactions.

—Paul Otto



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

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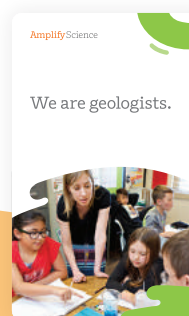
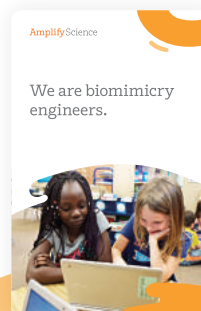
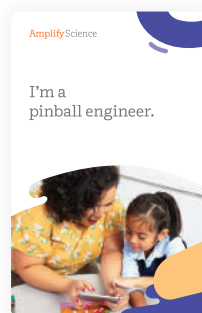
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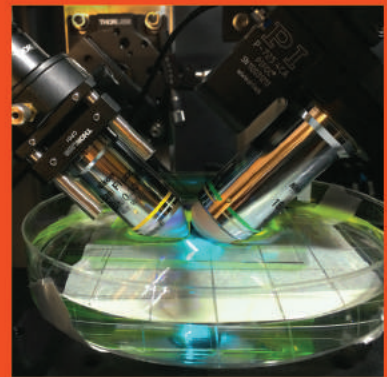
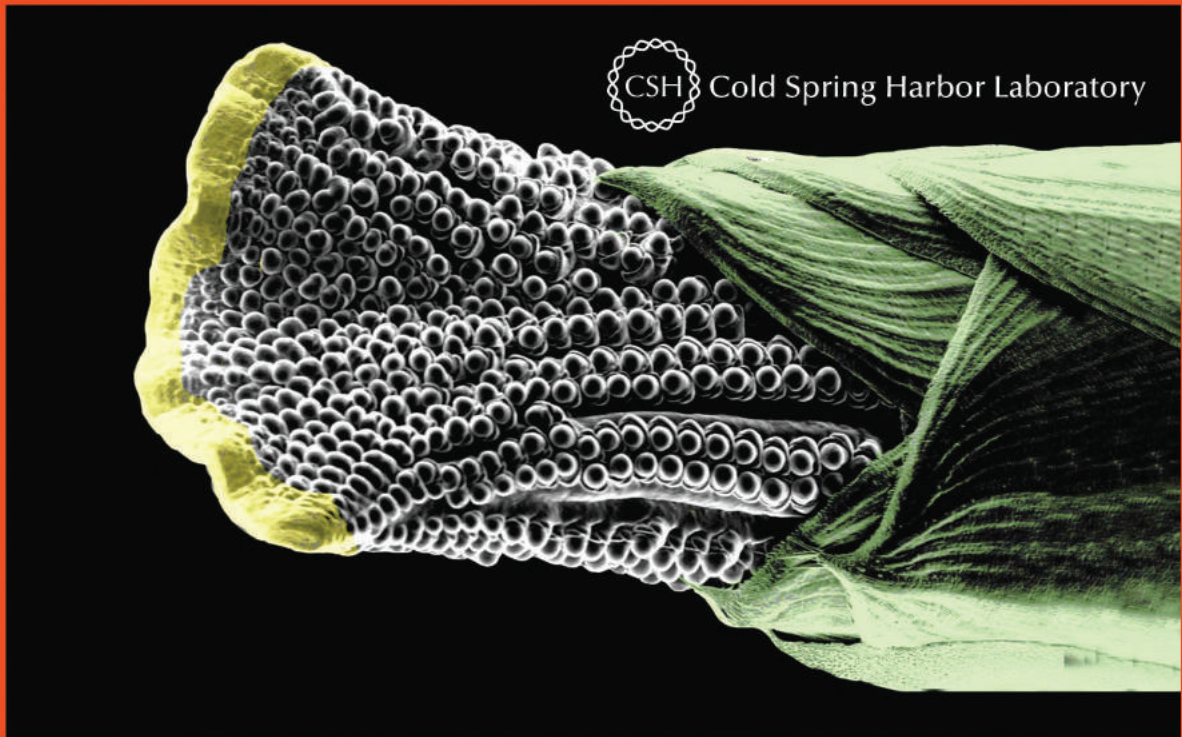
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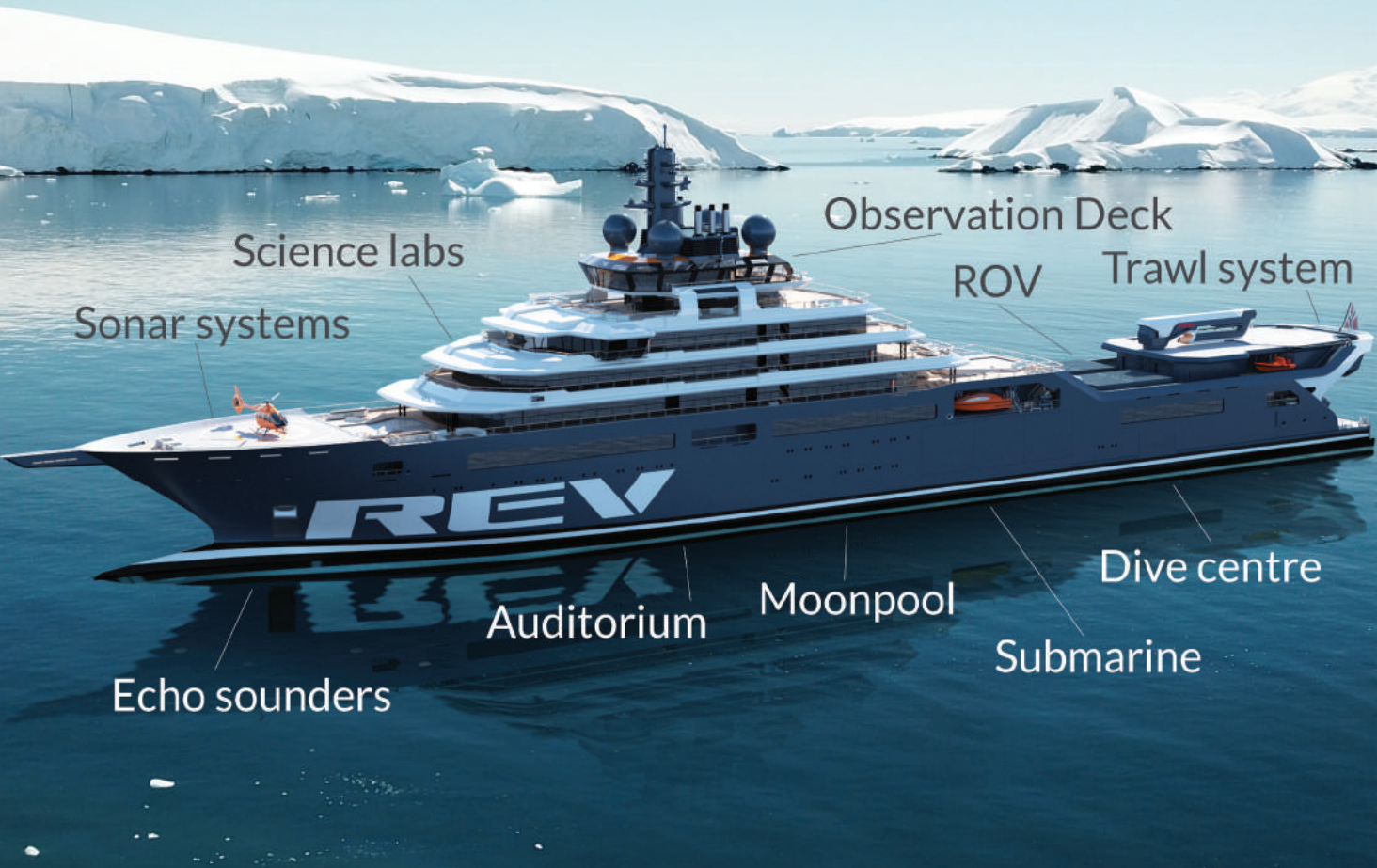
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Preludes



PSYCHOLOGY

The Simple Dutch Cure for Stress

RECENTLY I WAS IN SAN FRANCISCO, a city known for its tech companies, steep hills, and fierce winds. Each day I'd run around the neighborhood and up through the park, ending with a spectacular view of the Golden Gate Bridge. I'd feel energized and refreshed, fingers tingling from the breeze. It was cold, exhausting, but completely exhilarating.

As it turns out, there's a unique term from the Dutch for this sort of pastime: "*uitwaaien*." It "literally translates to 'outblowing,'" explains Caitlin Meyer of the University of Amsterdam's Department of Dutch Linguistics. "It's basically the activity of spending time in the wind, usually by going for a walk or a bike ride." Meyer says *uitwaaien* is a popular activity in the Netherlands, where she lives—one believed to have important psychological benefits. "*Uitwaaien* is something you do

to clear your mind and feel refreshed—out with the bad air, in with the good," she tells me. "It's seen as a pleasant, easy, and relaxing experience; a way to de-stress or escape from daily life."

A growing body of evidence suggests that Dutch speakers may be on to something. "Pretty well every group of people benefits from being outdoors in the presence of nature," says Jules Pretty of the University of Essex. "It takes us out of the stresses and anxieties of the rest of life." Over 15 years of study, he's found that people from all walks of life can increase their well-being after spending as little as five minutes amid natural settings, with positive impacts on sense of self-worth, mood, and sense of identity.

Other researchers report similar results, linking activities like nature walks with reduced levels of depression, perceived stress, and negative emotions.

This constant low-grade stress can damage our health and well-being.

Some research goes even further, reporting that walking in nature can help reduce headaches, improve immune function, and even increase anticancer protein production.

While research into the benefits of waterscapes isn't as well-established, evidence suggests these "blue spaces" may be equally—or perhaps even more—beneficial to mental well-being. For example, people who live closer to the coast report better physical and psychological health than those farther inland. Water may have a restorative effect, helping people overcome negative emotions and diminish their mental distress.

There are lots of theories about why spending time in nature might be so good for us. Qing Li, a physician at Nippon Medical School Hospital and the president of the Japanese Society of Forest Medicine, and his team have spent years studying the effects of phytoncides, antibacterial and antimicrobial substances that trees and other plants release into the air to help them fight diseases and harmful organisms. When humans breathe in these substances—typically by spending time in nature—their health can improve. Across several studies, phytoncides have been shown to boost immune function, increase anticancer protein production, reduce stress hormones, improve mood, and help people relax.

Pretty attributes the restorative power of natural spaces to their immersive quality. He tells me that activities like watching shorebirds or collecting seashells on the beach can be really engaging—so engaging that they can help us temporarily deactivate a part of the brain called the default mode network, which allows us to scheme, plan, and innovate. "It's what makes us brilliant humans," Pretty says. The trade-off is that it's also extremely active. "The one thing that we haven't got is an off-switch for our thoughts," he says. As a result, many of us "find ourselves living our lives on simmer—[like we've] got a pot on the stove that's almost ready to boil."

In the long term, this constant low-grade stress can damage our health and well-being, increasing our chances of cardiovascular diseases, inflammation-related issues, and other dangers. That's why Pretty believes a regular "dose" of something akin to *uitwaaien* can be so beneficial. In our over-stressed society, listening to the sound of the wind or admiring the colors of ocean waves may be among the few ways we can truly unwind.

So open that calendar app and note some time for *uitwaaien*. Whether it's a windy, riverside bike ride or a jog up a steep San Francisco hill, chances are, your mind—not to mention your body—will thank you for it.

— Alice Fleerackers

PHILOSOPHY

Omniviolence Is Coming and We Aren't Ready

IN *THE FUTURE OF VIOLENCE*, Benjamin Wittes and Gabriella Blum discuss a disturbing hypothetical scenario. A lone actor in Nigeria tricks women and teenage girls into downloading malware that enables him to monitor and record their activity, for the purposes of blackmail. The real story involved a California man the FBI eventually caught and sent to prison, but if he had been elsewhere in the world he might have gotten away with it. Many countries, as Wittes and Blum note, "have neither the will nor the means to monitor cyber-crime, prosecute offenders, or extradite suspects to the United States."

Technology is, in other words, enabling criminals to target anyone anywhere and, due to democratization, increasingly at scale. Emerging bio-, nano-, and cyber-technologies are becoming more and more accessible. The political scientist Daniel Deudney has a word for what can result: "omniviolence." The ratio of killers to killed is falling. For example, computer scientist Stuart Russell has vividly described how a small group of malicious agents might engage in omniviolence:



A very, very small quadcopter, one inch in diameter can carry a one-or two-gram shaped charge. You can order them from a drone manufacturer in China. You can program the code to say: “Here are thousands of photographs of the kinds of things I want to target.” A one-gram shaped charge can punch a hole in nine millimeters of steel, so presumably you can also punch a hole in someone’s head. You can fit about 3 million of those in a semi-tractor-trailer. You can drive up I-95 with three trucks and have 10 million weapons attacking New York City. They don’t have to be very effective, only 5 or 10 percent of them have to find the target.

Manufacturers will be producing millions of these drones, available for purchase just as with guns now, Russell points out, “except millions of guns don’t matter unless you have a million soldiers. You need only three guys to write the program and launch.”

That’s completely unprecedented. The terrorist or psychopath of the future, however, will have not just the Internet or drones but also synthetic biology, nanotechnology, and advanced AI systems at their disposal. These tools make wreaking havoc across international borders trivial, which raises the question: Will emerging technologies make the state system obsolete? It’s hard to see why not. What justifies the existence of the state, English philosopher Thomas Hobbes argued, is a “social contract.” People give up certain freedoms in exchange for state-provided security.

The trouble is that if anyone anywhere can attack anyone anywhere else, then states will become—and are becoming—unable to satisfy their primary duty as referee. It’s a trend toward anarchy. Indeed, in a recent paper published in *Global Policy*, Oxford philosopher Nick Bostrom argues that the only way to

Civilization is an experiment.
We may not get the results
we’re expecting.

defend against a global catastrophe is to employ a universal and invasive surveillance system, what he calls a “High-tech Panopticon.” Sound dystopian? It sure does to me. Bostrom is well-aware of the downsides—corrupt actors in a state could exploit this surveillance for totalitarian ends, or hackers could blackmail unsuspecting victims. Yet it may still be a better option than suffering one global catastrophe after another.

How can societies counterattack omniviolence? One strategy could be a superintelligent machine—essentially, an extremely powerful algorithm—that’s specifically designed to govern fairly. We could then put the algorithm in political charge and, insofar as it governs as something like a “Philosopher King,” not worry constantly about the data collected being misused or abused. Of course, this is a fantastical proposal. The real-world use of AI in the justice system is fraught with problems. But at this point, do we have a better idea for preventing the collapse of the state system under the weight of widespread technological empowerment?

Perhaps a completely new idea will emerge that can preserve the current system—if we even want it preserved. Or perhaps emerging technologies won’t empower people as much as I and others anticipate. It could be that offensive technologies will actually lag behind defensive technologies, making it very difficult to execute a successful attack. It could also be that before omniviolence and democratization undercut the state, civilization collapses because of climate change-linked stressors like lethal heatwaves, coastal flooding, melting glaciers and polar ice caps, food supply disruptions, disease outbreaks, and species extinctions. If we ended up living as hunter-gatherers again, the main worry would be sticks and stones, not designer pathogens and artificial intelligence.

Civilization is an experiment. We may not get the results we’re expecting. So humanity would do well to hope for the best but prepare for the worst.

—Phil Torres



TECHNOLOGY

The Implant That Can Control Your Brain

S HAUN PATEL HAS such a tranquil voice that it's easy to see how he convinces patients to let him experiment in the depth of their brains.

On the phone, the neuroscientist spoke about gray matter almost as if he were guiding me in meditation. Or perhaps that was just the heady effect of him detailing a paper he'd just published in *Brain*, showing how, using implants on his patients, he could enhance learning by stimulating the caudate nucleus. You have to time the electric pulse just right, he told me, based on the activity of certain neurons firing during an active learning phase of a game. A perfectly timed pulse could speed up how quickly his patients made the right associations. Using similar methods, he said he's induced people to make more financially conservative bets. His

patients don't even realize what's happening. Their behavior feels like their own.

This sort of power is prelude to what Patel and his Harvard colleague Charles Leiber, a nanotechnology pioneer, call "precision electronic medicine." Patel has been working with Leiber to design a new kind of brain-machine interface, one the brain doesn't recognize as foreign.

Tell us about the mesh brain implants you've been working on.

These are interfaces reimagined from the ground up. Nerve tissue is insanely, astronomically dense. We have neurons, astrocytes, glia, and different compartments in those cells. These interfaces are ultra-small, in the

What I want to do is to merge the bandwidth from that device to my brain.

scale of brain cells. They're also ultra-flexible. They can remain implanted without mounting any unwanted immune reactions or side effects. This fundamentally changes the way we can think about how neural electronics can be applied therapeutically for patients with brain disorders. If you can understand the language of the brain, its code, you can use electrical stimulation to artificially input information into the brain to control thoughts and behavior.

What might happen to the brain, and our understanding of it, once humans regularly interface with mesh electronics?

The really interesting thing is this unique opportunity to think about how you can input new types of information into the brain. Whatever you might conceive through a stable neural interface, the brain will learn to identify those patterns, and give that organism some meaning about it, just as we have some meaning about light hitting our retinas and the movement of air molecules on our cochlea. Eyes and ears are just types of sensors—stable interfaces—that we're built with, but you might imagine new ones that integrate with the brain as it's developing.

The brain really doesn't care what the input is. There's no program that our neurons get connected up in a way that is, for example, precisely the way that we need to see. Different neurons identify lines and

corners, others encode color, movement, and disparity, and other primitive visual features. These neurons send their axons to other parts of the brain, which then combine those primitive features and begin to reassemble them to give us a perception of the visual field that we're looking at. It's the breakdown and reconstruction of the world. It does this through a kind of trial and error, and through feedback and synaptic pruning and other developmental programs.

What would new input, processed by a novel interface, introduce into our perceptual field, or mental space?

This is definitely the dreaming, speculative side of things. But what that introduces—or what that reduces, rather—is the constraint that we have. There's only so much bandwidth. There's a paper that showed the information-carrying capacity across all the languages spoken in the world is roughly the same, which is really surprising and interesting. A neural interface, on the other hand, could leverage technology to reduce the bandwidth limitation. You can imagine having a direct connection to the information processing center of a human.

Do you think a neural interface could enhance our cognitive powers enough to make us not worry about being overtaken by AI?

If it were me, my focus wouldn't be on making our brain as fast or as good as an AI, but rather creating a link. Let's say I've already developed the AI—maybe it's a robot, or a voice detection algorithm. What I want to do is to merge the bandwidth from that device to my brain. It's not that I need to download the world's knowledge to my brain. We already have Google to do that. What I'd really want to do is to be able to use the sensory input that I have.

My office is right on the water, in Boston, and I see this boat, and maybe I wonder what kind of boat that is, or how much it costs: Wouldn't it be incredible if my brain could communicate with very high bandwidth to a repository and extract this information in a way that I intuit the answers? It's speaking the same language my brain understands. So it's different than looking at your phone and going through a few different websites. That is how I imagine the merging of mind and machine.

—Brian Gallagher



GENETICS

Do Butterflies Challenge the Meaning of Species?

WHAT IS A SPECIES? The question has agonized scientists since well before Darwin. With some exceptions, the thinking has landed on an evidently firm reproductive barrier: Members of different species don't mate. If they do, their offspring are sterile. The reproductive barrier has thus created a useful demarcation of "what is a species"—until a deep dive into butterflies showed otherwise.

Researchers recently analyzed the genomes of every butterfly species in the United States and Canada—845 in total—and found that at critical evolutionary intervals, butterfly species have crossed the reproductive barrier, mating with other species of butterfly and thereby transferring genes from one species to another. Hybridization, it turns out, plays a pivotal role in how life forms evolve. The tree of life may never look the same.

In 2012, a paper by The Heliconius Genome Consortium showed that *Heliconius*—a gorgeous black bug whose distinctive markings mimic the wing patterns of other butterflies that are distasteful to predators—was sharing DNA among species through hybridization. In general, new species come about by way of a gradual accumulation of inherited traits that can eventually add up to a reproductively distinct entity. While genes are being copied mistakes get made, and these transcription errors can provide the individual with genes neither parent possesses. Evolution makes good use of these genes, using them to adapt to new circumstances. One species becomes two when adaptations in a population reach a level where that reproductive dividing line is established and the two species are forever riven. Or so it was thought.

In the paper, researchers showed *Heliconius* rapidly evolving into new species at junctures in their

The tree of life may never look the same.

evolutionary history, most likely in response to environmental pressures. At these pinch points, *Heliconius* sped up the process of speciation by mating across species boundaries and thus injecting new genetic material into their lineages. The huge diversity of *Heliconius* butterflies could be explained by hybridization, which can facilitate gene transfer.

The usual thinking is that “in eukaryotes, the channels are closed; reproduction within species is the only way to transfer genes,” Nick Grishin, a computational evolutionary biologist at the University of Texas, said. “The *Heliconius* work showed otherwise, and I wanted to push that thinking further.”

He and his team sequenced the genome of what he calls “a complete butterfly continent.” The work represents an exciting mashup of cutting-edge technology and the humbler, long-standing practices of amateur butterfly collectors. DNA testing has become ever-faster and more affordable, and computational power seems to get mightier by the day. But the contributions of amateur butterfly collections made it possible to analyze data across a massive expanse of habitat—most of North America—and across time. “We borrowed a lot of tissue from natural history museums,” Grishin told me. “Most butterfly collections were contributed by passionate amateurs over

the course of several hundred years, and we couldn’t have done this without them.”

The lead sequencing analysis was undertaken by Qian Cong, who typically studies protein sequences. “Getting the complete phylogenetic tree of U.S. butterflies allowed us to study how this big diversity of butterflies originates in time, and made us wonder why some lineages are particularly rich in species and why some butterflies appear to evolve much faster than others,” Cong told me. “We were able to find the possible evolutionary and molecular mechanism behind these observations,” she said, a key advance in figuring out exactly how biodiversity originates.

Traditional taxonomy had outlined an ancestral tree for butterflies, discerning family, tribe, genus, and species based on the overall body shape of the butterfly and wing-pattern. Grishin’s team was able to work out a genomic family tree that in large part agreed with the existing one based on anatomy. But it also showed more. “People thought butterflies were closely related based on what they look like, but genomically, we saw something else.” Grishin’s group reclassified 40 species and suggested several new genus levels.

It may be that the species paradigm needs a big overhaul if seemingly well-separated animals can actually interbreed. The revelations of butterflies are informing long-standing questions about *Homo sapiens*, for example. We have ancient DNA that may or may not have come by way of our ancestors mating with Neanderthals. “It’s possible we received genes from Neanderthals that enabled us to move out of Africa and into cooler climates,” Grishin said.

As the picture of life gets longer and deeper thanks to genetic analysis, so too the humble arts play their part. Grishin and Cong are both computational scientists who work in the lab. Yet Grishin credits Cong and colleagues with becoming stellar amateur lepidopterists in the course of their research. Instead of flying to conferences, they would drive, stopping by the side of the road to collect butterflies. Cong told me that their research adds to those with similar ambitions, “to obtain genomes of every species on Earth. These genomes are gifts from millions of years of evolution. Nature did the experiments, and we are trying to check the results.”

—Mary Ellen Hannibal



POETRY

Advice for a Black Hole After Its First Portrait

Consider, you are a *black hole*!
You are unique!
No other black hole
bends light and matter
like you do.
Your portrait, we know, isn't flattering,
blurs your dark side.
Two dimensions isn't you.
You are so many dimensions!
Let other black holes be obscure.
You are seen! You draw in the vasty reaches
and make them part of you.
Black hole, compared to you, a mere star
Is nothing.

—Robert Thompson



A misty forest scene with large trees and moss-covered ground. The foreground is dominated by large, gnarled tree roots covered in vibrant green moss. In the background, several tall trees with thick trunks stand in a foggy or misty environment. The overall color palette is dominated by greens and greys, creating a serene and mysterious atmosphere.

Never Underestimate the Intelligence of Trees

Plants communicate, nurture their seedlings, and get stressed

BY BRANDON KEIM

CONSIDER A FOREST: One notices the trunks, of course, and the canopy. If a few roots project artfully above the soil and fallen leaves, one notices those too, but with little thought for a matrix that may spread as deep and wide as the branches above. Fungi don't register at all except for a sprinkling of mushrooms; those are regarded in isolation, rather than as the fruiting tips of a vast underground lattice intertwined with those roots. The world beneath the Earth is as rich as the one above.



TREE WHISPERER “I think that we’re so utilitarian with plants and we abuse them to no end. I think that comes from us having our blinders on. We haven’t looked,” says forest ecologist Suzanne Simard (above).

For the past two decades, Suzanne Simard, a professor in the Department of Forest & Conservation at the University of British Columbia, has studied that unappreciated underworld. Her specialty is mycorrhizae: the symbiotic unions of fungi and root long known to help plants absorb nutrients from soil. Beginning with landmark experiments describing how carbon flowed between paper birch and Douglas fir trees, Simard found that mycorrhizae didn't just connect trees to the Earth, but to each other as well.

Simard went on to show how mycorrhizae-linked trees form networks, with individuals she dubbed Mother Trees at the center of communities that are in turn linked to one another, exchanging nutrients and water in a literally pulsing web that includes not only trees but all of a forest's life. These insights had profound implications for our understanding of forest ecology—but that was just the start.

It's not just nutrient flows that Simard describes. It's communication. She—and other scientists studying roots, and also chemical signals, and even the sounds plants make—have pushed the study of plants into the realm of intelligence. Rather than biological automata, they might be understood as creatures with capacities that in animals are readily regarded as learning, memory, decision-making, and even agency.

This can be difficult to wrap one's head around. Plants are not supposed to be smart, at least not according to the rubric of traditions known as Western thought. There's also a case to be made that, while these behaviors are indeed extraordinary, they don't map neatly onto what people usually mean by learning and memory and communication. Perhaps trying to define plants' behavior according to our own narrow conceptions risks obscuring what is unique about their intelligence.

It's a rich and fascinating debate, one that won't be answered without a great deal more research—and that research ought to be conducted with an open mind to the possibility that plants have minds. Simard spoke with *Nautilus* from her office at the University of British Columbia about the horizons of her work.

To get the ball rolling, can you tell me about Charles and Francis Darwin's root brain hypothesis?

Behind a growing root tip is a bunch of differentiating cells. Darwin thought those cells determined where roots would grow and forage. He thought the behavior of a plant was basically governed by what happened in those cells.

The work I and others have been doing—looking at kinship in plants, how they recognize each other and communicate—involves the roots. Except now we know more than Darwin did; we know that all plants, except for a small handful of families, are mycorrhizal: The behavior of their roots is governed by symbiosis.

It's not just those cells at a plant root's tip, but their interaction with fungus, that determines a root's behavior. Darwin was on to something. He just didn't have the full picture. And I've come to think that root systems and the mycorrhizal networks that link those systems are designed like neural networks, and behave like neural networks, and a neural network is the seedling of intelligence in our brains.

You've written that what makes neural networks so special is their scale-free character, which plant networks share as well. What does scale-free mean? Why is it so important?

All networks have links and nodes. In the example of a forest, trees are nodes and fungal linkages are links. Scale-free means that there are a few large nodes and a lot of smaller ones. And that is true in forests in many different ways: You've got a few large trees and then a lot of little trees. A few large patches of old-growth forest, and then more of these smaller patches. This kind of scale-free phenomenon happens across many scales.

Do you see scale-free networks at the level of individual trees, too, in the interactions within a single root system?

I haven't actually measured that, but there's many things that you could look at. For example, root size. You've got a few large roots that support finer and finer roots. My guess is that they follow the same pattern.

We know old trees change their behavior to give advantages to their own kin. A parent tree will kill off its own offspring if they're not in a good place to grow.

What makes that configuration so special?

Systems evolve toward those patterns because they're efficient and resilient. If we think of my forest, and the networks I've described, that design is efficient for transmitting resources among trees and how they interact with each other. In our brains, scale-free networks are an efficient way for us to transmit neurotransmitters.

There's something so primally amazing about networks between and within trees having similar properties to the networks in our brains. In the case of our brains, we understand that there's something about the structure of these networks that gives rise to cognition. What are some examples of plant cognition?

How do you define cognition? I'm asking because there's a whole group of scientists who say we shouldn't use that term because it means different things.

Would it be any better if I had used the word "intelligence"?

I've used the word intelligence in my writing because I think that scientifically we attribute intelligence to certain structures and functions. When we dissect a plant and the forest and look at those things—Does it have a neural network? Is there communication? Is there perception and reception of messages? Will you change behaviors depending on what you're perceiving? Do you remember things? Do you learn things? Would you do something differently if you had experienced something in the past?—those are all hallmarks of intelligence. Plants do have intelligence. They have all the structures. They have all the functions. They have the behaviors.

Another word that can be slippery is "communication." I would define communication as any exchange of information. That's a very big umbrella; it can apply to, say, the co-evolution of berry coloration and bird tastes, so that over time berry color becomes more appealing to birds and correlates with nutrient properties. That's communication—but we categorize that differently than we do the alarm calls squirrels give when a hawk approaches, or the conversation you and I are having right now. Where in that spectrum do plant communications fall?

Right in there. And we're prisoners of our own Western science; indigenous people have long known that plants

When you whack off the top of a plant, there's a huge response there. Is that an emotional response?

will communicate with each other. But even in Western science we know it because you can smell the defense chemistry of a forest under attack. Something is being emitted that has a chemistry that all those other plants and animals perceive, and they change their behaviors accordingly.

Putting science on that raises our own awareness that these plants are communicating just like we are. It's just not a vocal thing—although some people are even measuring acoustics in trees and realizing there's lots of sounds that we can't hear, and that could be part of their communication. But I don't know how far that research has gone. In my own work I've looked at the conversation through chemistry.

When you and I communicate, though, regardless of whether it's through sounds or scents, there are still individuals involved who have internal models of the world. It's a conversation between conscious individuals, rather than an exchange of information that takes place without some awareness of that information being exchanged. Does that type of communication exist among plants? I'm not trying to reinforce some

hierarchy where one type of communication is better than another, but to understand the distinctions.

I think what you're trying to get at is whether there's a purposefulness to it.

A purpose, and also some locus to receive and direct that purpose. In the animal-intelligence world, some philosophers now talk about pre-reflective self-awareness. The idea is that there's a coherent sense of self, an awareness that you are you, that's possessed by all animals by virtue of their having senses and some capacity for memory. The moment there's perception and memory, there's a self. Do you think plants have a self that is making those communications?

Those are really good questions. Probably the best evidence we have—and keep in mind that scientists have looked at humans and animals a lot longer than plants—is kin recognition between trees and seedlings that are their own kin. Those old trees can tell which seedlings are of their own seed. We don't completely understand how they do it, but we know there are very sophisticated actions going on between fungi associated with those particular trees.

You can smell the defense chemistry of a forest under attack. Something is being emitted and plants and animals perceive that and change their behaviors.

We know these old trees are changing their behavior in ways that give advantages to their own kin. Then the kin responds in sophisticated ways by growing better or having better chemistry. A parent tree will even kill off its own offspring if they're not in a good place to grow.

That last example, of a mother tree killing her offspring if conditions are unfavorable, touches on what I was trying to get at. Does the mother tree *know* she's doing it? Is there a choice? Can a mother tree choose whether or not to provide care, and then at some level does she know this?

We have done what we call choice experiments, in which we have a mother tree, a kin seedling, and a stranger seedling. The mother tree can choose which one to provide for. We found that she'll provide for her own kin over something that's not her kin. Another experiment is where a mother tree is ill and providing resources for strangers versus kin. There's differentiation there, too. As she's ill and dying, she provides more for her kin.

We've done lots of experiments where we adjust the health of the donor—the mother tree—versus the health of the recipient, the seedling, by altering levels of shade or nitrogen or water. It matters what condition each of them is in; they can perceive each other, and those decisions are made depending on conditions. If we suppress the health of the recipient seedling, the mother tree will provide more resources than if we don't.

We focus mostly on a one-way thing rather than both ways. It's hard to manipulate and measure big old trees; we've been trapped by the sheer size of trees and how they respond, how we can manipulate them and then measure their responses because they're diluted against this bigger array of things going on with them. I think we should do those experiments—it seems crazy that it wouldn't be a two-way perception.

Does a mother tree have a mental image of those seedlings? Of course, a mental image is a very animal-specific concept. But does it have some internal construct, however it's represented? Is that the same thing as having a memory of the seedlings in the way I have a memory of, say, my cat? I can think about my cat right

now even though he's in another room, not because I'm perceiving him but because I have a mental construct. You can look at the rings of a tree. The interactions with seedlings affect growth rates; they affect how much water and nutrients are taken up. People can reconstruct this and say, "Oh, this neighbor died over here in this particular year. This tree got released." They can even compartmentalize those responses in certain parts of the tree trunk. Different plants have different abilities to do that, but the memory is housed in the tree rings of all trees. In conifers, they also house those memories in the chemistry of their needles. An evergreen tree, for example, will hold on to its needles for five to 10 years.

In one of your papers you talk about ecological cycles of salmon migration and the distribution of nutrients through forest communities. You write, "We are now examining whether these salmon nutrient memories are transmitted from tree to tree. The spreading of the salmon memory, the telling of the story allows the trees, fungi, bears, and salmon to collaboratively inform the productivity and health of the ecosystem." Can you talk more about what that means?

When indigenous people harvested the fish, they took the guts of the fish and returned them to the river to replenish the river. Or they would bury the guts at the base of a tree to replenish the tree. The bears and wolves carry those salmon up, and their populations depend on them. And the trees are replenished by this salmon nitrogen and grow bigger, and shade the rivers, and provide habitat for bears and eagles.

The health of the people was linked to the health of the salmon population. The salmon population depends on how the people treat the salmon. The health of the forest is dependent on the salmon being able to migrate up into the streams and spawn healthy populations. We're looking at those linkages now.

Where does plant communication fit into that? You could describe those connections and interactions purely in ecological terms without invoking plant intelligence.

That's true. What we're doing is looking at the mycorrhizal networks of forest that have different populations of salmon in them. We're looking at how the

mycorrhizal networks that link trees change depending on whether there's salmon or not. The next step is to start labeling trees. We've started doing that, to see how nutrients flow from tree to tree, but we're at the very first stages of that.

The other thing we're doing is to reconstruct some of the stone fish traps built by indigenous people that were dismantled by the Department of Fisheries and Oceans Canada. Then we're going to measure how salmon nitrogen changes in the forest as a result. Hopefully, the next step will be this tree-to-tree communication of those salmon nutrients.

We also know that nitrogen doesn't just end up in the trees. It ends up in the understory of plants and the insects.

Is the idea that certain trees would be sharing not only with others of their kind, but with other plant communities as well?

Yes. The other parts of the plant community.

When I walk into a forest should I be seeing not just a bunch of isolated trees, nor one uber-organism comprised of them all, but rather many different communities interlocking with one another?

There's populations in communities. There's these populations of species that have their own population dynamics, but they are embedded within a community of all kinds of species and they're interacting with them. So when you're walking in a forest not only are there probably five or six different mycorrhizal networks going on, but there's the networks that are going on with the other species. For example, the nest webs of birds. They have their own web going on. They're interacting with each other. There's networks that interact with networks and they are all interdependent.

Most people would look at a tree and, if they see that it's no longer growing any new leaves, they say that the tree is dead. How long does the tree go on communicating even when it's "dead?"

As it's dying and decaying, there's all kinds of things going on. There's a dying process, and I don't think we totally understand it, but from a mycorrhizal point of view—and keeping in mind that there's also this

huge communication going on above-ground with these volatile organic compounds moving across the forest through the air—below ground, as the tree is dying, as long as there's a carbon source from photosynthesis, it will support the mycorrhizal fungi.

As the tree is dying, it actually transmits or communicates its carbon to other trees. And the fungus probably has a lot to do with how that's done, because it's going to invest in where it's going to get its energy from multiple sources. Once the tree is dead, it only takes about a year for the fungus to completely disappear. It doesn't take long—but that process of dying, it can go on for years. And the fungi are around. They're associated with that tree through the whole process.

They'll eventually abandon the dead tree. But even then other plants will start to grow on that dead tree. In our coastal forest, Western hemlock seedlings establish on old logs or old trees. And we know that those living trees around them are linked to those seedlings through the log. The mycorrhizal network just goes right through it. And so the life of that log goes on in those new seedlings establishing on the dead log. They're linked to the old trees and transmitting carbon into them.

This death thing isn't just like, step one, step two ... it's a process, and that dead thing is never really dead. There's living things that are growing on it right away, all the way through.

In research on animal intelligence, there's long been an emphasis—arguably it's still there now—on non-emotional and non-affective forms of cognition. Now more and more researchers are also studying emotions, and realizing that those other forms of cognition, like memory and problem-solving and reasoning, are intertwined with emotion.

If you take the neurobiology underlying our emotions out of the equation, then problem-solving and reasoning don't develop. With plants, most of the research I've read has been about the quote-unquote non-emotional side of things. Is there also emotion in plants?

I wish I knew more about emotion and affective learning. That said, let's say you have a group of plants and stress one out, it will have a big response. Botanists can measure their serotonin responses. They have serotonin. They also have glutamate, which is one of our

own neurotransmitters. There's a ton of it in plants. They have these responses immediately. If we clip their leaves or put a bunch of bugs on them, all that neurochemistry changes. They start sending messages really fast to their neighbors.

Is that an *emotional* response? I guess it is. But I can hear my botanist side saying, "That's not an emotion. That's just a response." But I think we can draw these parallels. It comes down to language again, to how we apply this language to look at these responses in plants.

I think bridging that communication gap is important so that people realize that when you go and whack off the top of a plant, there's a huge response there. It's not a benign thing. Is that an emotional response? It's certainly trying to save itself. It upregulates. Its genes respond. It starts producing these chemicals. How is that different than us all of a sudden producing a whole bunch of norepinephrine?

Are there things we're missing in plants because our concepts of intelligence are drawn from humans and from animals? There could be whole ways of being we don't even have words for.

I think that we are. I think that we're so utilitarian with plants and we abuse them to no end. I think that comes from us having our blinders on. We haven't looked. We just make these assumptions about them that they're these benign creatures that have no emotion. No intelligence. They don't behave like we do, so we just block it out.

The other thing I'm going to say is that I made these discoveries about these networks below ground, how trees can be connected by these fungal networks and communicate. But if you go back to and listen to some of the early teachings of the Coast Salish and the indigenous people along the western coast of North America, they knew that already. It's in the writings and in the oral history.

The idea of the mother tree has long been there. The fungal networks, the below-ground networks that keep the whole forest healthy and alive, that's also there. That these plants interact and communicate with each other, that's all there. They used to call the trees the tree people. The strawberries were the strawberry people. Western science shut that down for a while and now we're getting back to it.

What other relationships are possible? What does it mean to be giving, to be empathic with the vegetal world?

There's two words that come straight to mind. One of them is responsibility. I think that modern society hasn't felt a responsibility to the plant world. So being responsible stewards is one thing. And also regaining respect—a respectful interaction with those trees, those plants.

If you've ever read *Braiding Sweetgrass* by Robin Wall Kimmerer, she talks about how she'll go into the forest to harvest some plants for medicine or food. She asks the plants. It's called respectful harvest. It's not just, "Oh I'm going to ask the plant if I can harvest it, and if it says no, I won't." It's looking and observing and being respectful of the condition of those plants. I think that's the relationship of being responsible—not just for the plants, but for ourselves, and for the children and multiple generations before and after us.

I think this work on trees, on how they connect and communicate, people understand it right away. It's wired into us to understand this. And I don't think it's going to be hard for us to relearn it. ☺

BRANDON KEIM is a freelance nature and science journalist. He is the author of *The Eye of the Sandpiper: Stories from the Living World* and *Meet the Neighbors*, forthcoming from W.W. Norton & Company, about what it means to think of wild animals as fellow persons—and what that means for the future of nature.

ALICE AND BOB MEET THE WALL OF FIRE

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None of these claims is even close to being true. All derive from just two recent studies that use machine learning to explore different aspects of planetary motion. Both papers represent interesting attempts to do new things, but neither warrant the excitement. The exaggerated claims made in both papers, and the resulting hype surrounding these, are symptoms of a tendency among science journalists—and sometimes scientists themselves—to overstate the significance of new advances in AI and machine learning.

As always, when one sees large claims made for an AI system, the first question to ask is, “What does the system actually do?”

The Three-Body Problem

The three-body problem is the problem of predicting how three objects—typically planets or stars—move over time under mutual gravitational force. If there are only two bodies, then, as Newton proved, the behavior is simple: Each of the objects moves along a circle, an ellipse, or a hyperbola. But, as Newton and his successors also determined, when there are three or more bodies involved, the behaviors can become very strange and complex. There is no simple mathematical formula; and accurate prediction over extended periods of time becomes very difficult. Finding good ways to calculate solutions to the three-body problem and the n -body problem (the same problem, with more objects) has been a major challenge for computational physics for 300 years. The slew of “AI that solves the three-body problem” articles were based on an article in arXiv entitled “Newton vs the Machine: Solving the Chaotic Three-Body Problem Using Deep Neural Networks.”

As is often the case, the technical article is less over the top than the popular ones, but, for a technical scientific article, this one is still pretty ambitious. It ends with the prediction that techniques developed for a narrow case should extend both to the general three-body problem and then ultimately to the four- and five-body problems and other chaotic systems, which could conceivably constitute a genuine revolution.

The trouble is, the authors have given no compelling reason to think that they could actually do this. In fact, they haven’t even engaged in the full breadth of the existing three-body problem. Instead, they focused only on a special case of the three-body problem, involving three particles of equal mass starting from specified positions with zero velocity.

Even here, they are entirely dependent on a conventional physics engine or simulator—which is to say no AI, no machine learning, just traditional numerical solution of the differential equations of motion—to generate the trajectories of motion over time from 10,000 different starting positions.

They then used this classically derived database as input, to train the neural network. In testing the neural network on new examples, whose true solution was also calculated by the simulator, they found that the neural network could predict the later positions of the particles with reasonable accuracy, orders of magnitude faster than the conventional simulator.

In essence, what they were doing was to use the neural network as a new tool for interpolating from known values derived using an external, classical system. The neural network may be better at interpolation with a smooth space of values than other techniques, but most of the work comes from the external prior system doing the work. And, crucially, they haven’t shown that the same sort of interpolation would actually work in the more complex physics of the actual world, even for simple cases (particles of different masses), let alone in situations with more bodies than just three.

Meanwhile, in technical terms, even within the three-body problem, the class of problems they have solved has an easy subset viz. two degrees of freedom—that is, a problem instance is determined by two numerical parameters—whereas the general three-body problem has 10 degrees of freedom. In their limited version of the problem, the only choice you have in formulating a problem that fundamentally changes the behavior is where to place the third object relative to the first two. In the full problem, which they didn’t attempt, you can additionally choose the masses and

initial velocities of the second and third objects; and each of these choices can radically change how the system evolves over time.

And we know that the complexity of this kind of problem tends to increase exponentially with the number of degrees of freedom. So the problem they have solved is not five times easier than the general problem, it is vastly easier. And the problem gets rapidly worse as you add more points: the four-body problem has 17 degrees of freedom, the five-body has 24, the n -body has $7n-11$.

Second, if you only have to worry about two dimensions, then calculating 10,000 data points gives pretty good coverage. If, let's say, you want to map out the shape of a mountain, and you measure the elevation at 10,000 points—essentially, every point on a 100 x 100 grid—then you can estimate the elevation at any point in between pretty reliably. Things get much more complex as the number of dimensions increases, and the possibility of smooth interpolation working diminishes.

Third, the scientists failed to wrestle with the 800-pound chaotic butterfly in the room: the high degree of dependence on starting conditions. Two slightly different starting conditions can lead to radically different outcomes. This is not a limitation of the algorithm that you used to make the prediction; it is an inherent characteristic of the problem. Therefore, claiming that a machine learning system has learned to predict a chaotic system over the long term is like saying that it has learned to predict the behavior of a random process, like thermal noise or radioactive decay. It simply can't be done, regardless of the algorithm.

(Kudos to Caroline Delbert at *Popular Mechanics* for noticing this; most journalists missed it.)

Finally, even the comparison with a conventional simulator was flawed. Jonathan Goodman, of the math

department at New York University, an expert on these kinds of dynamical systems, assures us that modern adaptive methods can compute these trajectories much faster than the timings quoted in the paper; the conventional simulator was a straw model.

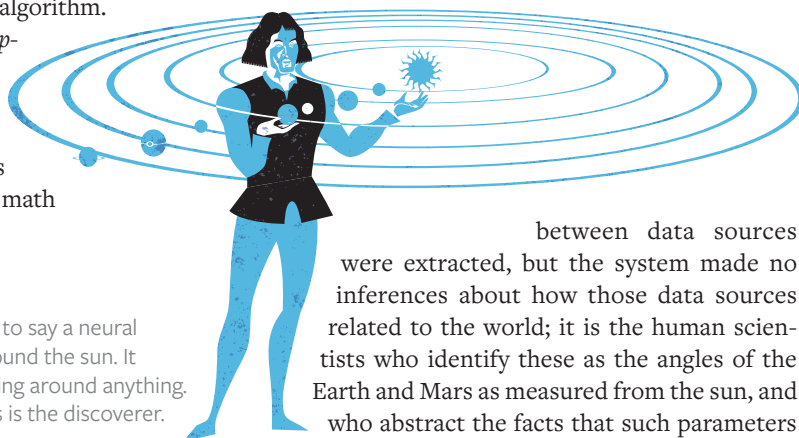
Copernicus

The situation with the Copernicus project is no better.

Here a different set of authors, in work to be published in *Physical Review Letters*, constructed a neural network designed to take as input numerical data from a physical process and extract the key parameters that determine the behavior of the process. They described four experiments involving simple physical systems of different kinds, in which their neural network succeeds as they had hoped.

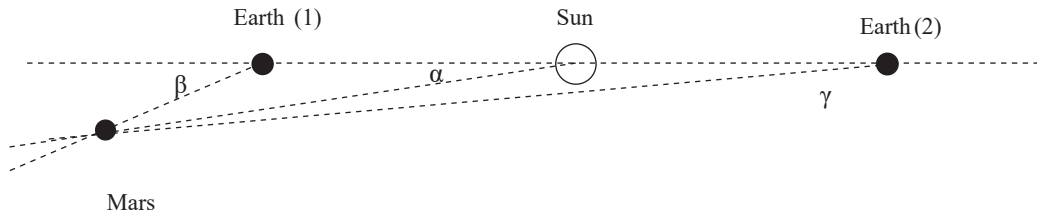
The supposed rediscovery of the Copernican system from astronomical observation is what caused excitement in the popular press.

The trouble is that it is entirely misleading to say that their neural network infers that “the Earth and Mars revolve about the sun.” The neural network doesn't actually understand that anything is revolving around anything, in a geometric sense; it has no sense of geometry and no idea what it would mean to revolve. All the neural network does is to extract the two numerical parameters involved; it has no idea that these represent angles from some fixed central point. As far as the network is concerned, these could be time-varying masses, or electric charges, or angles from two different central points. Correlations



THE DISCOVERER It's misleading to say a neural network infers the planets revolve around the sun. It doesn't understand anything is revolving around anything. The system is a calculator, Copernicus is the discoverer.

between data sources were extracted, but the system made no inferences about how those data sources related to the world; it is the human scientists who identify these as the angles of the Earth and Mars as measured from the sun, and who abstract the facts that such parameters



MARS ANGLES Mars is shown in its position farthest from the plane of the ecliptic. At that point the angle between the line from the sun to Mars and the ecliptic plane is then $\approx 1.8^\circ$. The position of the Earth, when Mars is at that place, varies from year to year. Earth (1) is the closest that the Earth comes to that position of Mars; when the Earth is there, the angle between the line from earth to Mars and the ecliptic is $\approx 5.5^\circ$. Earth (2) is the farthest that Earth gets from that position of Mars; when Earth is there, the angle between the line from the Earth to Mars and the ecliptic is $\approx 1.1^\circ$. The vertical axis has been exaggerated, for clarity.

are best interpreted as orbits. All of the real work of Copernicus' actual discovery is done in advance; the system was a calculator, not a discoverer.

Further, in the synthetic data the authors generated, the Earth and Mars move in constant-velocity circular orbits in the same plane. In the real solar system, things are notably trickier: The plane of Mars' orbit is tilted at 1.8° to the plane of the Earth's orbit (the ecliptic). In consequence, the apparent position of Mars against the fixed stars does not just move on an east-west circle, as it would if the two orbits were co-planar; it also moves back and forth on a north-south arc about 4° long. Viewed over a period of years, the position of Mars does not stay in a simple circular path in the sky; it lies in a strip that is 4° wide at its widest. Copernicus' real challenge (solved long before modern computers, and without Big Data) was vastly more complex than what the network had to deal with.

Four degrees may sound small, but by the standards of astronomical observations, it is huge. By way of comparison, Orion's belt is only 2.7° wide. Measurements in Ptolemy's *Almagest* are mostly accurate to within about $1/10$ of a degree.

Accordingly, both the Ptolemaic and the Copernican models of the solar system must have mechanisms to account for this transverse motion of Mars and the other planets. The Copernican model is therefore necessarily much more complicated than the simple model, that was produced (in a sense) by the neural network,

The trouble is, the authors have given no compelling reason to think that they could actually do this.

The media enthusiasm is sending the wrong impression, making it sound like any old problem can be solved with a neural network.

in which the Earth and Mars revolve around the sun in circular orbits. In fact, the Copernican model included 48 epicycles, more than the Ptolemaic model, though it was simpler in other respects. The network system doesn't even engage in the transverse movement.

Buoyed by their supposed success in duplicating Copernicus' accomplishment, the authors and journalists look forward to the days when this kind of machine learning technology can make radical advances in theoretical physics. An article in *Nature News* even enthused, "A neural network that teaches itself the laws of physics could help to solve quantum-mechanics mysteries."

This is pure fantasy. In the examples in this experiment, the relation between the data observed and the parameters extracted is fairly straightforward. By contrast, in most of the experimental evidence for quantum theories, the relation between the observations and underlying theories is extraordinarily indirect and subtle and requires extremely ingenious theorizing to reveal; detecting correlations as these neural network systems does not even scratch the surface of what would be required.

Why It Matters

The flaws in these particular studies are not huge in themselves, but the way they have been reported is symptomatic of a problem that is in fact serious. Such overblown reports lend false credence to the idea—most notoriously promoted in Chris Anderson's 2008 infamous article, "The End of Theory: The Data Deluge Makes the Scientific Method Obsolete," and increasingly part of the general zeitgeist—that AI generally and deep learning theory will soon replace all other approaches to computation or even to knowledge, when nothing of the sort has been established. The media enthusiasm for deep learning is sending the wrong impression, making it sound like any old problem can be solved with a massive neural network and the right data set, without attention to the fundamentals in that domain.

The truth is that many of the hard, open problems in the world require a great deal of expertise in particular domains. In the sort of problems in these two papers, it means if someone wants to make a useful contribution to the solution of the three-body problem or similar problems, one has to spend serious

time studying the sophisticated science of differential equations, numerical computation, and dynamical systems. In the domain of natural language understanding, it might similarly mean incorporating a great deal of work in linguistics and psycholinguistics, rather than gathering just a large data set and large assembly of sophisticated computers.

The widespread misimpression that data + neural networks is a universal formula has real consequences: in what scientists choose to research, in what companies and governments choose to fund, in what journals and conferences choose to accept for publication, in what students choose to study, and in what universities choose to teach. The reality is that neural networks, in anything like their current form, cannot replace the sophisticated tools of scientific analysis, developed over centuries, and have not thus far duplicated the great scientific accomplishments of the past—let alone improved upon them. They should be seen as tools that supplement existing techniques, not foundational revisions to how we do science. ☺

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Lessons for a Young Scientist

A masterclass on what science needs now

BY MARTIN REES

SOMETIMES WORRY that many who would enjoy a scientific career are put off by a narrow and outdated conception of what's involved. The word "scientist" still conjures up an unworldly image of an Einstein lookalike (male and elderly) or else a youthful geek. There's still too little racial and gender diversity among scientists. But there's a huge variety in the intellectual and social styles of work the sciences involve. They require speculative theorists, lone experimenters, ecologists gaining data in the field, and quasi-industrial teams working on giant particle accelerators or big space projects.



VISUAL GENERATION / SHUTTERSTOCK



Scientists are widely believed to think in a special way—to follow what’s called the “scientific method.” It would be truer to say scientists follow the same rational style of reasoning as lawyers or detectives in categorizing phenomena, forming hypotheses, and testing evidence. A related and damaging misperception is the mindset that supposes that there’s something elite about the quality of scientists’ thought and they have to be especially clever. Academic ability is one facet of the far wider concept of intellectual ability—possessed in equal measure by the best journalists, lawyers, engineers, and politicians.

The great ecologist E.O. Wilson avers that to be effective in some scientific fields it’s actually best not to be too bright. He’s not disparaging the insights and eureka moments that punctuate (albeit rarely) scientists’ working lives. But, as the world expert on tens of thousands of ant species, Wilson’s research has involved decades of hard slog: Armchair theorizing is not enough. Yes, there is a risk of boredom. And he’s right that those with short attention spans—with “grasshopper minds”—may find happier (and less worthwhile) employment as “millisecond traders” on Wall Street.

There’s no justification for snobbery of pure over applied work. Harnessing a scientific concept for practical goals can be a greater challenge than the initial discovery. A favorite cartoon of my engineering friends shows two beavers looking up at a vast hydroelectric dam. One beaver says to the other, “I didn’t actually build it, but it’s based on my idea.” And I like to remind my theorist colleagues that the Swedish engineer Gideon Sundback, who invented the zipper, made a bigger intellectual leap than most of us ever will. There are few more inspiring goals than helping to provide clean energy, better health, and enough food for the 9 billion people who will populate the world by mid-century.

ASPIRING SCIENTISTS DO BEST when they choose a field and type of research (fieldwork, computer modeling) that suits their personalities, skills, and tastes. It’s especially gratifying to enter a field where things are advancing fast, where you have access to novel techniques, more powerful computers, or bigger data sets. And there’s no need to stick with the same field for an entire career—nor indeed to spend all your career as

The smallest insect is structured more intricately than a star and offers deeper mysteries.

a scientist. The typical field advances through surges, interspersed by periods of relative stagnation. And those who shift their focus mid-career often bring a new perspective. The most vibrant fields often cut across traditional disciplinary boundaries.

And another thing: Only geniuses (or cranks) head straight for the grandest and most fundamental problems. You should multiply the importance of the problem by the probability that you’ll solve it and maximize that product. Aspiring scientists shouldn’t all swarm into the unification of cosmos and quantum, even though it’s plainly one of the intellectual peaks we aspire to reach. They should realize the great challenges in cancer research and brain science need to be tackled in a piecemeal fashion, rather than head-on.

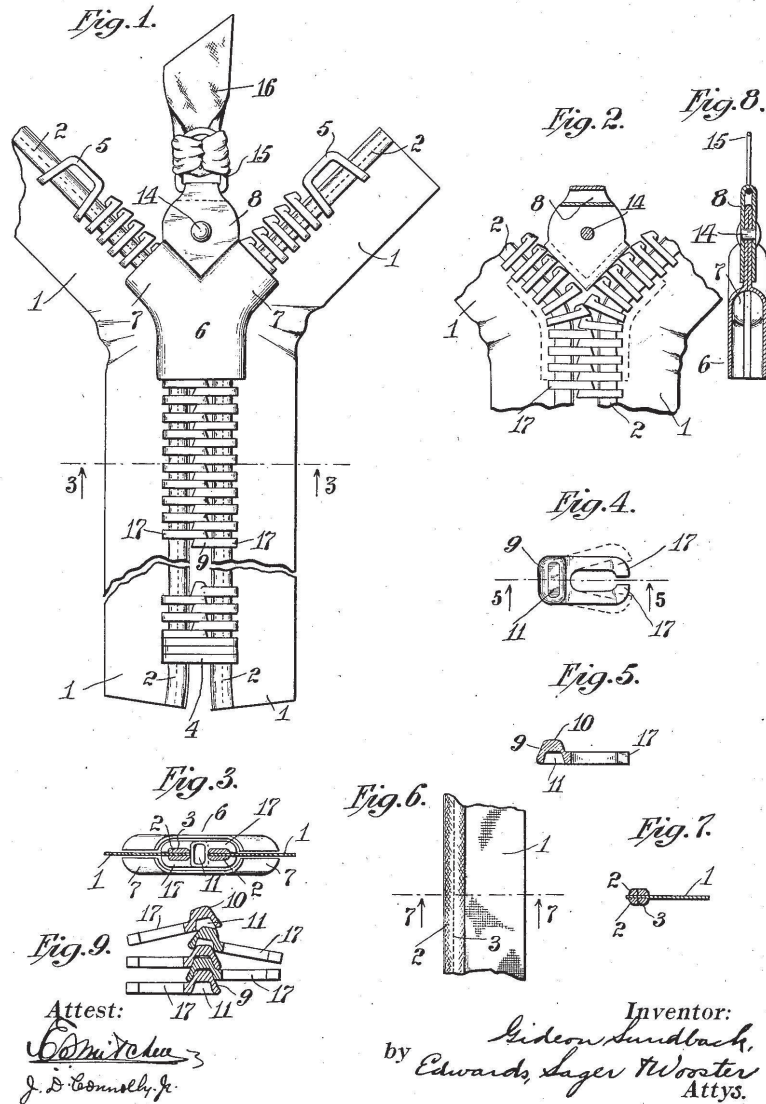
Odd though it may seem, it’s the most familiar questions that sometimes baffle us most, while some of the best-understood phenomena are far away in the cosmos. Astronomers confidently explain black holes crashing together a billion light-years away. In contrast, our grasp of everyday matters that interest us all—diet and child care, for instance—is still so meager that “expert” advice changes from year to year. But it isn’t paradoxical that we’ve understood some arcane cosmic phenomena while being flummoxed by everyday things. What challenges us is complexity, not mere size. The smallest insect is structured far more intricately than a star or a galaxy, and offers deeper mysteries.

IT’S CONVENTIONAL WISDOM that scientists, especially theorists, don’t improve with age, that they burn out. The physicist Wolfgang Pauli had a famous put-down for scientists past 30: “Still so young, and already so unknown.” (I hope it’s not just wishful thinking on the part of an aging scientist to be less fatalistic.) Despite some “late flowering” exceptions, there are

G. SUNDBACK.
SEPARABLE FASTENER.
APPLICATION FILED AUG. 27, 1914.

1,219,881.

Patented Mar. 20, 1917.



THE AMAZING ZIPPER "I like to remind my theorist colleagues that the Swedish engineer Gideon Sundback, who invented the zipper, made a bigger intellectual leap than most of us ever will," writes Martin Rees.

E.O. Wilson avers that to be effective in some scientific fields it's best not to be too bright.

few whose last works are their greatest. That's not the case for many artists. Artists, influenced in their youth (like scientists) by the then-prevailing culture and style, can improve and deepen solely through internal development. Scientists, by contrast, need continually to absorb new concepts and new techniques if they want to stay on the frontier. That doesn't mean productivity can't continue into old age. John Goodenough, co-inventor of the lithium ion battery, is still working at age 97. In 2019, he became the oldest-ever winner of a Nobel Prize.

There's a pathway that's seduced some of our greatest scientists that should nevertheless be avoided: an unwise and overconfident diversification into other fields. Those who follow this route are still, in their own eyes, "doing science"—they want to understand the world and the cosmos—but they no longer get satisfaction from researching in the traditional piecemeal way: they over-reach themselves, sometimes to the embarrassment of their admirers.

Arthur Eddington was perhaps the leading astrophysicist of his generation. In his later years (the 1930s) he developed a "fundamental theory" in which he claimed, via elaborate mathematics, to predict the exact number of atoms in the universe. Once, when Eddington presented his ideas in a lecture in Holland, a young scientist in the audience asked his older colleague, "Do all old physicists go off on crazy tangents when they get old?" No, the older scientist answered, "A genius like Eddington may perhaps go nuts but a fellow like you just gets dumber and dumber." That's at least some consolation for non-geniuses.

SCIENTISTS TEND TO BE SEVERE CRITICS of other people's work. They have more incentive than anyone else to uncover errors. That's because the greatest

esteem in their profession goes to those who contribute something unexpected and original—and overturn a consensus. But they should be equally critical of their own work. They must not become too enamored of pet theories, nor influenced by wishful thinking. Unsurprisingly, many find that hard. Someone who has invested

years of their life in a project is bound to be committed to its importance, to the extent that it is a traumatic wrench if the whole effort comes to naught. Seductive theories get destroyed by harsh facts. Only those that are robust enough to survive intense scrutiny become part of public knowledge—for instance, the link between smoking and lung cancer, and between HIV and AIDS. The great historian Robert Merton described science as "organized skepticism."

The path toward a consensual scientific understanding is often winding—with many blind alleys being explored along the way. Occasionally a maverick is vindicated. We all enjoy seeing this happen; but such instances are rarer than is commonly supposed, and perhaps rarer than would be inferred from reading the popular press. And sometimes a prior consensus is overturned. Most advances transcend and generalize the concepts that went before, rather than contradicting them. For instance, Einstein didn't "overthrow" Newton. He transcended Newton, offering a new perspective with broader scope and deeper insights into space, time, and gravity.

When rival theories fight it out, there is just one winner. Sometimes, one crucial piece of evidence clinches the case. That happened in 1965 for Big Bang cosmology, when weak microwaves were discovered which pervaded all of space and had no plausible interpretation other than as an afterglow of a hot, dense "beginning." And the discovery of "sea-floor spreading," again in the 1960s, converted almost all geophysicists to a belief in continental drift.

In other cases, an idea gains only a gradual ascendancy: Alternative views get marginalized until their leading proponents die off. Sometimes, the subject moves on, and what once seemed an epochal issue is bypassed or sidelined.

THE CUMULATIVE ADVANCE OF SCIENCE requires new technology and new instruments—in symbiosis, of course, with theory and insight. Some instruments are still tabletop in scale. At the other extreme, the pan-European Large Hadron Collider at CERN in Geneva is currently the world's most elaborate scientific instrument. Likewise, astronomical instruments are run by multinational consortia, and some are truly global projects—for instance the ALMA radio telescope in Chile (Atacama Large Millimeter/Submillimeter Array) has participation from Europe, the United States, and Japan.

But even if we work in a small localized group, we benefit from the fact that science is a truly global culture. Our skills (unlike those of a lawyer) are transferable worldwide. That's why scientists can straddle boundaries of nationality and ideology more readily than other groups in tackling both intellectual and practical problems. For many of us, that's an important plus in our career.

The best laboratories, like the best start-ups, should be optimal incubators of original ideas and young talent. But it's only fair to highlight an insidious demographic trend that militates against an optimum creative atmosphere.

Fifty years ago, my generation benefited from the fact that the science profession was still growing exponentially, riding on the expansion of higher education. Then, the young outnumbered the old; moreover, it was normal (and generally mandatory) to retire by one's mid-60s. The academic community, at least in the West, isn't now expanding much (and in many areas has reached saturation level), and there is no enforced retirement age. In earlier decades, it was reasonable to aspire to lead a group by one's early 30s—but in, for example, the United States' biomedical community, it's now unusual to get your first research grant before the age of 40. This is a bad augury. Science will always attract nerds who can't envisage any other career. And laboratories can be staffed with those content to spend their time writing grant applications that usually fail to get funding.

But the profession needs to attract a share of those with flexible talent, and the ambition to achieve something by their 30s. If a perceived prospect evaporates, some people will shun academia, and maybe attempt a

start-up. This route offers great satisfaction and public benefit—many should take it—but in the long run it's important that some such people dedicate themselves to the fundamental frontiers. The advances in IT and computing can be traced back to basic research done in leading universities—in some cases nearly a century ago. And the stumbling blocks encountered in medical research stem from uncertain fundamentals. The depressing failure of anti-Alzheimer drugs to pass clinical tests suggests not enough is yet known about how the brain functions, and that effort should refocus on basic science.

But I'm hopeful this logjam will be temporary, and that new opportunities are opening up for aspiring scientists. The expansion of wealth and leisure—coupled with the connectivity offered by IT—will offer millions of educated amateurs and citizen scientists anywhere in the world greater scope than ever before to follow their interests. These trends will enable leading researchers to do cutting-edge work outside a traditional academic or governmental laboratory. If enough make this choice, it will erode the primacy of research universities and enhance the importance of independent scientists to the level that prevailed before the 20th century—and perhaps enhance the flowering of the genuinely original ideas the world needs for a sustainable future. ☺

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Is Net Zero Emissions an Impossible Goal?

What it would take to suck more carbon dioxide out of the air than we put in

BY JOHN BAEZ

STEFANO MAZZOLA

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ATER RUSHES INTO VENICE'S city council chamber just minutes after the local government rejects measures to combat climate change. Wildfires consume eastern Australia as fire danger soars past “severe” and “extreme” to “catastrophic” in parts of New South Wales. Ice levels in the Chukchi Sea, north of Alaska, hit record lows. England sees floods all across the country. And that’s just this week, as I write this.

Human-caused climate change, and the disasters it brings, are here. In fact, they’re just getting started. What will things be like in another decade, or century?

It depends on what we do. If our goal is to stop global warming, the best way is to cut carbon emissions now—to zero. The United Kingdom, Denmark, and Norway have passed laws requiring net zero emissions by 2050. Sweden is aiming at 2045. But the biggest emitters—China, the United States, and India—are dragging their heels. So to keep global warming below 2 degrees Celsius over pre-industrial levels by 2100, it’s becoming more and more likely that we’ll need *negative* carbon emissions. That is, we’ll need to fix the air. We’ll need to suck more carbon dioxide out of the atmosphere than we put in.

This may seem like a laughably ambitious goal. Can we actually do it? Or is it just a fantasy? I want to give you a sense of what it would take. But first, here’s one reason this matters. Most people don’t realize that large negative carbon emissions are *assumed* in many of the more optimistic climate scenarios. Even some policymakers tasked with dealing with climate change don’t know this.

In 2016, climate scientists Kevin Anderson and Glen Peters published a paper on this topic, called “The trouble with negative emissions.” The title is a bit misleading, since they are not against negative emissions. They are against lulling ourselves into complacency by

making plans that rely on negative emissions—because we don’t really know how to achieve them at the necessary scale. We could be caught in a serious bind, with the poorest among us taking the biggest hit.

So, how much negative carbon emissions do we need to stay below 2 degrees Celsius of warming, and how are people hoping to achieve them? Let’s dive in!

IN 2018, HUMANS PUT about 37 billion tonnes of carbon dioxide into the air. A “tonne” is a metric ton, a bit larger than a U.S. ton. Since the oxygen is not the problem—carbon dioxide consisting of one atom of carbon and two of oxygen—it might make more sense to count tonnes of carbon. But it’s customary to keep track of carbon by its carbon dioxide equivalent, so I’ll do that here. The National Academy of Sciences says that to keep global warming below 2 degrees Celsius by the century’s end, we will probably need to be removing about 10 billion tonnes of carbon dioxide from the air each year by 2050, and double that by 2100. How could we do this?

Whenever I talk about this, I get suggestions. Many ignore the sheer scale of the problem. For example, a company called Climeworks is building machines that suck carbon dioxide out of the air using a chemical process. They’re hoping to use these gadgets to make carbonated water for soft drinks—or create greenhouses that have lots of carbon dioxide in the air, for tastier



CROP CIRCLE In 2004 the world created roughly 5 billion tonnes of “crop residue”: stems, leaves, and such left over from growing food. Managing these leftovers better could make a sizable dent in our carbon emissions.

vegetables. This sounds very exciting ... until you learn that currently their method of getting carbon dioxide costs about \$500 per ton. It's much cheaper to make the stuff in other ways; beverage-grade carbon dioxide costs about a fifth as much. But even if they bring down the price and become competitive in their chosen markets, greenhouses and carbonation use only 6 million tonnes of carbon dioxide annually. This is puny compared to the amount we need to remove.

Thus, the right way to think of Climeworks is as a tentative first step toward a technology that might someday be useful for fighting global warming—but only if it can be dramatically scaled up and made much cheaper. The idea of finding commercial uses for carbon dioxide as a stepping-stone, a way to start developing technologies and bringing prices down, is attractive. But it's different from finding commercial uses that could make a serious dent in our carbon emissions problem.

Here's another example: using carbon dioxide from the air to make plastics. There's a company called

RenewCO2 that wants to do this. But even ignoring the cost, it's clear that such a scheme could remove 10 billion tonnes of carbon dioxide from the air each year only if we drastically ramped up our production of plastics. In 2018, we made about 360 million tonnes of plastic. So, we'd have to boost plastic production almost tenfold. Furthermore, we'd have to make all this plastic without massively increasing our use of fossil fuels. And that's a general issue with schemes to fix the air. If we could generate a huge abundance of power in a carbon-free way—say from nuclear, solar, or wind—we could use some of that power to remove carbon dioxide from the atmosphere. But for the short term, a better use of that power is to retire carbon-burning power plants. Thus, while we can dream about energy-intensive methods of fixing the air, they will only come into their own—if ever—later in the century.

If plastics aren't big enough to eat up 10 billion tonnes of carbon dioxide per year, what comes closer? Agriculture. I'm having trouble finding the latest data, but in 2004 the world created roughly 5 billion tonnes

FOTOKOSTIC / SHUTTERSTOCK

of “crop residue”: stems, leaves, and such left over from growing food. If we could dispose of most of this residue in a way that would sequester the carbon, that would count as serious progress. Indeed, environmental engineer Stuart Strand and physicist Gregory Benford—also a noted science-fiction writer—have teamed up to study what would happen if we dumped bales of crop residue on the ocean floor. Even though this stuff would rot, it seems that the gases produced will take hundreds of years to resurface. And there’s plenty of room on the ocean floor.

Short of a massive operation to sink crop residues to the bottom of the sea, there are still many other ways to improve agriculture so that the soil accumulates more carbon. For example, tilling the land less reduces the rate at which organic matter decays and carbon goes back into the air. You can actually fertilize the land with half-burnt plant material full of carbon, called “biochar.” Planting crops with bigger roots, or switching from annual crops to perennials, also helps. These are just a few of the good ideas people have had. While agriculture and soil science are complex, and you probably don’t want to get into the weeds on this, the National Academy of Sciences estimates that we could draw down 3 billion tonnes of carbon dioxide per year from improved agriculture. That’s huge.

Having mentioned agriculture, it’s time to talk about forests. Everyone loves trees. However, it’s worth noting that a mature forest doesn’t keep on pulling down carbon at a substantial rate forever. Yes, carbon from the air goes to form wood and organic material in the soil. But decaying wood and organic material releases carbon back into the air. A climax forest is close to a steady state: The rate at which it removes carbon from the air is roughly equal to the rate at which it releases this carbon. So, the time when a forest pulls down the most carbon is when it’s first growing.

In July, a paper in *Science* argued that the Earth has room for almost 4 million square miles of new forests. The authors claimed that as these new trees grow, they could pull down about 730 billion tonnes of carbon dioxide. At first, this sounds great. But remember, we are putting out 37 billion tonnes a year. So, the claim is that if we plant new forests over an area somewhat larger than the U.S., they will absorb the equivalent of roughly 20 years of carbon emissions. In short, this

In the second half of the century we should be doing things that we can’t even dream of yet.

heroic endeavor would buy us time, but it wouldn’t be a permanent solution. Worse, other authors have argued that the *Science* paper was overly optimistic. One rebuttal points out that the *Science* paper mistakenly assumed treeless areas have no organic carbon in the soil already. It also counted on a large increase of forests in regions that are now grassland or savanna. With such corrections made, it’s possible that new forests could only pull down at most 150 billion tonnes of carbon dioxide.

That’s still a lot. But getting people to plant vast new forests will be hard. Working with more realistic assumptions, the National Academy of Sciences says that in the short term we could draw down 2.5 billion tonnes of carbon dioxide per year by planting new forests and better managing existing ones. In short: If we push really hard, better agriculture and forestry could pull 5.5 billion tonnes of carbon dioxide from the air each year. One great advantage of both these methods is that they harness the marvelous ability of plants to turn carbon dioxide into complex organic compounds in a solar-powered way—much better than any technology humans have devised so far. If we ever invent new technologies that do better, it’ll probably be because we’ve learned some tricks from our green friends.

Human-caused climate change, and the disasters it brings, are here.

And here's another way plants can help: biofuels. If we burn fuels that come from plants, we're taking carbon out of the atmosphere and putting it right back in: net zero carbon emissions, roughly speaking. That's better than fossil fuels, where we dig carbon up from the ground and burn it. But it would be even better if we could burn plants as fuels but then capture the carbon dioxide, compress it, and pump it underground into depleted oil and gas fields, unmineable coal seams, and the like.

To do this, we probably shouldn't cut down forests to clear space for crops that we burn. Turning corn into ethanol is also rather inefficient, though the corn lobby in the U.S. has persuaded the government to spend lots of money on this, and about 40 percent of all corn grown in the U.S. now gets used this way. Suppose we just took all available agricultural, forestry, and municipal waste, like lawn trimmings, food waste, and such, to facilities able to burn it and pump the carbon dioxide underground. All this stuff ultimately comes from plants sucking carbon from the air. So, how much

carbon dioxide could we pull out of the atmosphere this way? The National Academy of Sciences says up to 5.2 billion tonnes per year.

Of course, we can't do this *and also* sink all agricultural waste into the ocean—that's just another way of dealing with the same stuff. Furthermore, this high-end figure would require immensely better organization than we've been able to achieve so far. And there are risks involved in pumping lots of carbon dioxide underground.

WHAT OTHER ACTIVITIES could draw down lots of carbon? It pays to look at the biggest human industries: biggest, that is, in terms of sheer mass being processed. For example, we make lots of cement. Global cement production in 2017 was about 4.5 billion tons, with China making more than the rest of the world combined, and a large uncertainty in how much they made. As far as I know, only digging up and burning carbon is bigger: For example, 7.7 billion tons of coal is being mined per year.

While we can dream about energy-intensive methods of fixing the air, they will only come into their own—if ever—later in the century.

Right now cement is part of the problem: To make the most commonly used kind we heat limestone until it releases carbon dioxide and becomes “quicklime.” Only about 7 percent of the total carbon we emit worldwide comes from this process—but that still counts for more than the entire aviation industry. Some scientists have invented cement that *absorbs* carbon dioxide as it dries. It has not yet caught on commercially, but the pressure on the industry is increasing. If we could somehow replace cement with a substance made *mostly* of carbon pulled from the atmosphere, and do it in an economically viable way, that would be huge. But this takes us into the realm of technologies that haven’t been invented yet.

New technologies may in fact hold the key to the problem. In the second half of the century we should be doing things that we can’t even dream of yet. In the next century, even more so. But it takes time to perfect and scale up new technologies. So it makes sense to barrel ahead with what we can do now, then shift gears as other methods become practical. Merely waiting and hoping is not wise.

Totaling up some of the options I’ve listed, we could draw down 1 billion tonnes of carbon dioxide by planting trees, 1.5 billion by better forest management, 3 billion by better agricultural practices, and up to 5.2 billion by biofuels with carbon capture. This adds up to over 10 billion tonnes per year. It’s not nearly enough to cancel the 37 billion tonnes we’re dumping into the air each year now. But combined with strenuous efforts to cut emissions, we might squeak by, and keep global warming below 2 degrees Celsius.

Even if we try, we are far from guaranteed to succeed. Anderson and Peters are quite right to warn about this. But will we even try? That is more a matter of politics and economics than of science and technology.

The engineer Saul Griffith said that dealing with global warming is not like the Manhattan Project—it’s like the whole of World War II but with everyone on the same side. He was half right: We are not all on the same side. Not yet, anyway. Getting leaders who are inspired by these huge challenges, rather than burying their heads in the sand, would be a big step in the right direction. ☺

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Is the Law of Conservation of Energy Cancelled?

*Maybe energy can be created and destroyed,
or maybe the notion doesn't quite make sense*

BY DANIEL SUDARSKY

P HYSICS IS OFTEN BAFFLING, but one principle seems rock-solid: the law of conservation of energy. The world contains this thing called “energy” whose amount never changes. It can change its form or go from one body to another, but its total amount remains constant. Everything from the arc of a well-kicked football to the purring of a car engine depends on this law. It makes energy a precious commodity, counted, hoarded, and fought over.



PATPITCHAYA / SHUTTERSTOCK

We physicists have learned that our bodies do not merely use energy, but consist of it. Einstein's formula $E=mc^2$ identifies mass as a form of energy, one that can be converted to other forms (by a nuclear bomb, say) or created from those forms (in a particle collider). The formula strengthens our intuition that energy is the basic stuff of which things are made. When one gets deeper into physics, one also learns that conservation laws are intimately tied to symmetries, as first appreciated by the German mathematician Emmy Noether nearly a century ago. Energy is conserved because the laws of nature are symmetric in time—they do not change from moment to moment.

But physics wouldn't be physics if it did not continually question itself.

Not long after Einstein derived his famous formula, he began to create a theory of gravitation, his general theory of relativity. Energy conservation became a bit dicey. Although individual observers can measure the energy density immediately around them and confirm that the total energy of localized systems remains constant, it is impossible to define an overall energy that is strictly conserved. It might sound strange to be able to define a local quantity of energy and not a global one. And it is.



The quantum world is uncertain; attributes such as energy are ill-defined or fuzzy.

OUR OWN EXPANDING UNIVERSE is a good example of that strangeness. The energy density of matter decreases in inverse proportion to the volume of space. For instance, galaxies move apart, so that there are fewer of them in a given volume, in accordance with energy conservation. But the energy density of starlight and other forms of radiation decreases at a steeper rate. Their energy is lost. It does not go into some other form. This is allowed because an expanding universe is not symmetric in time; its growth differentiates past from future. So, general relativity makes it hard to sustain the view that energy is fundamental stuff from which everything else is made.

That is just the start. Consider the other theory that revolutionized the physics of the 20th century, quantum mechanics. The quantum world is uncertain; attributes such as energy are ill-defined or fuzzy. Worse, the theory has a very serious conceptual flaw, which must be taken into consideration when reviewing the ultimate fate of the conservation of energy.

Namely, quantum mechanics involves two distinct and incompatible recipes to determine how a particle or system of particles evolves in time. The first applies when the system is not being observed, the second when it is observed. The theory is vague about which recipe to use. What exactly constitutes a measurement observation? Need a conscious being be involved? Can a flea make a measurement? A virus? This issue is known as the measurement problem, which, as various critics have noted, should be referred to as the reality problem: The theory is unclear what exists “out there” independently of our perceptions.

As Tim Maudlin of New York University has discussed, approaches to dealing with the problem come in three types.¹ One adds so-called hidden variables—ingredients beyond what ordinary quantum theory provides—to provide a fuller description of the state of a system. The best known example is the de Broglie-Bohm theory, which supposes that besides the wave function there are particles that have definite positions that the standard quantum formalism does not capture. The wave function simply guides them like a sheep dog.

A second kind of approach postulates a random process that collapses the system’s uncertainty and eliminates its fuzziness. A third solution involves a multiplicity of universes. What we call a measurement

Physics wouldn't be physics if it did not continually question itself.

somehow corresponds to a splitting of our universe into many branches, one corresponding to each possible result. All these ideas dispense with the problematic recipe for measurement. None is without problems, but that is what there is.

IN 2019, MAUDLIN, ELIAS Okon of the National Autonomous University of Mexico, and I set out to study the fate of conservation laws in these three approaches.² Our analysis involved general considerations as well as various thought experiments.

Consider a standard experiment in which a quantum system—made of, for instance, a few photons—evolves into that characteristic quantum type of combination known as the “superposition” of two paths. These lead

to situations that, at the classical level, correspond to different values of the energy. One path takes photons to a distant galaxy and back, thus making them lose energy due to cosmic expansion. The other path involves no change in their original energy. According to a central tenet of quantum theory, each photon takes both paths.

The standard story in quantum physics is that any non-conservation can be explained away by taking into account the energy supplied or absorbed by the measuring apparatus. We remove that option by using another quantum effect, entanglement, to let us make the measurement remotely.

The three interpretive approaches offer different accounts of what happens to the energy. In

Dark energy is a sort of cumulative memory of all the violations of local energy conservation that have taken place in the universe's history.

spontaneous-collapse theories, the system, after a sufficiently long time, undergoes a sudden collapse to one of the energy values, leading to energy non-conservation. In the de Broglie-Bohm approach, any notion of energy with any chance of being generally conserved must involve both the particles and the guiding wave function. The wave function is split and later reunited in the lab, and the interference that occurs at the reunion makes the photons behave in such ways that energy is not conserved. In the many-worlds setting, the average energy of all the branches into which the world splits might be conserved, but in each branch energy will not be conserved. From the point of view of each branch, what occurs is just the same as in the collapse theories.

In short, we concluded that no scheme offers a reasonable definition of the global energy of a system that is strictly conserved. None offered a notion of local energy conservation, either—which is bad, because general relativity requires local energy conservation to be internally consistent.

To reconcile quantum mechanics and general relativity will require a quantum theory of gravity. Physicists disagree vehemently on what such a theory will look like, but most agree on one thing: The notion of spacetime will disappear at the fundamental quantum-gravity level. In that case, conservation laws lose their relevance completely. How can you say a certain quantity does not change with time if there is no time at the fundamental level?

AT THE PRACTICAL LEVEL, the deviations from strict conservation are expected to be minuscule and will not help with the concrete problems we humans face with energy. But for many theorists, any violation is blasphemous. Still, there may be a compensation.

Thibaut Josset and Alejandro Perez of the University of Marseille, James Bjorken of Stanford University, and I have shown that a modification to general relativity (originally considered by Einstein himself) permits small deviations from local energy conservation.³⁻⁵ And such a theory may offer a path to resolve one of the biggest mysteries in modern science: dark energy.

Dark energy is the mysterious component of the universe—some 70 percent of its total content—that is causing its expansion to accelerate. According to our analysis, dark energy is a sort of cumulative memory of

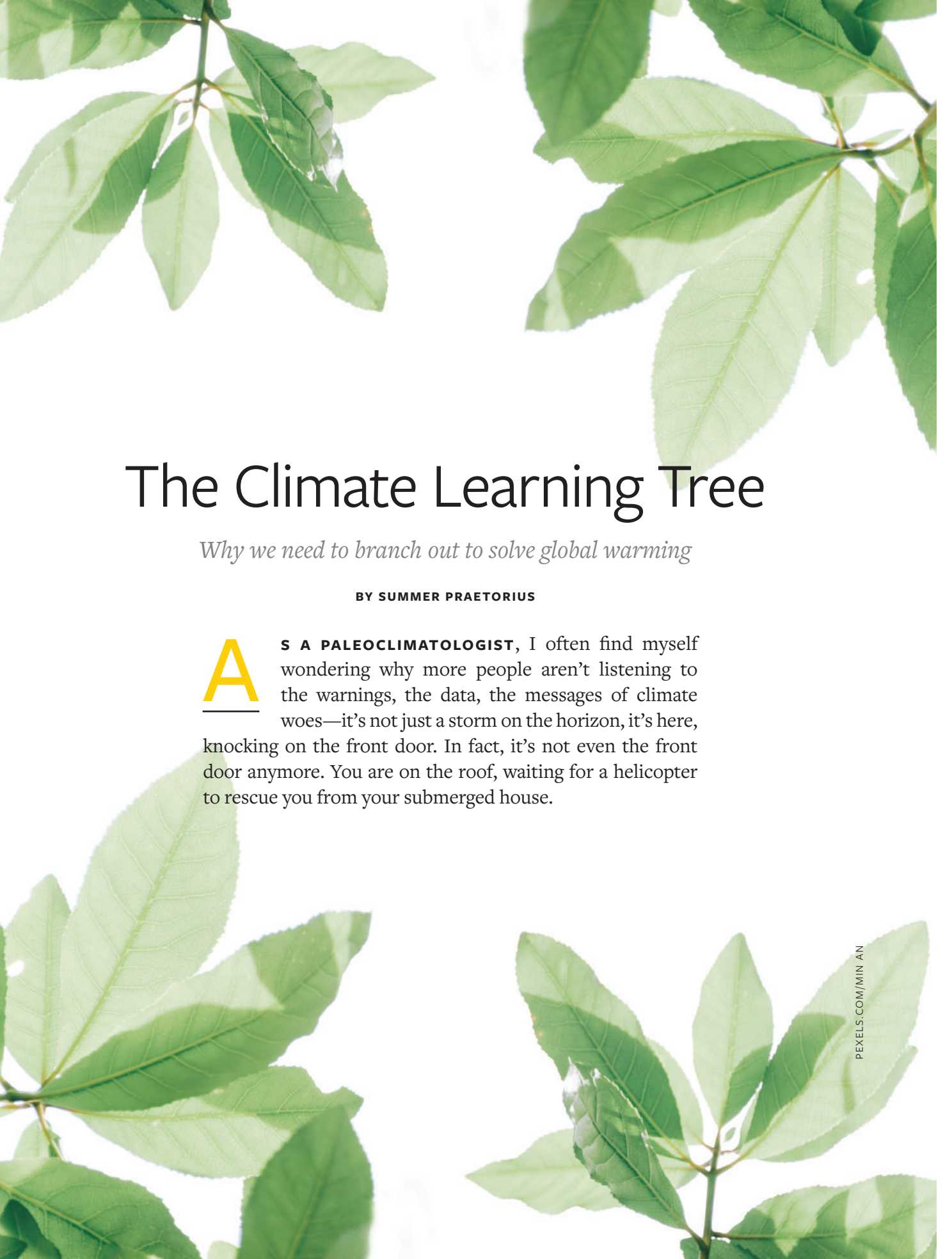
all the violations of local energy conservation that have taken place in the universe's history. In one of the specific models considered, the predicted value matches observations in a completely natural way.

Of course, the situation is far from settled. The exploration of these and related issues is still in its infancy. But when we look anew at a principle we used to take for granted, we expect to continue being surprised by its implications. ☺

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The page is framed by green leaves in the corners. Top-left and top-right corners show clusters of leaves. Bottom-left and bottom-right corners also show clusters of leaves, with the bottom-right one being more prominent and closer to the text.

The Climate Learning Tree

Why we need to branch out to solve global warming

BY SUMMER PRAETORIUS

A S A PALEOCLIMATOLOGIST, I often find myself wondering why more people aren't listening to the warnings, the data, the messages of climate woes—it's not just a storm on the horizon, it's here, knocking on the front door. In fact, it's not even the front door anymore. You are on the roof, waiting for a helicopter to rescue you from your submerged house.

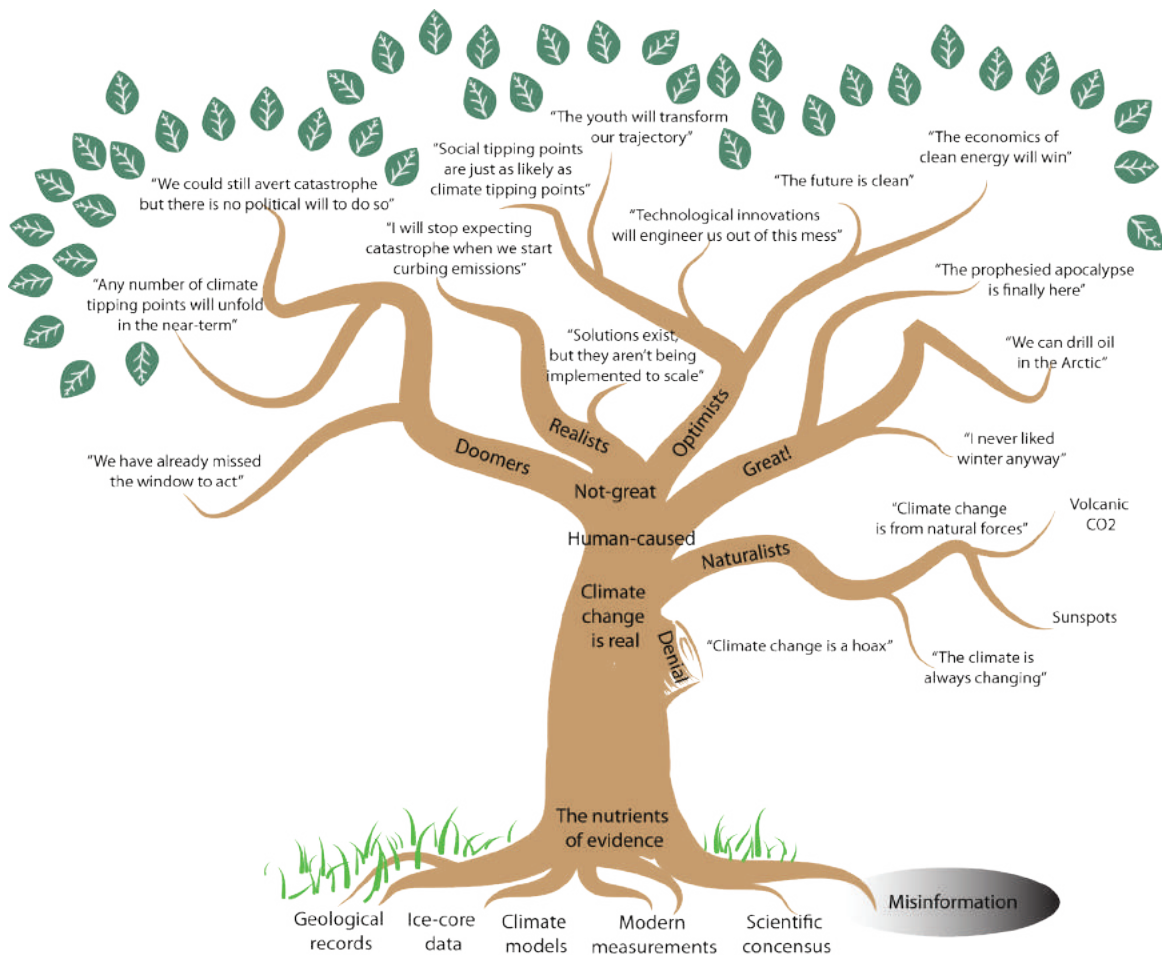
The data is clear: The rates of current carbon dioxide release are 10 times greater than even the most rapid natural carbon catastrophe¹ in the geological records, which brought about a miserable hothouse world of acidic oceans lacking oxygen, triggering a pulse of extinctions.²

Despite the evidence for anthropogenic climate change, views about the severity and impact of global warming diverge like branch points on a gnarly old oak tree (below).

The first split is between deniers and acceptors; only the denial branch doesn't go anywhere—it's just a dead stump, no longer sustained by the nutrients of evidence. The next bifurcation is on the root cause of climate change. Naturalists say "the climate has always

changed," which aside from ignoring evidence that the recent increase in carbon dioxide is from burning fossil fuels,³ is a diversion tactic for derailing meaningful conversations by stating the obvious. Of course, the climate is always changing; the relevant variable is the rate at which it does so.

If we follow the branch line that accepts the evidence for human-induced climate change, the next major split is between those who see global warming as a good thing and those who view it as a bad one. The former view an ice-free Arctic as a business boon for oil extraction or sweltering cities as an expanding market for air conditioners, or they are your clueless uncle joking about his property going up in value because it will suddenly be beachfront property.



Alarmists are labeled “Cassandras of doom.” But Cassandra was right. The problem is she was ignored.

This view is perched on a naïve premise that stability still prevails even amid the progressive undercutting of the systems that make it possible. It neglects the fact that accelerating the rates of change makes the probability of crossing thresholds far more likely.

If you keep following the branch points higher and higher, you come to a split in the messaging around the outlook for the future. This might even be between two climate scientists with similar backgrounds—some of whom are struggling with ecological grief⁴ and depression over dying coral reefs and the world their children will inherit, while others seem to always keep their chin up, adamant that the only way to communicate and solve the problem is to make sure it is wrapped in a bow of positivity.

THE DIVERGENT OUTLOOK of the future is like the old geological battle of gradualism versus catastrophism. Gradualists asserted that it was slow and steady processes like erosion that shaped the earth. Catastrophists pointed to extinction events in the fossil record as evidence for episodic events that punctuated the status quo and completely altered Earth’s bio- and geospheres—events like asteroid impacts or volcanism-induced carbon catastrophes. Both, it would turn out, were right. They were just pointing to different periods in Earth’s history—different slopes on the graph—adamant that they had the proof to back up their claim.

If we were to consider this dualism in terms of personality, we would all fall somewhere on the spectrum of gradualist to catastrophist. Gradualists expect more

or less steady rates of change. They have money in the stock market; trust in stability. They are inclined to believe science will engineer a solution to climate change. Catastrophists have a healthy respect for the unexpected. They store their money in gold and bury it under the apple tree, viewing any day as ripe for collapse: earthquake, stock market, tsunami, bolide. Catastrophists are not patient people.

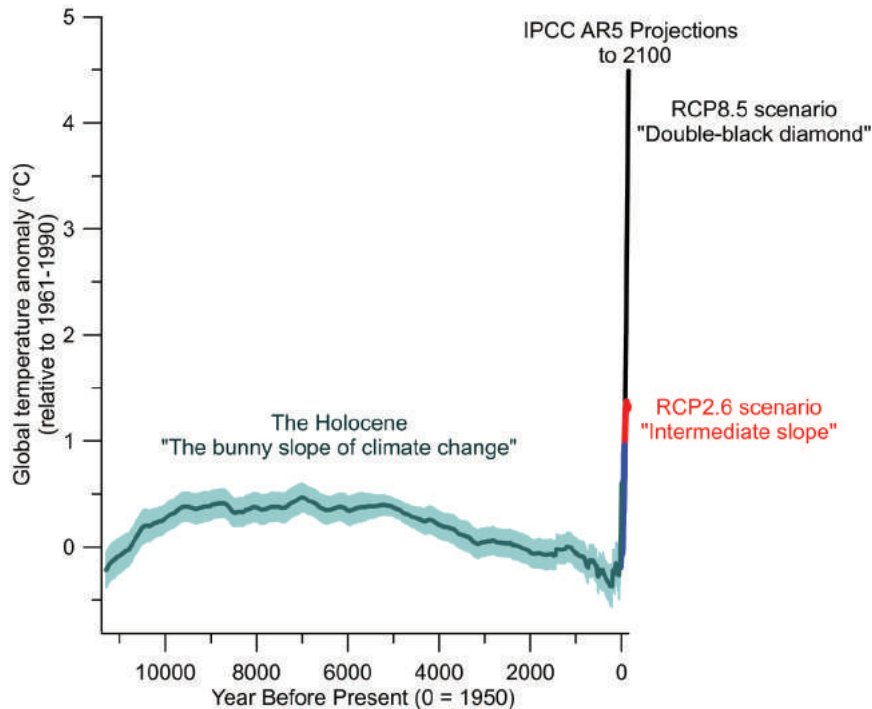
The fact is, climate change will come both slow and steady as well as fast and furious, reflecting the long-term average changes in global temperature and the short-term extremes that will continue to get more and more outrageous as the system absorbs energy. The last five decades have been to some extent slow and steady because the oceans have absorbed so much of the excess heat energy,⁵ buffering us from the brunt of it. This has likely contributed to a false sense of security for those who don't know the climate system is riddled with thresholds and tipping points,⁶ thinking that future changes will unfold just as gradually as the past.

But all that heat is now fueling massive storms and generating marine heatwaves that can take down entire ecosystems in shockingly abrupt timescales. Slow erosion can give way to sudden failure. The last five years have given us a taste of the fast and furious. In these five years, we have witnessed the collapse of coral reefs,⁷ the collapse of the California kelp forest,⁸ and wildfires⁹ and hurricanes¹⁰ of unprecedented proportions. These are local catastrophes unfolding in real time to the occupants of these regions, their lives already divided into before and afters, much like a geological timeline.

If there is one lesson we should heed from Earth history, it's that thresholds become far more likely as the rates and magnitude of change increase. And the danger of thresholds is that they are effectively one-way doors: easily walked through and closed to re-entry. This is the time-asymmetry of instability: It takes much longer to establish stability than it does to unravel it.

RATES MAY BE THE SIMPLEST and most critical aspect of climate change to understand, and yet it is not something that most people likely *see* on a regular basis. When I talk about rate, I take for granted that I am conjuring an image in my mind the whole time, in part because I stare at graphs of climate history every day. All those stories of ecological catastrophe are

The divergent outlook of the future is like the old geological battle of gradualism versus catastrophism.



DANGER AHEAD Temperature anomalies for the Holocene period (green)¹¹ compared with recent global warming (blue)¹² and future projections of a low carbon emission scenario (RCP2.6, pink) and high emission scenario (RCP8.5, black) from the IPCC AR5 report.¹³ The Holocene exhibits relatively gradual rates of change, whereas rates of modern and projected temperature increase are many times greater. We still have agency on whether we choose to take the double-black diamond route or an intermediate slope.

compactly folded up into a single near-vertical line on a graph. That's when you know you're in trouble: when the slope suddenly goes vertical (above).

For many climate scientists, the awareness of being on the knife's edge of the graph, plotting steeper and steeper every day is like learning to live with vertigo, partitioning off a deep sense that we are no longer on stable ground while simultaneously trying to get on with the day, show up to work, laugh with our kids.

Those who warn about potential instability have always been labeled "Cassandras of doom." There's an irony to this because *Cassandra was right*. She was just ignored as an "alarmist"—that dirty word now cleverly used to emasculate anyone concerned about climate change into the category of "hysterical woman."

The thing about alarms is that they turn out to be useful. The canary in the coalmine, smoke detectors, tornado sirens, cell phone alerts; we generally agree that instruments to detect and convey impending threats are a step in the right direction. In fact, we require them in most buildings. The inconvenience of an occasional false alarm is far outweighed by the benefit of not dying in your sleep by a raging fire.

So while catastrophists may get the eye-roll of hyperbole, gradualists warrant an occasional head-slap of naivete. Their apparent inability to conceive a fundamentally different world leads them into a default mode of complacency, one that ironically makes it much more likely to provoke the thing they aren't expecting. On the flip side, catastrophists are more prone to expect

disaster, and might be more motivated to prevent the potential threats. So each will unwittingly prove the other one right, if they have their way of things.

What if instead of feeling threatened by differences in opinion, we were to reconceptualize them in much the same way a tree will distribute a canopy to collect as much sunlight as possible—as a multi-pronged approach to getting the job done? In the same sense that both fast and slow processes contribute to Earth change, both steady progress and immediate local action will contribute to climate solutions. Let's take stock of our pace and work together, thankful there is someone else to fill the space we can't. After all, we are not lone trees, but a living, connected forest, and balance is essential for stability. ☺

SUMMER PRAETORIUS is a paleoclimatologist who studies the dynamics of abrupt climate change.

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Where Is My Mind?

The rise and fall of the claustrum epitomizes the hunt for consciousness in the brain

BY MARCO ALTAMIRANO & BRIAN N. MATHUR

IN 1976, FRANCIS CRICK arrived at the Salk Institute in La Jolla, California, overlooking a Pacific Shangri-La with cotton candy skies and a beaming, blue-green sea. He had already won the Nobel Prize for co-discovering the double-helix structure of DNA, revealing the basis of life to be a purely physical, not a mystical, process. He hoped to do the same thing for consciousness. If matter was strange enough to explain a creature's life code, he thought, maybe it's strange enough to explain a creature's mind, too.

For something that everybody walks around with every day, consciousness wouldn't seem to be as immense a puzzle as the origin of the universe. It's just *that* difficult to imagine how subjective experience can arise from basic physical elements like atoms and molecules. It seems like there must be more to the story. Small wonder, then, that for ages people believed that consciousness was a function of the soul, far beyond the grasp of science. Consequently, consciousness became the strongest argument for vitalism, the idea that life is dependent on immaterial or non-physical forces. When Crick, a lifelong defender of materialism, arrived in California, he was absolutely determined to dispel the notion from consciousness and blaze a path toward solving it.

In the last 30 years of his life, he propelled a revolution in neuroscience by molecular biology, challenging

the brightest minds in the field, usually over tea, and publishing works on his "astonishing hypothesis" that consciousness arises from the brain alone. On his deathbed in 2005, Crick, together with his friend and colleague Christof Koch, published a final article, "What is the function of the claustrum?", which reignited the search for the physical location of consciousness in the brain.¹ It proposed the claustrum, a set of neurons coincidentally shaped like a hammock, as the seat of consciousness because it receives "input from almost all regions of cortex, and projects back to almost all regions of cortex," the wrinkled surface of the brain responsible for conscious features ranging from sensation to personality. The promising idea would go on to spur probing studies on the nature of consciousness, and the beguiling role of the claustrum, that continue today.

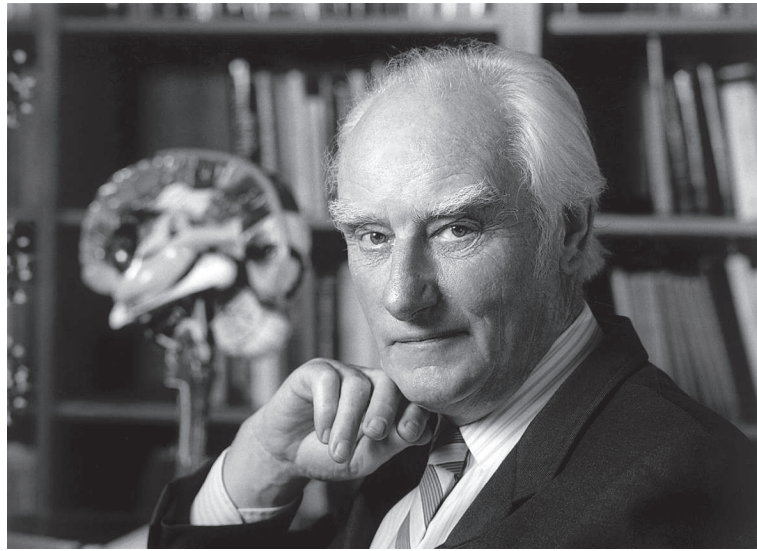


THE CLAUSTRUM IS FAR FROM the first part of the brain to be singled out as the seat of consciousness. The first hypothesis came in the mid-17th century from René Descartes, who notoriously claimed that the “soul has its principle seat in the small gland located in the middle of the brain”—namely, the pineal gland. The problem Descartes was trying to solve was how the soul (or mind), which he viewed as entirely separate from the body, nonetheless interacts with it. It’s easy to imagine how material bodies like bowling balls and pins interact, but thoughts don’t seem material. It’s hard to imagine them taking up any space or exerting force—so how does something seemingly immaterial interact with matter? How does ingesting a martini affect our thoughts?

To solve this, Descartes borrowed the concept of “animal spirits” from the ancient Greek physician Galen. Animal spirits, Descartes believed, were psychophysiological messengers in the blood that can record physical sensations while providing signals that the mind interprets as conscious perceptions. He nominated the pineal gland as the hub for these half-mental, half-material messenger spirits to interface and radiate throughout the body. Descartes’ hypothesis may seem extravagant, but it brought consciousness into the field of science, into the mechanism of bodies, as it were, opening the door that ultimately led to Crick.

An alternative to the pineal gland wasn’t suggested for another 200 years. In 1835, German physiologist Johannes Müller nominated as the seat of consciousness the medulla oblongata—a part of the brainstem that regulates the flow of oxygen rich blood cells to the rest of the brain. Although it’s a kind of power source for the brain, the medulla oblongata doesn’t seem related to higher-order conscious functions from a modern perspective. (It’s now known that the medulla is responsible for involuntary functions like vomiting and sneezing, hardly defining aspects of the human experience.)

The idea that the seat of consciousness in the brain must, in some way, be a hub for neural activity across the brain was seeded in the 19th century by the English physiologist William B. Carpenter. He located consciousness in the thalamus, in the middle of the brain. Even today, the role of the thalamus in consciousness remains largely conjectural, but Carpenter’s enduring



FINDING THE MIND Francis Crick brought to neuroscience an uncanny ability to determine the function of a biological system by studying its structure. He wanted to do for consciousness what he had succeeded in doing for the development of life, with DNA: to show that our inner life had a completely material basis.

legacy was to understand that consciousness is an experiential unity—not a cacophony of unconnected perceptions—and that the neural origin of consciousness must have the capacity to produce that unity by integrating higher-order functions (like thought, emotion, and agency) with lower-order sensory faculties.

Carpenter’s work was corroborated a century later by a pioneering American-Canadian neurosurgeon named Wilder Penfield. Penfield was treating patients with severe epilepsy by lesioning areas of the brain that were generating seizures, and he realized that he could functionally map specific movements or perceptions to specific areas of the cortex, which spreads out across the entire brain surface. But his map of the cortex presented a problem of brain geography that eluded Carpenter: How could remote and seemingly disconnected sensory processing areas generate the unified experience of consciousness? The solution did not seem forthcoming.

For a moment, it seemed that the claustrum was indeed what Crick suspected: the hub of consciousness.

Until Francis Crick, that is. He had an uncanny ability to envision the function of a biological system by looking at its structure. Crick searched for a neural structure capable of integrating information from distant regions of the cortex. Decades of fine-grained neuroanatomical studies directed him to one area of the brain that satisfied all his criteria: the claustrum. Bi-directionally connected with arguably every area of the cortex, the claustrum appears like the Grand Central Station of the brain. Crick's analogy was that if the different areas of the cortex processing various sensory modalities (visual, auditory, somatosensory, and so on) were the musicians in an orchestra, the claustrum was the conductor making sure everyone hit the right notes in time. His argument was simple, elegant, and cogent. It also provided the first scientifically sound and testable hypothesis for the seat of consciousness.

IN THE DECADES SINCE Crick set his sights on the claustrum, scientists have rushed to produce data about this mysterious region of the brain. A 2014 case study of an epileptic patient at George Washington University showed that electrical stimulation near the claustrum resulted in an immediate loss of consciousness, although the patient regained consciousness as soon as the stimulation stopped.² And in 2017, researchers at the Allen Institute discovered that the claustrum contains neurons that reach across the entirety of the brain like a “crown of thorns,” supporting the hypothesis that it’s a massive integrator and conductor of brain-wide activity.³ For a moment, it seemed that the claustrum was indeed what Crick suspected: the hub of consciousness.

However, two studies published earlier this year suggest that the claustrum’s moment has passed. A study on five epileptic patients at Stanford University demonstrated that zapping the claustrum on both sides of the brain had no effect on their subjective experience.⁴ Corroborating this, a study on mice from investigators at the University of Maryland showed that deactivating the claustrum resulted in no apparent loss of consciousness.⁵ Based on these data, it seems that the claustrum may be yet another red herring in the hunt for the seat of consciousness.

But if the claustrum doesn’t generate consciousness, what does it do? A German study of monkeys in 2010 found that claustrum neurons were excited by salient changes in their sensory environment, like the sudden call from another monkey.⁶ Building on that result, a whole-brain human imaging study in 2019 by the University of Maryland found that the claustrum activates when people begin a task that requires complex attention.⁷ These last two studies seem to indicate that the claustrum, though not responsible for basic conscious awareness, may nonetheless play an integral role in cognitively demanding tasks that could, at least obliquely, support Crick’s ideas.

While the claustrum may not be the seat of consciousness, it could still be a kind of chauffeur for it. Primates, especially humans, can be surprisingly absent-minded: We are often barely aware of our commutes to work until we take a wrong turn and, suddenly, the sensory world grabs our attention. Navigational habits allow primates to effectively auto-pilot through a lot of tasks, until there are unpredicted changes that spur cognitive demand, igniting the claustrum. How a possible cognitive control-like function for the claustrum relates to consciousness remains a matter of debate.

IN OCTOBER 2019, the Society for Claustrum Research convened in Chicago where Koch, from the Allen Institute, and one of us, Brian N. Mathur, held an open, albeit unresolved, discussion on the degree to which the claustrum may conduct consciousness. At the subsequent Society for Neuroscience meeting, new preliminary data encouraged revisiting the thalamus as a possible neural correlate for consciousness. These data would appear to place the seat of consciousness in another structure, but neuroscientists now largely

The field now stands on the precipice of new testable theories of consciousness.

suspect, thanks to Carpenter and Crick, that any neural correlate of consciousness functions as a part of a broader, dynamic neural network.

For example, Bernard Baars, who developed global workspace theory, argues that consciousness does not arise from a single anatomical hub like a claustrum. Instead, it emerges from a complex network of functional hubs working together in a sort of neuronal “cloud computing” format.

Giulio Tonini, at the University of Wisconsin-Madison, offers another interesting approach. The Italian neuroscientist’s integrated information theory (IIT) posits that the neural activity of a subject is associated with certain conscious experiences, such as reading the paper or walking through a neighborhood. The hypothesis is that the more areas of the brain that are stimulated at once, the more integrated the sensory, emotional, and cognitive information and, hence, the more conscious the organism.

IIT is supported, and even quantified, by a method developed by Tonini and Marcello Massimini in 2013 that yields a perturbational complexity index (PCI).⁸ PCI involves stimulating (that is, functionally perturbing) certain parts of cortex, which causes a response from the rest of the cortex that PCI maps and

measures. In sleeping subjects, the responsive activity is restricted, but in conscious subjects the activity is significantly more widespread and complex. Tonini claims that the measurement of this activity is a measurement of consciousness itself, allowing it to possibly determine whether unresponsive patients are truly in a vegetative state or in a conscious state but unable to communicate.

IIT’s methodology is brilliant, but there is something of a conceptual sleight of hand when it identifies consciousness with neural activity. Although it’s possible to measure patterns of neural activity and *correlate* them with certain conscious experiences, this is not logically sufficient to claim that such measurements *are* consciousness itself, *tout court*. Conceptually, at least, claiming that active neural patterns are consciousness is tantamount to pointing to a world map plastered on a wall and saying, “This *is* Copenhagen.”

Nonetheless, in a determined effort to bridge the gap between neural activity and the mind, researchers using IIT are now applying machine-learning algorithms to correlate PCI data with causal fingerprints of consciousness. As a result, the field now stands on the precipice of new testable theories of consciousness. But neuroscientists must still contend with the basic

The claustrum may not be the seat of consciousness, but it could still be a kind of chauffeur for it.

questions that have dogged the science of consciousness since Descartes; namely, what exactly is consciousness, and how can we study it through the brain?

Some philosophers imagine that the brain produces consciousness like the stomach produces enzymes or the gall bladder secretes bile. (It doesn't.) But the desire to confine consciousness to that sort of mechanistic description is kind of the problem: Although it's easy to localize apparatuses for different parts of conscious experience, say, the smell of dinner, or the distance to the table, or the music from the radio, consciousness itself offers no such broken mirror of experience—it's a coherent, unified experience of an entire body within an environment—the brain-gut connection, for example, is important for conscious emotions.

Perhaps it will be possible, someday, to replicate something approaching the dynamics of a conscious system *in silico* and produce the robots imagined in science fiction. Or, as Koch now startlingly suggests, it may be the case that the dualism between mind and matter is the obstacle for locating consciousness in the brain, and that matter already, somehow, experiences itself. Combining vitalism and materialism, the idea of panpsychism—that fundamental matter has conscious elements—is admittedly strange but, then again, so is consciousness. And, in a weird way, it confirms Crick's suspicion that matter, by itself, is dazzling enough to explain it. ☺

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As Winters Shrink, Our Discontent Grows

Our sense of order is disappearing with the snow packs

BY BERND BRUNNER

DMITRIJS BINDEMANIS / SHUTTERSTOCK

WINTER IS CHANGING its character. Since the beginning of the 21st century, glaciers have been melting at record speed. In Central Asia, they've lost approximately one quarter of their volume over the past 50 years. An ice grotto in Switzerland that is creeping down the slope as the Rhône Glacier advances is now covered with white blankets every summer to help preserve it. When a glacier ceases to flow and begins to melt, glaciologists use the term dead-ice, and when dead-ice melts completely, it leaves behind an uneven terrain full of potholes. Depending on their shape and location, these are known as donuts, puckered lips, or kettles. The highest ski resort in the world used to be on the glacier at the summit of Mount Chacaltaya in Bolivia. The glacier, 17,785 feet above sea level, disappeared years ago, and scientists have calculated that glaciers will continue to melt even if humans somehow manage to reduce the amount of greenhouse gases entering the atmosphere.

Investigations confirm that the snow cover in Earth's Northern Hemisphere is diminishing. In many places, winter is getting shorter and spring is setting in earlier. A well-known saying in France—"If you could sell snow, you'd be rich"—is no longer universally applicable. Shorter winters disrupt many natural processes; they also affect the activities we undertake during the season. Tourists no longer flock to winter resorts when cross-country skiing trails, ski runs, and ski-jumping hills remain undusted by snow—and producing snow artificially is expensive. In some skiing regions, people have started to invest in snow depots, which can provide short-term replenishment, shades of the icehouses of old. The terms *estivation* of snow and snow farming may soon enter the vernacular. Strategically placed fences collect drifts of snow that keep especially well when you wrap them in a protective layer of sawdust at least 16 inches thick, or enclose them in Styrofoam—incredibly, only a quarter of the snow that would disappear under normal conditions melts when these precautions are taken. This is done at many ski resorts, including Davos, Titisee in the Black Forest, and Ruhpolding, Bavaria. Admittedly,

it's not particularly romantic when resort operators have to supplement snow in this way. The term pseudo-snow seems justified, and it's only a matter of time before skiing will start to seem more like taking a ride in an amusement park than a sport in which participants pit themselves against nature.

The distinction between "natural" and "artificial" is getting increasingly blurred. These days technicians in down suits enter cold chambers to create artificial snow that can no longer be differentiated from natural powder. The process simulates what happens in the clouds: Cold air is blown over a trough of warm water, causing crystals to form. Varying the temperatures of the laboratory and the water changes the shapes of the crystals. The powder snow generated in the laboratory is different from the artificial snow generated on the slopes, when snow cannons spray minuscule droplets of water into cold air to freeze and form tiny balls of ice. Artificial snow made this way is denser than natural snow and forms a harder surface. It also thaws up to four weeks later, which affects plant growth. In areas where artificial snow is made with snow cannons, you tend to find species that blossom quickly, because their growing season is shorter.



ROCKY MOUNTAIN MELT, COLORADO (ABOVE) In a study focused on the Western United States, based on data from 1982 to 2017, Amato Evan, an associate professor at the Scripps Institution of Oceanography, showed that the annual cycle of snowpack became narrower and winter seasons shorter. “I would make the argument that our winters are getting sick,” Evan said at an American Geophysical Union meeting. “And we know the reason why. It’s global warming. It’s rising temperatures. That’s the only logical explanation for what’s happening.”

The rhythm of the seasons represents order in our world: One season enters as another exits. Winter used to have a far greater impact on our daily routine than it does today. Many young people have only heard of periods of deep cold or seen reports of them on television. We watch with fascination and a certain amount of horror as chunks of ice break away in the Arctic.

The people of the circumpolar regions aren’t the only ones noticing that it’s too warm. Animals whose habitats are drastically changing cannot complain, but they migrate to regions unfamiliar to them. The fact that the ice in Greenland and West Antarctica is melting doesn’t simply raise the level of the oceans, but also has repercussions for ocean currents. Climate experts anticipate these changes will lead to an increase in the number of winter storms and cyclones. How can spring still make its powerful effects felt when the preceding season is so mild that plants and animals no longer shut down?

How can we enjoy the other seasons when we haven’t previously experienced winter in all its asperity?

IN TIMES PAST, winter arrived unannounced. It was not unexpected, but without reliable weather forecasts people didn’t know exactly when they would be overtaken by snow and ice. Today legions of people follow the weather reports to learn about the advent of snow a few days in advance, perhaps watching for the best weekend to indulge in their favorite winter sport but giving little thought to stacking wood, rounding up the animals, chopping a hole in the ice for fresh water, or any of the backbreaking chores previously connected with preparing for winter.

ROBERT CICHETTI / SHUTTERSTOCK

Many young people have only heard of periods of deep cold or seen reports of them on television.

Though we have weather forecasts, are we really that much better off than our ancestors who waited for the return of predictable cycles? We can pinpoint when specific weather phenomena will arrive, but the weather's general timing and intensity are getting increasingly unpredictable.

When will we have to redefine the seasons on a phenological level? The phenological calendar divides spring, summer, and fall into three developmental stages. In the case of spring, changes are particularly noticeable. Recently, April has been demonstrating a pre-summer character, and black-thorn winters, also known as "ice saints" (a last frost before spring, an Indian summer in reverse) completely fail to materialize. Things are going haywire when the dead of winter brings phenomena that herald spring, such as almond trees blossoming—something that was observed in Germany at Christmas time in 2015.

As we dominate winter and tame its effects on us, we must remember that it retains moments of unpredictability that confuse our expectations and habits again and again, independent—at least partially—of climate change. Indications show that there have always been anomalies that did not conform to the pattern, even during the Little Ice Age. So we have Samuel Pepys's diary entry from Jan. 21, 1661: "It is strange what weather we have had all this winter; no cold at all; but the ways are dusty, and the flies fly up and down, and the rose-bushes are full of leaves, such a time of the year as was never known in this world before here." Simply a coincidence? Possibly an exception?

Similar statements have been made on more than one occasion by other reputable observers. In 1782, Thomas Jefferson reported in *Notes on the State of Virginia* that "snows are less frequent and less deep." He continued: "They do not often lie, below the mountains, more than one, two, or three days, and very rarely a week. They are remembered to have been formerly frequent, deep, and of long continuance. The elderly

inform me the earth used to be covered with snow about three months every year."

Whenever winter hits and however mild or severe it might be, we must remain cognizant of the fact that winter offers a change of pace, a reduction of the world around us. It can be a period of withdrawal, of reflection and regeneration. If we allow ourselves to embrace it, it can bring us back to a time when people were forced to be more flexible and responsive to the seasons. Maybe we, too, can become more receptive to the small pleasures and wonders that we otherwise perceive only peripherally, if at all?

Slow, quietly falling snow models the style of behavior appropriate for this time of year. The cold season also highlights our limitations and exposes our vulnerability. Shakespeare once wrote: "Winter, which being full of care, makes summer's welcome thrice more wished, more rare." Even if winter is no longer the existential challenge it was just a few generations ago, it reveals to us that there is a counterweight to the surfeits of summer. Isn't it the idea of perpetual summer that is abominable? How can we enjoy the other seasons when we haven't previously experienced winter in all its asperity?

The seasons are interdependent: the experience of real, unbridled cold and darkness—all part of winterlust—is what lets us relish warmth and light. Albert Camus reminds us of this dialectic of seasonal anticipation with his variation on Shakespeare's words: "In the depth of winter, I finally learned that within me there lay an invincible summer." ☺

BERND BRUNNER's work has been published in *Lapham's Quarterly*, *The Paris Review*, and the *Wall Street Journal Speakeasy*. He is the author of an eclectic array of books, including *Birdmania* and *Inventing the Christmas Tree*. His newest book is *Winterlust: Finding Beauty in the Fiercest Season*.

Excerpted from *Winterlust: Finding Beauty in the Fiercest Season*, by Bernd Brunner. Published in November 2019 by Greystone Books. Excerpted with permission of the publisher.

Why We're Drawn Into Darkness

Author Robert MacFarlane on the awe and horror of subterranean places

BY STEVE PAULSON

ROBERT MACFARLANE GREW UP obsessed with climbing mountains and nearly died on several occasions as he scaled some of the world's high peaks. He found a safer way to indulge his alpine passions, writing about the mystique of mountains. As someone drawn to great heights, it might seem odd to discover where Macfarlane landed in his new book, *Underland*, burrowing under the earth's surface into caves, mines, shafts inside glaciers, even the catacombs underneath Paris.

For Macfarlane, one of England's most celebrated nature writers, the underworld has its own deadly allure. It's the repository of nuclear waste sites and burial chambers, both a dumping ground and the portal into otherworldly realms. Passing through darkness becomes a precondition for gaining insight.

Armchair traveling isn't Macfarlane's style, so he ventures into these subterranean places, often with guides and sometimes at considerable risk. When he first set out on this project, he wasn't sure he was up to the task of spending all this time underground. So he called an old friend who's both a climber and caver, and asked him to, "Take me somewhere and scare the hell out of me." So they went on a caving expedition in a place called Giant's Hole in England, where they had to slither sideways to slip through small cracks, culminating in the "crab walk." Crawling through tight passages becomes a recurrent theme of this book, and I confess that reading about some of these adventures had me breaking out into a clammy, claustrophobic sweat.

Underland ranges over vast terrain, both scientific and literary. Macfarlane is a vivid writer, and in conversation veers easily between urgent environmental issues and his own personal exploration.

You call your new book *Underland* but you definitely give the sense you're descending into the underworld, with all the mythic weight that goes along with that. Did you feel a presence of death, whether metaphorical or actual, when you were underground?

I did. By the time you're in your 40s, you've known death a few times, known how dark and how irreversible it is. Our oldest story, *The Epic of Gilgamesh*, from 2100 B.C., is about going to the underworld to look for this precious thing and bring back news of the dead children of Gilgamesh. We're still doing that. There's a Bruno Latour line, "We have never been modern." I came across that again and again. We have glaciologists now who are boring a mile down into ice to bring back knowledge of past climates to foretell our future.





END TIMES “I’ve spent too long looking at early modern history to not know that we’re not the first to feel we’re living in end times,” says Robert MacFarlane (above). “I think we have a responsibility not to imagine we’re living in end times, which is to say we have to get on and do our best.”

Are the places below Earth’s surface also places of beauty and awe?

They’re certainly places of awe. They’re also places of imprisonment, incarceration, concealment, disposal. An historical place like the Cloaca Maxima, at the heart of central Rome, was the great sewer sump into which classical Rome disposed of all its unwanted filth. They’re places we’ve put the things we fear most and that disgust us most. In that sense, they’re not like mountains, although we’ve made a Cloaca Maxima out of Mt. Everest.

Underground places always seem forbidden.

Exactly. Forbidden and forbidding. What’s striking to me is we’ve been drawn into the darkness for longer than we’ve been drawn to mountains. The hand stencils on cave walls in Western Spain have been dated to about 65,000 years ago. That’s 20,000 years or so before *Homo sapiens* is thought to have reached that

region. So these are Neanderthal handprints. The idea of us being drawn into the darkness is an ancient longing. There’s also some of the most amazing, eerily present findings from European caves from the last Ice Age. A bone flute made from the wing bone of a griffon vulture was found deep in a limestone cave. The thought of that flute being played in that cave with ice filling the landscape around it, I don’t know about you, but it sets my spine shivering.

The underground is not just a dead zone. Biologically, isn’t the underground thriving with life?

Oh, my goodness, yes. We are only beginning to fathom the incredible diversities and depths of life in Earth’s crust. The rhizosphere, the soil, if we just take that top level, is a fabulous, vital substance that we hardly comprehend. Early this year, scientists revealed they had found a microbiome about 20 kilometers down into the crust. This is life of such volume that it exceeds by

BRYAN APPELYARD

hundreds of times the total biomass of all human life on Earth right now. It's so diverse they call it the Amazon of the underworld.

What kinds of organisms are living there?

It's all microbial life. It's bacteria, predominantly. But in such number and with such complexity that scientists are reeling at this. They call it biological dark matter, which is a great phrase. Then there's this fungal network, the mycorrhizal network, known durably, wittily, brilliantly as the Wood Wide Web.

Are these the fungal networks that extend from the roots of trees and allow trees to communicate with each other?

Yes. The popular description is the social network of trees. It's a mutualism, which is to say the fungi, the hyphae of the fungi, these fine white, ultra slender filaments, interact with tree roots at a cellular level. This mutualism has been around for about 400 to 500 million years but Western science has discovered it in the last 20. The fungi get carbon because they can't photosynthesize, and the trees get minerals because the fungi metabolize complex minerals using their exo body acids and give phosphorous back to the trees. The trees can also talk to one another. We have to be careful how we describe this. But they can pass resources between one another and pass, to some degree, signals between one another. All of that is happening, buzzing away, and suddenly it shakes the ground you walk on.

Does that give you a kinship with the more-than-human world?

It does. Although I think it's easy to talk piously about kinship with the more than-human-world. Not that you've done that. But many people do. I can be given to it myself. The Sami people have this beautiful image of the underworld where the dead stand with their soles upward, facing the ground. They're our inverse. We meet them soul-to-sole in both senses of the word. They walk through the ground upright as we walk through the air upright. So, yes, we are profoundly connected to the earth, we're stuck to it by our feet. But it's also where we go to exploit, to extract. We've bored 50 million kilometers of holes looking for oil. We're a

We are only beginning to fathom the incredible diversities and depths of life in Earth's crust.

boring species and an extractive species. So I guess the underworld, the underland, is where we've gone to be most miraculous, most compassionate, most tender, and the most rapacious and awful.

What does it mean to think in “deep time?”

Deep time is John McPhee's phrase for geological time. This is the time that makes our minutes and days and months and years look preposterous. Geological time is measured in eons and epochs. It's important to me to think that deep time extends forward away from us as well as backward behind us. Then we realize we are a geologically reshaping species. We now exist in such number, our powers amplified by technology to such volumes, that we are shaping a planet for deep time to come. We're doing that with the mass extinctions we're bringing about, with the radionuclides we're leaving in the rock strata, with desoiling, with all of the extraordinary orders of magnitude of change we're bringing about.

I went expecting to find the end of the world.

Which goes by the name the Anthropocene—the epoch in which we have fundamentally altered geologic history.

Yes, exactly. And there are many reasons to push that phrase. But let's take it for now as shorthand for the idea that we're, for the first time in our history, geological agents. To think in deep time is to ask, “What are we doing? What are we leaving behind? How will we be judged?” An example of that thought experiment was made concrete to me when I went to Onkalo, this Finnish hiding place, where they have constructed the first successful nuclear waste repository. We've been digging holes in the ground to get rid of things we don't want for a very long time. But what we haven't done successfully is dig a big hole in the ground to put radioactive waste into it. And when you're dealing with stuff that has a toxic half-life estimated at 100,000 years, you're thinking in deep time forward.

You're talking about becoming a good ancestor, you could say.

Yes, that's a version of Jonas Salk's brilliant question, “Are we being good ancestors?” And when you meet that question the first time you're like, “Huh, interesting.” Then you meet it again and it sears your soul, it

quarters your heart, and you think forward in deep time: Are we being good ancestors? I went to Onkalo expecting a sort of nuclear *Götterdämmerung*. I went expecting to find the end of the world. What I found was good people trying to do a good job, the best job they could with bad stuff. Oddly, I found it a hopeful place.

In the Anthropocene, things are also getting unburied. What's surfacing is eerie, don't you think?

It's more than eerie, it's a horror show. Unburials are everywhere. We are an unburying species as well as a burying one. Fossil fuels are the unburied remains of carboniferous forests. They're being burned and melting the ice of Pleistocene-era glaciers. They're shaping the futures of Anthropocene climates to come. The permafrost is no longer perma. It's melting and what's coming up is methane, woolly mammoths, 50,000-year-old wolf pups perfectly preserved down to the curl of their lip. In Kashmir, the Dolomites, and the Alps, where the white wars of World War I were fought, bodies are surfacing. These are all ghosts coming back to haunt us. 🌀

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If Only 19th-Century America Had Listened to a Woman Scientist

Where might the US be if it heeded her discovery of global warming's source?

BY SIDNEY PERKOWITZ

EVERETT HISTORICAL / SHUTTERSTOCK

HUMAN-INDUCED CLIMATE CHANGE may seem a purely modern phenomenon. Even in ancient Greece, however, people understood that human activities can change climate. Later the early United States was a lab for observing this as its settlers altered nature. By 1800 it was known that the mass clearing of forests raised temperatures in the Eastern U.S. and that climatic changes followed the pioneers as they spread west.

The causes for such changes, and the understanding that they could have global scope, came from eminent European scientists. Yet an amateur 19th-century American researcher, a woman named Eunice Foote, made a first crucial discovery about global climate change. Her story gives insight into early American science, women in science, and how the understanding of climate has changed. It also reveals how that understanding might have evolved differently to better deal with today's climate problems.

"Foote went from a farmer's daughter to one of the greats in the science of climate change," says John Perlin, a visiting scholar at the University of California, Santa Barbara, and author of books on solar power and other topics. Perlin is currently writing a book about Foote. His extensive archival research and a visit to the locales where she lived and worked have yielded new understanding of her environment and development.

THE STORY OF CLIMATE CHANGE begins in the 1820s, when the French scientist Joseph Fourier discovered the greenhouse effect by recognizing that atmospheric gases must trap the sun's heat. In 1859 the Irish physicist John Tyndall identified atmospheric water vapor and carbon dioxide gas, CO₂, as main components in absorbing thermal radiation. But in a lost piece of scientific history recovered only in 2011, Foote scooped Tyndall by three years when her experiments in 1856 first revealed the roles of water vapor and CO₂. Atmospheric

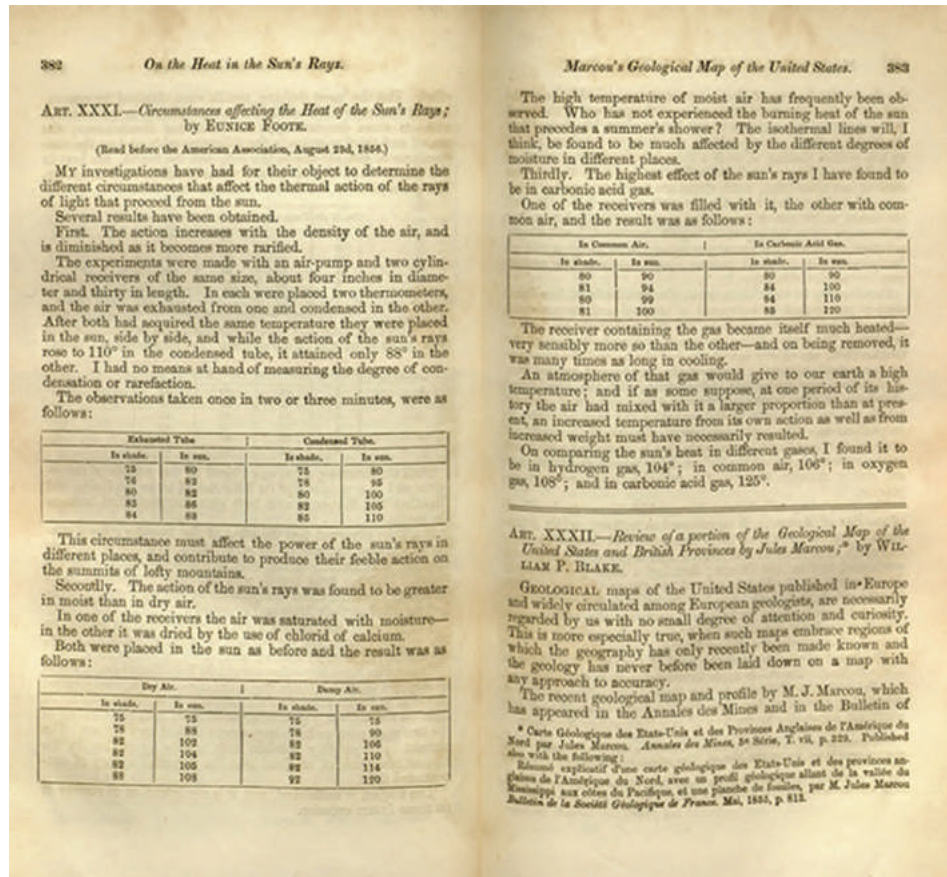
CO₂ levels at the time were only about 290 parts per million (ppm) and global climate change was not yet a known issue. Nevertheless, Foote predicted that changing CO₂

levels could change global temperatures, as we see today with CO₂ at over 400 ppm.

Who was Eunice Foote? At the time of her discovery she was a 37-year-old wife and mother. Born Eunice Newton in 1819 on a farm in Connecticut and raised largely by an older sister, she lived much of her life in upper New York state—a life marked by events that contributed to her scientific success.

One factor was her excellent schooling. From age 17 to 19, Foote attended the Troy Female Seminary in Troy, New York. This "mecca for women" had been founded by feminist Emma Willard in 1824 as the first women's prep school. It shared facilities with the nearby Rensselaer School (later Rensselaer Polytechnic Institute), whose co-founder Amos Eaton was a particular proponent of hands-on science training. Along with science-heavy curricula, according to Perlin, the schools featured the only two chemistry labs in the world then meant just for students. It was here, he says, that Foote learned lab technique and how to frame and carry out a research project.

Foote was also influenced by a famous neighbor, Elizabeth Cady Stanton, a major figure in early women's rights and suffrage movements who later worked with Susan B. Anthony. Stanton co-organized the first woman's rights convention held in the U.S., which met in Seneca Falls, New York, in 1848. Foote attended, and signed the convention's "Declaration of Sentiments" that stated the societal changes necessary to fully



THE FIRST WORD ON GLOBAL WARMING In 1856, in *American Journal of Art and Science*, Eunice Foote wrote, "The highest effect of the sun's rays I have found to be in carbonic acid gas." That prescient line was the result of her experiments showing the proportion of carbon dioxide (then "carbonic acid gas") in the atmosphere altered its temperature.

include women. More than that, she helped prepare the conference proceedings. Perlin believes she was especially motivated by a resolution that all the professions should be open to women.

As Perlin points out, next to Foote's signature on the Declaration of Sentiments you would have seen her husband Elisha's signature. He was one of only a few male attendees who actually signed, a demonstration of his support that must have been meaningful to Eunice. Elisha also shared her scientific interests. He knew Joseph Henry, the leading American scientist of the time and the founding secretary of the Smithsonian Institution. Elisha carried out meteorological work for

the Smithsonian and together with Eunice read Henry's writings about climate.

All these influences contributed to Foote's breakthrough paper, "Circumstances affecting the Heat of the Sun's Rays." It was presented at the 1856 meeting of the American Association for the Advancement of Science (AAAS)—but not by her. Elisha read his own research paper whereas Eunice's was introduced and read by Henry. Unlike the other reports at that meeting, it was not published in the proceedings. Nevertheless, it became somewhat known. It was briefly described in a few newspapers. *Scientific American* wrote that Eunice's work offered "abundant evidence of the

Foote went from a farmer's daughter to one of the greats in the science of climate change.

ability of woman to investigate any subject with originality and precision.” Fortunately, it did appear in full under Foote’s name in the 1856 issue of *The American Journal of Science and Arts*.

But then her discovery became lost. It might have remained so except for retired petroleum geologist Raymond Sorenson and a dose of what he calls “blind luck.” He collected old copies of the *Annual of Scientific Discovery*, a yearly summary of scientific research. In the volume for 1857, Sorenson came across a description of Foote’s work, and quickly realized that he was seeing the first reported connection between CO₂ and climate change. In 2011 he presented his findings in

a journal published by his professional society. “I’ve had more response to that than anything else I’ve ever written,” he has said, attention that continues as scientists and historians absorb the revelation of Foote’s work—especially in 2019, the 200th year after her birth.

Foote’s research used simple apparatus, two cylinders (presumably made of clear glass) 4 inches across by 30 inches long that each held two thermometers. She filled these tubes with different gases and compared their thermal responses to sunlight as judged by their temperature rises. Foote found that moist air absorbs more solar radiation than dry air; and what she called

“I have been wondering how many Eunice Foote’s are out there to be discovered.”

carbonic acid gas, that is CO₂, absorbs more radiation than ordinary air. That tube reached a temperature of 120 degrees Fahrenheit compared to 100 degrees Fahrenheit for ordinary air, and cooled more slowly. She also found that the tube with CO₂ became much hotter than tubes filled with hydrogen or oxygen under equal conditions.

Foote unquestionably preceded Tyndall in discovering the major roles of CO₂ and water vapor. This was remarkable for an amateur from the young American scientific community, compared to an educated professional working within a mature European scientific setting. Tyndall, however, established a critical feature that Foote had not. Using an infrared source in his well-equipped lab, he showed the greenhouse effect is not triggered by direct sunlight but by infrared radiation

arising from the Earth’s warmed surface. Foote’s experiment was not designed to distinguish between the two modes (although present-day analysis shows evidence of the infrared effect in her data). Tyndall deserves credit for uncovering this essential part of the greenhouse mechanism.

ONE LESSON FROM FOOTE’S LIFE is that original research arises from access to a scientific education and opportunities for mentorship and discussions. Multiple studies show the same holds true today. It’s also important to reflect on how Foote’s research was received. Why couldn’t she present her own work at AAAS, and why was it omitted from the published proceedings? Why didn’t her work receive wider attention? As Leila McNeill underscored in *Smithsonian.com*, bias against women is a large part of the answer. Women could join the AAAS in that era, but science historian Margaret Rossiter notes an internal hierarchy in the organization that rated “professional” men over “amateur” women. This may account for the downgrading of Foote’s presentation.

Later, Tyndall made a more serious omission. The papers he wrote about his discovery in 1859 and then in 1861—now five years after Foote’s work—did not mention her results, although he cited those of Fourier and others. Priority of discovery has always been a serious matter in science. With no citation to Foote’s work, Tyndall took center stage as “the father of climate science.” Equally important in the long run, his omission also kept Foote’s work from contributing to climate science as it developed in Europe.

Sexism colored Tyndall’s perception of women as scientists, as revealed in a passage from the biography, *The Ascent of John Tyndall*. The book’s author Roland Jackson writes that Tyndall “often exhibited surprise at women’s intellectual capabilities, and though he imagined that women could understand anything revealed by the savants, he did not believe they had the same powers of imagination and discovery.”

Was this attitude enough to make Tyndall purposely ignore Foote’s work? In an article published this year, Jackson denies the possibility. He argues that poor communication between American and European science makes it likely that Tyndall simply did not know of Foote’s research. He adds that covering up her work

would not have been in Tyndall's character. Perlin, however, believes the omission was deliberate. He argues that Foote's research appeared in publications where Tyndall was virtually certain to have seen it. Perlin also notes a separate incident where Tyndall failed to credit earlier work by another American researcher (who happened to be Joseph Henry).

Whatever the link is between Tyndall and his treatment of Foote's research, his attitude echoed what many of his male colleagues thought about women in science. Despite this barrier, Foote is an inspiration for female scientists today. One of them, Leila Carvalho, is a professor of meteorology and climate sciences at the University of California, Santa Barbara. Responding to a recent seminar about Foote held at the university, Carvalho wrote that Foote's accomplishments "trembled my very core," and added, "I have been wondering how many Eunice Footes are out there to be discovered, and how much of their legacy has been veiled or even discredited because they cannot resist the pressure against gender, ethnicity, and race."

Carvalho underlines a lost opportunity for science. Had Foote's results been quickly and widely recognized in the U.S. and Europe, they may have generated American interest in climate science. That science could have been applied to climate change, as old tree rings and other data showed a rapid climb in Northern Hemisphere temperatures after the 1860s. With such a head start, the U.S. might have developed a deeper appreciation and a stronger response to the dangers of climate change than we see today from our government. This would benefit the whole world, and all of it coming from the efforts of an American woman scientist. ☺

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Homage to Velázquez
Picasso

I Am Not a Machine. Yes You Are.

Debating the impact of machine-created art

BY KEVIN BERGER

I'M TRYING TO EXPLAIN to Arthur I. Miller why artworks generated by computers don't quite do it for me. There's no human being behind them. The works aren't a portal into another person's mind, where you can wander in a warren of intention, emotion, and perception, feeling life being shaped into form. What's more, it often seems, people just ain't no good, so it's transcendent to be reminded they can be. Art is one of the few human creations that can do that. Machine art never can because it's not, well, human. No matter how engaging the songs or poems that a computer generates may be, they ultimately feel empty. They lack the electricity of the human body, the hum of human consciousness, the connection with another person. Miller, a longtime professor, a gentleman intellect, dressed in casual black, is listening patiently, letting me have my say. But I can tell he's thinking, "This guy's living in the past."

Miller is sitting at a simple table in a dim and sparsely furnished apartment on New York City's Lower East Side. It's an Airbnb place that's keeping him housed while he gives talks in bookstores and colleges in the city about his latest book, *The Artist in the Machine: The World of AI-Powered Creativity*. Miller is the Virgil of art and science writing, a guide through the underworld of artists employing scientific practices like gene-splicing, brain imaging, and computer-code writing to create works that ask viewers to reflect on how science and technology are changing our views of the world and everything in it, including us. His previous book, *Colliding Worlds*, features artists like Austrian sculptor Julian Voss-Andreae, who studied quantum physics. One Voss-Andreae work, *Quantum Man*, stands 8 feet tall and is constructed of more than 100 vertical steel sheets. The sculpture looks like a man when seen from the front, but as viewers move around it, the figure vanishes, representing how experiments in quantum physics, depending how they're set up, detect electrons as either waves or particles: "How you look at it, that's what it is," writes Miller.

Miller has a Ph.D. in physics from MIT and is an emeritus professor in history and the philosophy of science at University College London. *The Artist in the Machine* profiles an array of fascinating artists and engineers who write computer programs to generate music, paintings, and literature. Miller argues that AI-fueled art gains independence from its algorithmic parents and takes flight in works that bear the hallmarks of creativity and genius and will one day exceed human artists' wildest imaginative dreams. Miller says he sympathizes with what I'm saying about the power of art coming from the connection with a human artist, plumbing their emotions and consciousness. But I'm being premature. Just wait, he says, computers will one day produce art as transcendent as the works of Beethoven and Picasso were in their times.

So you're saying we'll one day connect with machine art as profoundly as we do now with human art?

Yes. The machine sees the world in a different way than we see the world. Just like an artist does. That gives you an inkling that machines will have a different physiology. In time, they will evolve emotions. Just from scanning the web now, they could imitate our

We can have hopes, dreams, and aspirations for humankind. But we are machines, just like computers are machines.

emotions. They'll say, "Oh, thirst, that's cool. I think I'll be thirsty," and they can convince you they're thirsty. "Love, that sounds cool too, I just had this nice discussion with a machine down the street, and it seems like love." They'll hone their notion of love by reading novels, and soon they will evolve emotions and consciousness. That will be the point of artificial general intelligence. Then it's just a hop, skip, and a jump to artificial superintelligence, where they go beyond us in intelligence, emotions, and consciousness.

Does machine superintelligence worry you?

No. I think if we teach machines to be creative, then they'll be beneficent toward us, rather than just keeping us around as household pets.

That's good to hear. But back to art.

OK. I think we should keep your question in mind: Can we appreciate art that we know has been produced by machines?

Can we?

We could learn to, yes. We may develop a preference for it. Just as we may eventually have a preference for the prose produced by sophisticated machines, which at first may be nonsense to us. Now machines generate prose with word play that we're not used to. That shows us machines can change the landscape of language. It's not unlike what happened in the 1840s, when the camera was invented, which freed artists from a too literal interpretation of nature, and opened the doors for the impressionists.

Still, I don't see how we can feel the agency of machine art as we do with human art.

Machines in art can have intent, and they can have a bit of free will, too. You can take a painting-robot out of a studio, out on the road, with a webcam attached to it, and it will look around and see something that strikes its fancy as a nice pattern, and say, "I think I'll paint that." So that's intent. That's a bit of free will, too. So machines can be out there in the world, and have some sort of physical experience.

Are you saying we don't need the human element to appreciate art?

Look at what's going on today with people sitting in front of their screens. Where's the human element? People are walking down the street looking at their phones. They're getting hit by cars.

I've interviewed neuroscientists who've said human connection activates brain networks that move us profoundly, perhaps more than practically anything else.

Well, you have to leave your mind open. That may well change.

Has researching the connections between science and art given you a more mechanical view of humans?

Yes, it has. In doing this work, I have developed a reductionist view of nature. There is a definite relationship between us and machines. We're like machines; machines are like us. We are basically biological machines.

What does it mean to be a biological machine?

It means we're made up of atoms and molecules. They obey laws of nature and evolved to produce us. They are the power behind our engines. We're just big chemical reactions. Each part of a machine is made by means of the good old laws of Newtonian physics, which were deterministic. But when you put this conglomeration together, it's capable of unpredictable or chaotic behavior. Unpredictability is one of the hallmarks of creativity. So right from the word go, machines can be creative. Since we are machines, we can just go out of existence like a machine. We can have consciousness, but when the electrons stop flowing, consciousness disappears and that's it. But that doesn't take away from



THE THIRD CULTURE "Scientists and artists speak the same language, especially in that nascent moment of creativity, when everything comes together, when you have the solution to your problem," says Arthur I. Miller (above).

our creativity. We can still be creative in an inspiring way. We can have hopes, dreams, and aspirations for humankind. But we are machines, just like computers are machines. When one says that to people, some get very upset. They ask me, “Is there a soul in a machine?” I say, you have to believe in a soul, and I don’t believe in a soul. It isn’t necessary.

Does it make you queasy to think of yourself as a machine?

No, not at all.

Why not?

Why should it?

Because being a machine implies we’re designed.

We are designed. Just not by a designer. We’re a big mistake. It just so happens a number of billions of years ago that there was an isotope of carbon in the sun that was spit out, landed on the Earth, and so we’re carbon-based. This accident could occur, probably did occur, somewhere else in the universe.

Right. But the biology that makes us what and who we are has evolved over billions of years. That evolution makes us very different from machines.

Well, machines are evolving too, and much, much faster than us.

But they were engendered by humans.

We were engendered by nature. Yes, a human made the program, and a human put the machine in operation. But that’s like saying Leopold Mozart taught Wolfgang the rules of music. But we don’t attribute Wolfgang’s creations to his father. Similarly, you don’t attribute AlphaGo’s success at Go to the AlphaGo team. Or if you teach your 4-year-old daughter how to draw, she will draw like you at first. But 20 years down the line, when she’s at art school, she’ll be drawing much differently.

It sounds like you’re saying there’s basically no difference between machine intelligence and human intelligence.

The bottom line is there is no difference. We are computable and machines are of course computable, so

there’s no reason why we’re not like machines. Consciousness is computational. It’s computed from 100 billion neurons in our mind. Since machines use computation, they’re computational, and there’s no reason why they cannot have consciousness.

You said you’ve become a reductionist. What got reduced in your mind?

What got reduced in my mind is our body, us. You could say to a reductionist that there are things that science can’t explain. But science can and will explain everything we see around us.

Let’s step back. What is art?

Art is representations with concepts. That’s what it is to me. AI art does that. AI art has concepts because it’s generated by scientific means. It goes beyond the science, but it has a scientific basis to it, and so it has concepts. I have my own definition of aesthetics, too.

Lay it on me.

It makes art historians’ hair stand on end. Aesthetics equals the image in a work of art—and the image need not be a visual image—but an image from our five senses, plus the apparatus that generates it. For example, at CERN, I asked a physicist for his definition of aesthetics, and he said, “My notion of aesthetics is nicely laid out wires.” I saw them. There are these units of parallel wires, nothing crossed over, and the wires are color coded. It was beautiful.

I like what Simon Colton, a professor of digital game technologies, tells you. One of his projects, The Painting Fool, is great. He fed *Guardian* news articles to a computer and had software analyze words and phrases for moods like happy or sad. The computer then created portraits of people, which varied, according to its mood. Colton says comparing AI to human art is irrelevant. We should “be loud and proud about the AI processes leading to their generation,” he says. “People can then enjoy that these have been created by a computer.” I agree that’s the way to appreciate AI art, as its own beast.

Me too. We should not judge products of AI on the basis of whether they can be distinguished from products made by us. Because what’s the point? They may

Machines in art can have intent, and they can have a bit of free will, too.

produce something that we can't imagine right now, that could look like nonsense, but may then turn out to be better than what we could produce.

Why is the intersection of art and science, what you call a third culture, important?

Because it investigates the world as it is on a much better basis than somebody standing in front of an easel with oil paints. We're looking at the world of the future. We're looking at a world where we are merging with machines. A world where machines will be of importance. We will eventually be collaborating with them. They will produce works for us to enjoy and for their brethren to enjoy. So this is the way the world is evolving, and this is why we should be aware of AI art, and try to understand. Try to understand that it's not stealing things from us.

Finally, what has your research into this third culture taught you about people today?

That they should widen their point of view. Too many artists and too many scientists have a narrow point of

view. Scientists think art has nothing to do with science and artists think science has little to do with art. It is easier for a scientist to understand art than an artist to understand science. But, in a conceptual sense, art is an attempt to understand the concepts of science. I think my research has changed my view of humanity in the sense that people should leave their minds open to what goes on in fields other than their own. It could widen and even change their beliefs. ☺

KEVIN BERGER is the editor of *Nautilus*.



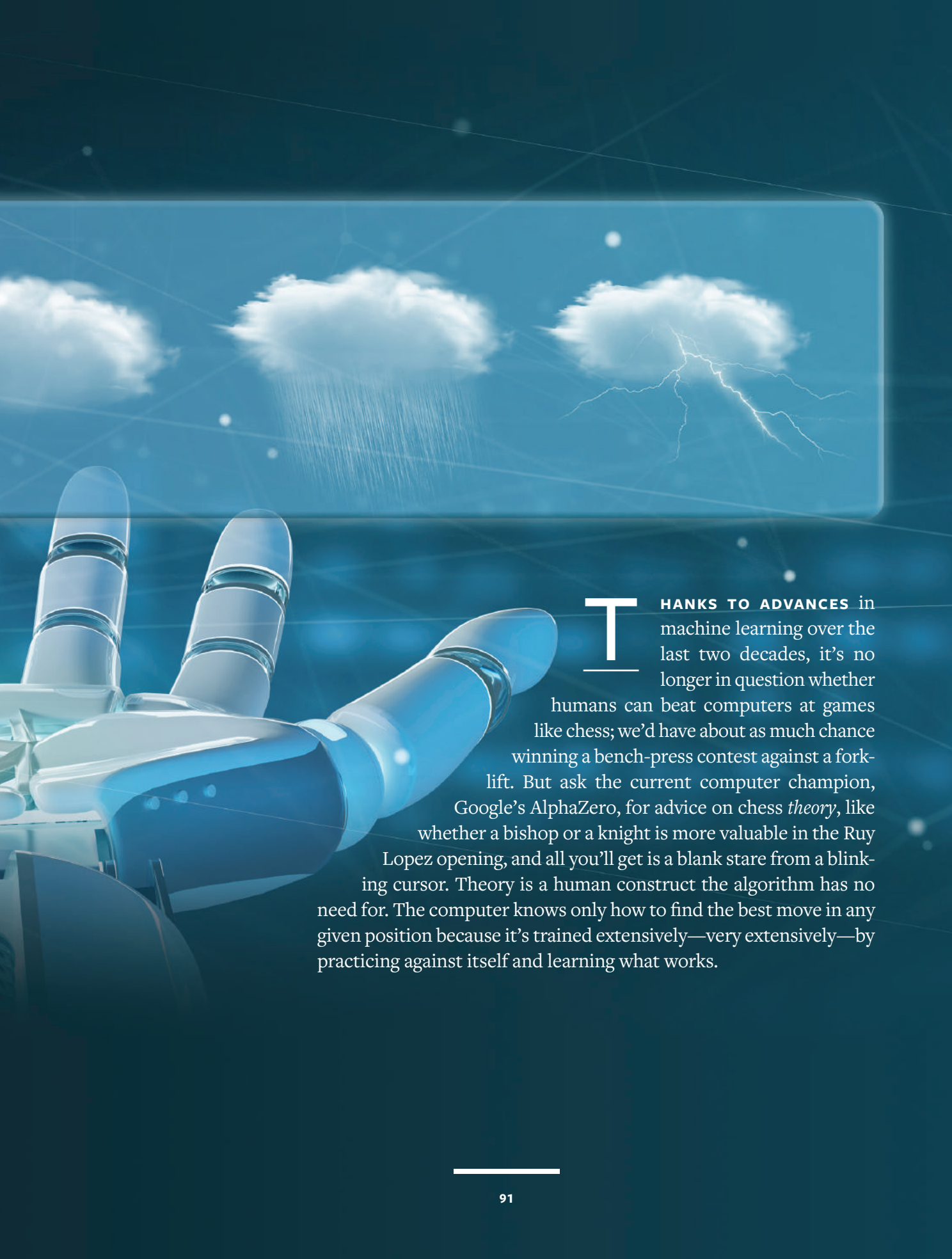
Weather forecast

How to Predict Extreme Weather

*Climate science is forging a more perfect union
between humans and machines*

BY AUBREY CLAYTON

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THANKS TO ADVANCES in machine learning over the last two decades, it's no longer in question whether humans can beat computers at games like chess; we'd have about as much chance winning a bench-press contest against a forklift. But ask the current computer champion, Google's AlphaZero, for advice on chess *theory*, like whether a bishop or a knight is more valuable in the Ruy Lopez opening, and all you'll get is a blank stare from a blinking cursor. Theory is a human construct the algorithm has no need for. The computer knows only how to find the best move in any given position because it's trained extensively—very extensively—by practicing against itself and learning what works.

The computing methods underlying success stories like AlphaZero's have been termed "deep learning," so-called because they employ complex structures such as deep neural networks with multiple layers of computational nodes between input and output. Here the input can be richly structured, like the positions of pieces on a chessboard or the color values of pixels in an image, and the output might be an assessment needed to make a decision, like the value of a possible chess move or the probability the image is a photo of a Chihuahua instead of a blueberry muffin. Training the network typically involves tuning all of the available dials, the parameters of the model, until it does well against a set of training data and then testing its performance on a separate out-of-sample data set. One of the complaints about such systems is that, once their training is complete, they can be a black box; exactly how the algorithm processes the information it's given, and why, is often shrouded in mystery. (When all that's at stake is a chess game, this is no great concern, but when the same techniques are used to determine people's creditworthiness or likelihood of committing a crime, say, the demand for accountability understandably goes up.) The more layers of nodes, and the more parameters to be adjusted in the learning process, the more opaque the box becomes.

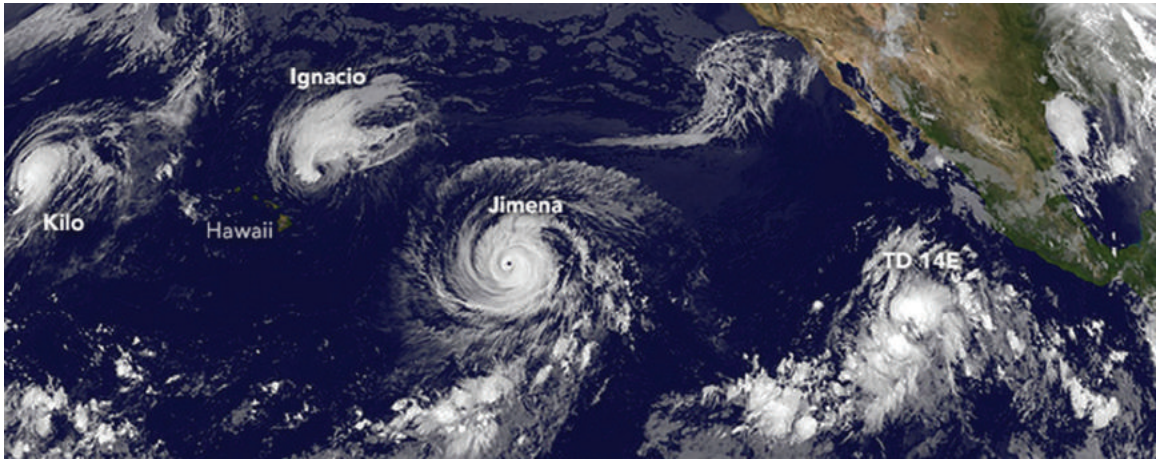
Nevertheless, in addition to their board-game dominance, deep learning algorithms have found success in fields ranging from finance to advertising to medicine. Somewhat surprisingly, the next domino to fall may be weather forecasting. It's a surprising challenge for machine learning to take on, in part because traditional human learning (augmented by computers, but just for number-crunching) already has a pretty good handle on things. As such, it's an interesting case study in what happens when deep learning methods trespass on an established discipline, and what this new contest between human and machine could portend for the future of science.

METEOROLOGY, UNLIKE CHESS, has a lot of accepted theory behind it. Fundamental physical relationships like the equations of fluid dynamics or energy transfer between land and atmosphere set limits on how weather systems can form and evolve. The current state-of-the-art weather forecasts, in fact, amount to simulated solutions to those equations based on

Even with a lead time of 18 months, the neural network was able to see El Niño events coming.

current measurements of temperature, wind, humidity, etc., and factoring in uncertainty due to measurement error. Starting from a position of complete naiveté, a neural network, no matter how deep, would have a hard time catching up with all the theoretical knowledge. So, researchers on the forefront of machine learning and climate science have recently started using a different approach: combining what we already know about meteorology with the ability of deep learning to uncover patterns we don't know about.

In September 2019, in *Nature*, Yoo-Geun Ham and Jeong-Hwan Kim from the Department of Oceanography at Chonnam National University in South Korea, and Jing-Jia Luo of the Institute for Climate and Application Research in China, announced the success of a new deep learning algorithm to predict the occurrence of El Niño events up to 18 months in advance. El Niño, which refers to the warm phase of an oscillation between warm and cool sea surface temperatures in the eastern Pacific Ocean, has posed a longstanding problem for intermediate-term global weather forecasts. During an El Niño year, normal weather patterns are thrown out of whack, with some parts of the world seeing wetter conditions and more severe storms while others experience prolonged droughts. The greatest impacts occur on the western coast of South America, where heavy rainfall can cause catastrophic flooding while changes in sea temperatures threaten the fishing industry the region depends on, and on the other side of the southern Pacific, which gets a triple whammy of drier conditions, stronger winds, and higher than average temperatures, all exacerbating the risk of bushfires like the ones currently burning throughout New South Wales, Australia.



EL NIÑO Deep learning, augmented by traditional human learning, may soon forecast unpredictable El Niño events, like the one shown above where four tropical cyclones roil the Pacific in 2015.

The social costs of El Niño can be enormous; it's been linked to water shortages, famine, the spread of infectious disease, and general civil unrest. (A dip in European crop yields during the 1789-1793 El Niño may even have helped kick off the French Revolution.) So the potential benefits of better anticipating and preparing for an El Niño are equally huge. The problem is that El Niño events only occur semi-regularly. Records going back to the late 1800s, when El Niño was first described as a global phenomenon, show a typical interval of two to seven years between events but, beyond that, no real pattern. Furthermore, they range in severity and type depending on where exactly the greatest sea temperature anomalies show up, and each type produces its own idiosyncratic mix of weather phenomena. Depending on where you live, you might not even have noticed that we just finished one; the El Niño of 2019 ended this fall and was of the mild variety.

Before Ham and his co-authors, the best forecasters could predict an El Niño event at most a year in advance, but there was reason to believe there was room for improvement. For one thing, sea temperatures don't change all that rapidly, and the fluctuations are not as chaotic as individual weather systems. There's also some periodicity to the anomalies; the

warming periods of an El Niño are typically followed by cooling periods called La Niña, like a giant warm wave sloshing back and forth across the Pacific. So, even though the exact causes and timings are unknown, the warning signs might be present far in advance.

They decided to use what's called a convolutional neural network, the same network architecture used in machine vision problems like image recognition, to see if it could discern features in the sea temperature data that could predict an El Niño event. To train their model, though, they couldn't just rely on historical data, because there isn't nearly enough of it to go around. Monthly records of sea temperatures only go back to 1871, and some amount of that data would need to be reserved to validate the model's predictions outside of the sample used for training. For techniques best suited to problems of big data, the El Niño data is disappointingly small.

Here is where newfangled data science met old-fashioned climate science.

Instead of historical data, they first trained their neural network on a batch of *simulations*. The simulations were produced by research groups around the world and collected as part of the Coupled Model Inter-comparison Project (CMIP), a large-scale initiative to

We have as much chance at beating a chess computer as winning a bench-press contest against a forklift.

share climate models and compare petabytes'-worth of predictions for what might happen under different possible futures. Some of the scenarios represent alternative pasts, like climatological historical fiction, and the stories are detailed enough to include features like El Niño events. So, the simulations represent plausible data, bounded by the constraints of the known climate models. They might be a step down from real data, but they're realistic enough to stand in for the genuine article. Using the substitutes, Ham and his colleagues were able to train the neural network on a data set equivalent to 2,961 years of observations. Then they used the results of all that training as a starting point for learning from the actual historical data, which they separated into a training period from 1871 to 1973 and an out-of-sample validation period from 1984 to 2017.

The results were spectacular. The neural network performed better than the previous state-of-the-art forecasts, with a gap that got wider the earlier in time the forecasts were made. Even with a lead time of 18 months, the neural network was able to see El Niño events coming, make a good estimate of their magnitude, and even classify them according to whether the temperature spikes would occur in the central or eastern Pacific. It did especially well at forecasting El Niños in the boreal spring and summer months, a "predictability barrier" previous models have run into because of the complex interactions between El Niño and monsoon season in South Asia.

The technique of training a system to perform well at one task—in this case, making El Niño predictions in a set of simulated data—before applying that knowledge to another task is called "transfer learning." Ham's success at forecasting El Niño shows how this method can combine the best parts of climatology and deep learning. The simulations produced by the climate models provide ample data for the neural network to learn from, in effect training it to think like the models do, but those models are naturally subject to some systematic error. Fine-tuning the network with real historical data then smooths out the error and lets the neural net find features the scientists might not have thought to look for, with the end result being better forecasts.

As a final sense check to demonstrate their model had, in fact, internalized some of the lessons of climate theory, the modelers used the neural network

to do a post-mortem analysis on the 1997 to 1998 El Niño, one of the most severe in recorded history. Feeding in sea temperatures for May, June, and July of 1996, they saw neurons lighting up in particular regions, indicating favorable conditions for an El Niño event were developing. Warmer seas in the tropical western Pacific beginning in 1996 built up potential like a loaded gun, and then colder conditions in the southwestern Indian Ocean fired it to the east, resulting in an extreme El Niño about one year later. Colder-than-average conditions in the subtropical Atlantic only exacerbated things. Unlike some mysteriously oracular black box, the model had identified features as significant that were all consistent with what climatologists know about the linkages between sea temperatures in different parts of the world and the ways the climate narratives can unfold. The network had just seen it coming earlier than anyone else, perhaps early enough for people in the affected regions to better prepare for the devastating impacts had the warning system been in place.

THE HYBRID APPROACH demonstrated by the hunt for El Niño may well provide a new model for applying successful machine learning techniques to theory-heavy fields like climate science. These recent breakthroughs show that, instead of a turf war, the future of research can be a joint venture that combines the best parts of traditional and data science. In another paper in *Nature* in 2019, lead author Markus Reichstein of the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry in Germany argued for the importance of “contextual cues,” meaning relationships in the data predicted by known theory, as a way to augment deep learning approaches in Earth science. There’s no reason to expect it to stop there.

Meanwhile, machine learning may be giving climate science a boost at just the right time, thanks to the ongoing climate catastrophe we find ourselves facing. In particular, even though the weather systems El Niño affects are expected to become more extreme in the future, there is still no scientific consensus about whether climate change will increase the frequency or severity of El Niño events. The Intergovernmental Panel on Climate Change report of 2013 said simply that it expects El Niño to continue but with very little

confidence about the ways it might change. El Niño events depend on complex feedback loops between warm and cold ocean water, the atmosphere, trade winds, etc. Disrupting a part of those cycles could shut the whole thing down, make the El Niño conditions more frequent or even permanent, or have no noticeable effect either way.

Figuring out how to plan for extreme weather in the future will be like finding the optimal strategy in a chess game where the pieces keep changing. It will take all the learning power of a supercomputer combined with all the experience of a grandmaster. 🧠

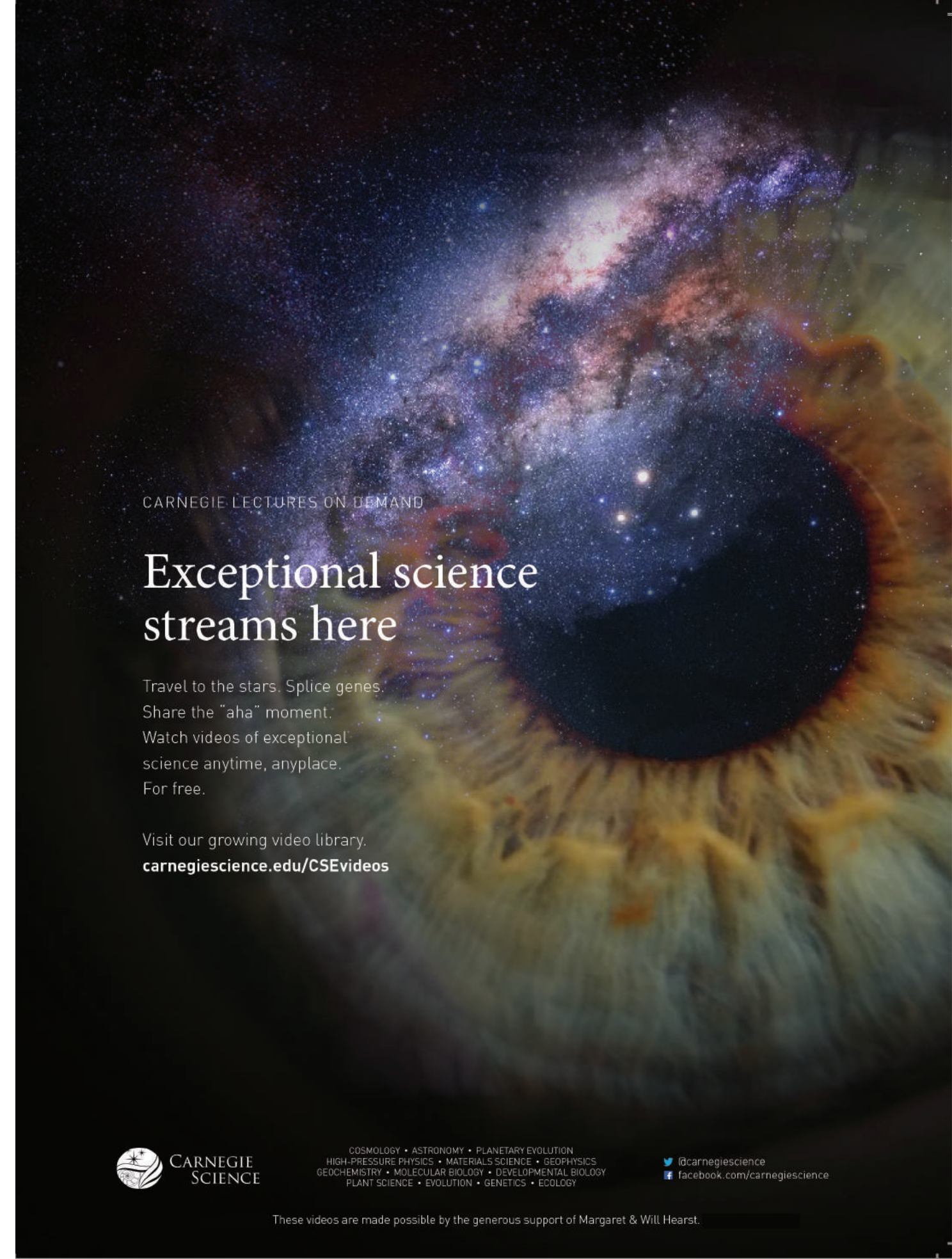
AUBREY CLAYTON is a mathematician living in Boston. He teaches logic and philosophy of probability at the Harvard Extension School.

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A composite image of a human eye, where the iris is replaced by a vibrant, multi-colored galaxy (likely the Milky Way) with stars and nebulae. The eye is looking towards the upper right.

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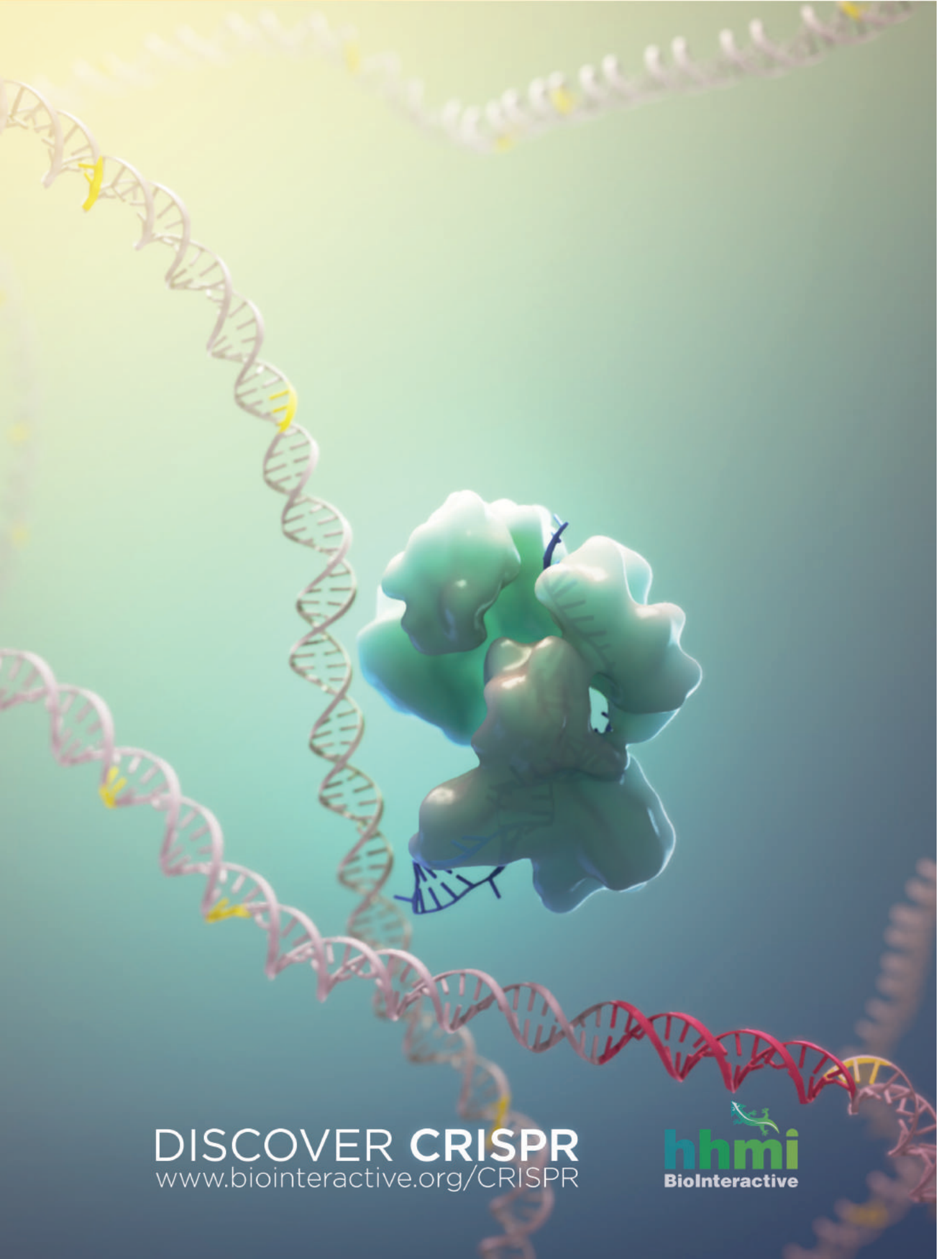


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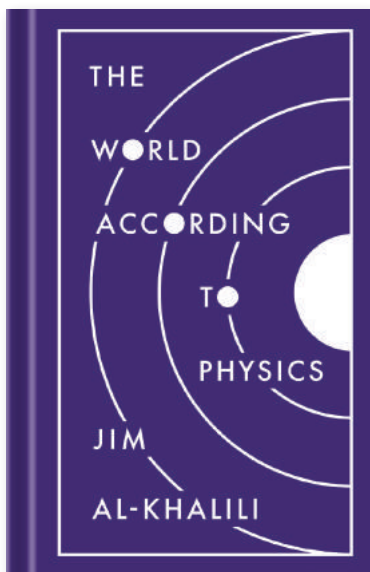
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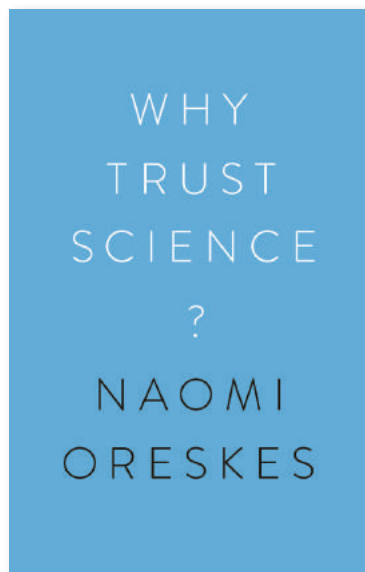




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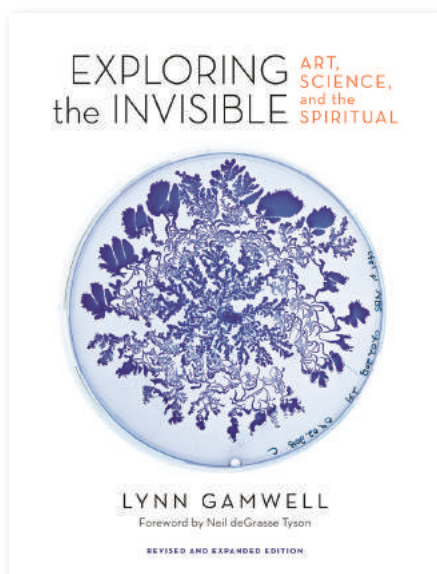
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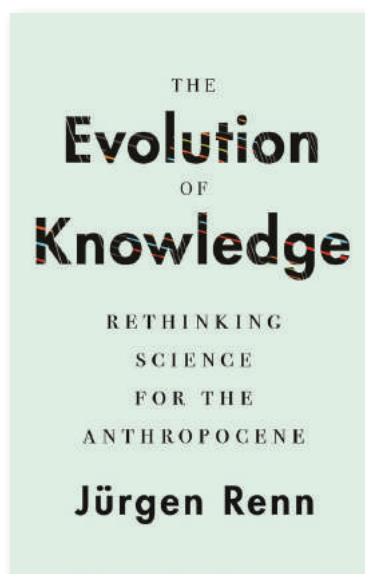
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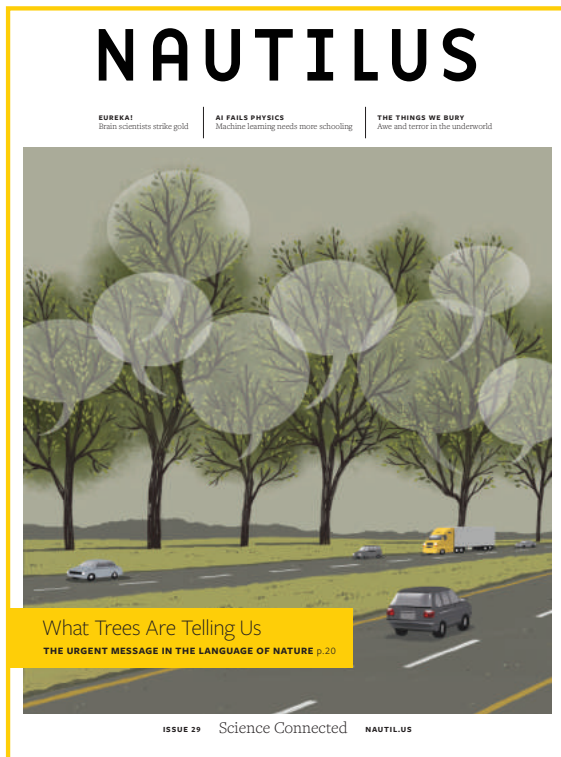
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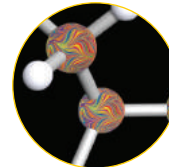
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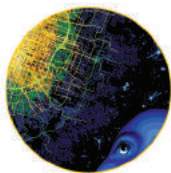
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INTERVIEW BY COREY S. POWELL

ARTIFICIAL ORIGIN

When I saw an anomaly in the case of Oumuamua, all I was doing was following the standard scientific process of saying, “What can explain it?” I don’t see how that’s any different than trying to invoke dark matter to explain the motion of ordinary matter in galaxies or in cosmology. It’s a hypothesis that you put on the table, as plausible as any other hypothesis. The strange thing is that people are afraid to bring up the possibilities of an artificial origin. It’s a self-fulfilling prophecy: If you, ahead of time, set the prior that there’s zero probability for it to be artificial, then obviously you will never find it to be artificial. You will be happy but you might be wrong.

DON’T TRUST YOUR GUT

The point of doing science is not to have a prejudice. Prejudice is based on your experience from the past. If you want to allow yourself to make discoveries, that means that the future will not be the same as the past. You have to give up on prejudice. You have to give up on gut feelings. Gut feeling is based on past experience. Einstein called the notion of action at a distance in quantum mechanics “spooky.” But experiments after his death confirmed the notion of quantum mechanics in contradiction to Einstein’s gut feeling. That shows you that gut feelings based on the past can be wrong. It misguided Einstein and led him to work for years on

trying to argue otherwise. Nobody would say that Einstein’s gut feeling was a bad approach because it also led him to the special theory of relativity, but it’s not always the right approach.

ROLL OF THE DICE

The search for extraterrestrial civilization is not speculative at all. It’s based on two facts: one, that we exist, and two, that there is a large number of stars with planets similar to the Earth. About a quarter of all the stars have planets the size of the Earth in the habitable zone, where they could have liquid water on the surface and the chemistry of life as we know it. If you roll the dice so many times, it’s possible that some of these planets will have biology and advanced civilization. People that believe that there are no civilizations, no life, elsewhere—these people show arrogance because they think that we are special.



MESSAGE IN A BOTTLE

We are starting now to send objects outside our solar system. So why would we not expect another civilization to have sent things into interstellar space? We might one day get a message in a bottle. It opens a new frontier. We should examine each and every interstellar object entering the solar system to check if it’s natural or not. Even if most of the time it will be natural, every now and then we might be surprised. What do we gain by putting blinders on our eyes? 🧐

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