NAUTILUS

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NAUTILUS *Next*

City of Dreams

BY KEVIN BERGER

I **USED TO WRITE** about cars and the environment and got a kick out of discovering that traffic clogged America's roads long before suburbs boomed in the 1960s. Muddy streets with Model As bunched up and going nowhere are images to be treasured.

Similarly, I thought criticism of the car's assault on our cities and skies grew out of the environmental movement in the 1970s, when scholarly young activists turned their gaze from the romance of *American Graffiti* to the brown horizons shrouding cities.

But every problem we blame on cars today was sounded before gridlock became a Los Angeles landmark. Social philosopher Lewis Mumford, an urban critic with a bullhorn, sarcastically remarked in 1958 that America's national flower is the concrete cloverleaf. That was just a warmup for a city planner named Kenneth Schneider, who in 1971 uncorked a Rabelasian broadside called *Autokind Vs. Mankind*.

"Automobility," Schneider bellowed, "ravages the landscape, endangers and oppresses the pedestrian, boxes and deforms the body, contaminates the breadth of life, enrages the ears, insults the eyes, makes an automaton of the nervous system, puts every citizen nearer the clutches of the law, denies casual association, rigorizes organization, distorts public purpose, and dulls the human sensibilities."

I met Schneider at his home in Flagstaff, Arizona, a decade before he died in 2005. He drove into the Utah desert one day and never returned; his body was never found. He was a steadfastly serious man with a big philosophical vision. Tall stacks of typewritten pages, surrounded by notes on restaurant napkins and Post-its, and sketches of city plazas and parks, covered his living room table. He had just completed a 596-page manuscript called *Forging a More Perfect Union: Creating a New Harmony of Cities, Democracy, Ecology*. Cities should be designed to foster "interpersonal casualness and creative serendipity, which form the heart and soul of a community," he told me.

I thought of Schneider and the city visionaries before and after him when I came across a book this year, *Ghost Road*, by Anthony Townsend, Urbanist in Residence at Cornell Tech's Jacobs Institute. Ghost roads are streets dedicated not to cars but to automated delivery vehicles and transit fleets. We don't pile into cars to commute to jobs and stores; ghost roads bring them to us.

Blueprints for city neighborhoods where cars aren't king have never quite got off the drawing boards. Warring interests stalemate every beautiful plan. But in "The Flexible City," this issue's cover story, Townsend presents a scenario that feels like it has a chance. How do we know? The coronavirus pandemic, with its requisite quarantines, has shown us a rough draft. I think you will be as delighted as I was to learn that urban areas may finally achieve the kind of creative serendipity that visionaries like Schneider dreamed.


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Readers Respond

Comments and letters about stories from print issue 33.

"DAMNED LIES"

The facts concerning this article are simple and irrefutable: It does matter whether a scientist is a eugenicist, racist, etc. Why does it matter? It matters because the lens through which one perceives the world determines one's conclusion. Science and mathematics are not immune to this truth since most scientists are often prey to it.

—Starhawk

"ARE YOU YODA OR DARTH VADER"

I've come across and taken one version of the Kaufman survey and found it to be by far the most accurate way of reflecting one's personality in the real world. I have not tended toward greater beneficence as I've gotten older, but I recognize the context of human culture has also changed over that time, due in many ways to the problems created by a simplistic way of understanding human nature, which Kaufman tries to address.

Kaufman is actually demonstrating one of the most fundamental problems with all human mythology, whether from ancient Greece or *Star Wars*. Both the gods and the characters in Star Wars demonstrate how destructive unlimited power is in the hands of basically unstable beings. The idea that such beings could also create on a similar scale and thus balance the destruction they cause is pure fantasy, yet propels humanity.

—brian

It's called "integrating the shadow" and Jung was on about this about a hundred years ago: Long before any *Star Wars* metaphor (which simply exploits the Western notion of dualities and their divisions which inflate and promote conflict). And don't even get me started about the lineage of practical alchemy that goes back several hundreds of years which inspired Jung's thoughts and work on the matter of integrating one's "dark side," which itself grew out of even older knowledge and teachings.

On the other hand, if it takes some Twitter star to promote a pop-psychology *Star Wars* metaphor to the masses to get people to wake up and quit with all their "us vs. them" division of dualities, then, hey, I guess ignorance of the past can be forgiven. May the force be with us all, because we seem to need it now more than ever.

—Eve Orslaloy

"THE HARD PROBLEM OF BREAKFAST"

The sign of real intelligence is someone who can laugh at him or herself. Poking fun at the complexity with which we explore this world is as crucial to scientific and philosophic inquiry as the inquiry itself. You cannot be sure you are willing to open up to concepts far beyond what you've ever considered if you cannot cede the fact that you are only human. Humor is an indication you are. Live a little.

—CitizenRed

Good lord, are there really scientifically-minded people who are so immune to humor that they can't enjoy a bit of fine satire? This piece was great fun, he got the context and tone perfectly! And apparently is aware of the real science as well. Sheesh.

—openreels

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

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Preludes

SERGEY NIVENS / SHUTTERSTOCK

NEUROSCIENCE

Where in the Brain Is Consciousness?

CHRISTOF KOCH is a neuroscientist distinguished by his rock-solid scientific work and romantic yearning to understand consciousness. He recently closed an essay by wondering: "What is it about the brain, the most complex piece of active matter in the known universe, that turns its activity into the feeling of life itself?" He argues that consciousness is produced by the brain but that it's also more widespread in nature than we might suppose.

His essay described new experimental work, from neuroscientist Kieran Fox and his colleagues, that explored the effects of electrically stimulating the brain, which revealed an ordering principle. That is, the more removed from sensory input or motor output structures a brain region is, the less likely it is that it contributes to our subjective experience. The "exacting data," Koch wrote, "provides critical causal, not just observational, evidence to identify the neuronal correlates of consciousness."

Neuronal correlates of consciousness are the parts of the brain thought to be required for consciousness to occur. The idea that there are only neuronal correlates of consciousness, and that these correlates are the patterns of synaptic firing in specific parts of the brain, is what you might call the conventional view in neuroscience. If we peer deeply into the brain, in other words, what we'll find is that electrochemical synapse firings—produced by neurons of various types—are responsible for, as Koch puts it, the feeling of life itself, consciousness.

But what if there's more to the story? What if the electromagnetic fields generated by, but which are not identical to, the neuroanatomy of the brain, are in fact the primary seat of consciousness? The brain's fields are generated by various physiological processes in the brain, but primarily by trans-membrane currents moving through neurons.

Some neuroscientists have long considered the brain's oscillating electromagnetic fields to be interesting but merely "epiphenomenal" features of the brain—like a train whistle on a steam-powered locomotive. Electromagnetic fields may just be noise that doesn't affect the workings of the brain. Koch still seems to lean this way.

"While at this early stage of the exploration of the brain it would be foolish to categorically rule out any physical process," he told me, "as an electrophysiologist I'm less enthused about ascribing specific functions to specific frequency bands, let alone experience. The causal actors between neurons that act at the time scale relevant for consciousness (5-500 milliseconds) are action potentials that cause, in turn, synaptic release of packets of neurotransmitters." He thinks the extent to which oscillations affect neuronal firing patterns remains an open question. "Consider the sounds the beating heart makes," he said. "These can be picked up by a stethoscope and can be used to diagnose cardiac conditions. However, there is no evidence that the body exploits these sounds for any function."

I asked Wolfgang Klimesch, a professor at the University of Salzburg, what he thought about Koch's view on electromagnetic fields. Klimesch developed the "binary hierarchy brain-body oscillation theory," which says that consciousness is a function of various levels of resonance both within the brain and between the brain and various other organs, like the heart and stomach.

"With respect to Christof's view that they are too weak in order to play a role for higher brain functions, he is right if one looks at only one oscillation of the field," he said. "The critical point is the interplay and sync between oscillations. Even if each oscillator is weak, sync between them can induce a strong and very selective force."

One of Koch's collaborators, György Buszaki, was fairly clear as far back as 2004 in terms of where he stood on this debate, highlighting various functions

What if the brain's electromagnetic fields are in fact the primary seat of consciousness?

that the brain's electromagnetic fields perform, including linking different areas of the brain together, facilitating synaptic changes, and creating and consolidating memory. So Buzsaki accepts that these fields have functional roles and are not like the sounds of a beating heart or a locomotive whistle.

Perhaps the most compelling recent research in favor of the functional role of electromagnetic fields can be found in a 2019 paper from Dominique Durand's team. They examined slow electromagnetic field oscillations (less than 1 hertz) in hippocampus tissue from decapitated mice. The researchers found that slow oscillations could trigger synaptic activity in neurons that were not connected by synapses. If they're not connected synaptically, they can't communicate through synaptic firing. Durand's team wrote, "Results support the hypothesis that endogenous electric fields, previously thought to be too small to trigger neural activity, play a significant role in the self-propagation of slow periodic activity in the hippocampus."

Durand was as surprised by their results as others were. He said, "It was a jaw-dropping moment, for us and for every scientist we told about this so far."

Koch is, however, skeptical of these results, given their statistical validity and effect size. He told me: "Of course, at this point, no neuronal mechanisms can be definitely ruled out (including exotic macroscopic quantum effects), as long as they don't violate the laws of physics." Like most new scientific findings that challenge consensus views, other teams will have to replicate Durand's results for others to find them convincing.

—Tam Hunt

TECHNOLOGY

Does Social Media Poison Everything?

VICTOR MOUSSA / SHUTTERSTOCK

THE POWER OF PLATFORMS like Facebook and Google has escaped the control of the optimistic technocrats at their helm. And it is wreaking havoc in ways that we lab rats have only just begun to understand. At least, that's the case Netflix's documentary *The Social Dilemma* makes. Through interviews with repentant tech leaders, we learn how websites that began as ostensibly innocent attempts to bring people closer together have since mutated into sophisticated, self-teaching, attention-harvesting machines that are getting better and better at keeping us glued to our devices.

The nefarious algorithms at work analyze our online activity to build a detailed model of our preferences. They then use these to spoon-feed us personalized content and cleverly timed notifications, all in service of selling valuable ad space.

The film dramatizes the runaway consequences of this profit strategy with periodic vignettes of a fictional family struggling to navigate their digital landscape. There's a young girl dealing with "Snapchat dysmorphia," for example, while her older brother, feeling alienated in his real-world social life, is dragged down a fringe YouTube rabbit-hole that ends with his arrest at a protest. While the dramatization is sometimes heavy-handed, it gets its message across: Social media can indeed harm mental health, radicalize vulnerable users, and disrupt a society's ability to agree on basic facts.

The film treads carefully, perhaps too carefully, in its treatment of the political implications of its argument. For example, it declines to acknowledge that fake news is disproportionately shared by people who are older and more conservative, and the dramatized vignettes about polarization feature a vague movement called the "extreme center." These large tech companies' numerous political conflicts of interest—say, Facebook's reliance on rightwing populism for engagement, or its clear financial incentive to help elect politicians who won't raise its taxes or break it apart—could have been an interesting topic for discussion.

Social media can indeed harm mental health.

Also, there's an unnecessary touch of "social media is changing our brains!" alarmism. The fact is that just about everything changes our brains. As science blogger Neuroskeptic pointed out, "The brain's job is to respond to things. Its activity is change. Brain activity is ever-changing and, for that reason, changes are almost always reversible." Many changes certainly are for the worse, like an increase in depressive symptoms or the development of an addiction, but to treat social media-induced brain change as a bad thing in and of itself is unproductive.

In general, though, the film's treatment of the psychology and neuroscience of the attention-extraction economy is compelling. One section highlights the stark mismatch between the prehistoric social environments our brains evolved to handle and the much larger and more gamified social environments we face now. "We curate our lives around this perceived sense of perfection because we get rewarded in these short-term signals—hearts, likes, thumbs-up," says former Facebook executive Chamath Palihapitiya. "And we conflate that with value and we conflate it with truth." The film mostly covers this mismatch with reference to adolescent mental health, but it's also worth considering how it can distort our sense of right and wrong.

One of the most intriguing debates surrounding social media is how much agency we should expect of ourselves. Can't we just choose to put down our phones once in a while? Or has this technology hooked us so deeply that our only chance of salvation is government regulation?

The film strongly endorses the latter stance. At one point, Tristan Harris, a former design ethicist at Google who has been called "the closest thing Silicon Valley has to a conscience," claimed that social media, with all the "addiction, polarization, radicalization, outrageification, and vanityification" it inflicts on us, represents "checkmate on humanity."

Research on willpower suggests that systemic changes are indeed better than effortful self-restraint at helping us avoid temptation and behave more intentionally. Plus, the argument that we should deal with the dangers of social media on our own can come across as cruelly individualistic tech-apologia. But whether we've truly been "checkmated" as a species seems more of an open question than the film acknowledges.

Either way, if there's one thing that *The Social Dilemma* does extremely well, it's to force us to confront the possibility that we have far less control over our behavior than we like to think. Now keep scrolling.

—*Scott Koenig*

NEUROSCIENCE

Your Brain Makes You a Different Person Every Day

BRAIN "PLASTICITY" is one of the great discoveries in modern science, but neuroscientist David Eagleman thinks the word is misleading. Unlike plastic, which molds and then retains a particular shape, the brain's physical structure is continually in flux. But Eagleman can't avoid the word. "The whole literature uses that term plasticity, so I use it sparingly," he says. Eagleman also discounts computer analogies to the brain. He's coined the term "livewired" (the title of his new book) to point out that the brain's hardware and software are practically inseparable.

> Every moment of your life, your brain is rewiring.

You say we've barely begun to understand how malleable our brains are. Are they getting rewired every day?
Every moment of your life, your brain is rewiring. You've got 86 billion neurons and a fraction of a quadrillion connections between them. These vast seas of connections are constantly changing their strength, and they're unconnecting and reconnecting elsewhere. It's why you are a slightly different person than you were a week ago or a year ago. When you learned that my name is David, there's a physical change in the structure of your brain. That's what it means to remember something.

Are these just tiny changes or can significant rewiring happen over the course of a week?
It's both. Right now, COVID is a time when everyone has lots of changes going on. We suddenly find ourselves kicked off the hamster wheel and having to rethink things and be creative. The brain builds an internal model of the world so it can predict what's going to happen next, and all of a sudden our predictions became frayed. The only silver lining to the lockdown is the fact we're getting a lot of brain plasticity out of it. For those of us who haven't caught the illness, it's sort of a beneficial COVID brain. We get to challenge ourselves with novelty. Which is the most important thing for the brain.

Do you think one day we'll be able to map all the neural connections in someone's brain and know what kind of person that is?
Maybe. This will never happen in our lifetimes, for better or worse. But in theory, every experience you've had is getting mapped and stored into your brain. That's not just the strength of connections between neurons. It goes much deeper inside the cells. The exact distribution of channels, the exact biochemical cascades, all the way down to the nucleus of the cell in which genes are getting expressed. All of these things represent your history in the world. In theory, maybe in 300 years, you could read out somebody's brain.

Is all subjective experience just reducible to brain function?

Sure. You can take drugs and have completely different experiences. Or you can have hallucinations because of brain damage. We know that it has to do with the brain. But we don't have a great theory of what conscious experience is about—the smell of cinnamon to you or the beauty of a sunset.

It appears that consciousness arises from the brain, but there is still a possibility of something else. I mentioned this in my book *Incognito*. Imagine that you were a Kalahari Bushman who found a radio in the sand and you'd never seen anything like this. You notice that if you wiggle the knob, you hear voices coming out of the radio. And if you take the screws off the back, you realize that as you change any of the wires, it garbles the voices. As a radio materialist, you might come to the conclusion that somehow this arrangement of wires causes the voices to happen, but you wouldn't even be aware that there are distant cities with radio towers. You have no way to touch or feel or even suspect the existence of electromagnetic radiation, but that is where the voices are coming from.

If there's one unanswered question about the brain that you most want to figure out, what is it?

Fundamentally, it's this question of consciousness. Why does it feel like something to be alive? We can build very sophisticated machines, but I don't suspect my laptop is having internal subjective experience. Yet somehow we have that experience. This is right at the center of what it means to be a human. Not only do we not have a good theory, we don't even know what a good theory would look like.

—Steve Paulson

PSYCHOLOGY

It Pays to Be a Space Case

IT'S A FEELING we all know well—you're at a work meeting or in the middle of a book, when you realize that you have no idea what just happened. Without noticing it, your thoughts have drifted away from you.

Like many people, I've found my mind wandering more than usual since March, when shelter-in-place measures destroyed what little structure I had cobbled together as a freelance writer and student. Suddenly, my tidy university office was replaced by half of a couch, my "work schedule" transformed into little more than a hypothetical idea. As I struggled to stay focused, my thoughts drifted endlessly: from my work, to what to have for lunch, to whether our world was truly on the brink of collapse.

In the months since the pandemic began, I've found myself coming back to those musings again and again. Are our moments of distraction—the daydreams and memories, the anxieties and reflections—really such a bad thing?

I called up my old colleague, neuropsychologist and author Ylva Østby, to find out. "Mind wandering is the opposite of control: It's free," she explains from her home in Norway. "In some situations, it is important to be able to control your mind and to focus on the task at hand, but that does not mean that mind wandering is in itself a negative thing. We just don't recognize the situations where mind wandering is useful."

It's true: When it comes to tasks that demand deep focus, losing control of our thoughts can have obvious

AGSANDREW / SHUTTERSTOCK

Researchers estimate that our minds wander for about half of our waking lives.

SERGEY NIVENS / SHUTTERSTOCK

negative consequences. There's even research suggesting that we feel less happy while mind wandering than when we're more focused.

But, as Østby explains, distraction doesn't necessarily have to be a problem. Studies have found that mind wandering most often takes place during tasks that don't require many mental resources—that is, when we can afford to pay less attention.

Jonny Smallwood, a psychology professor, agrees. "In my opinion, there is far too much emphasis on the value of being in the here and now," he says. "[Mind wandering is] where all of the creativity of our species comes from."

A growing body of evidence suggests Østby and Smallwood may be on to something. These studies find that mind wandering can play an important role in planning for the future and solving challenging problems, for example. Some psychologists have even found that it can help solidify memories, much like sleep does.

Researchers estimate that our minds wander for about half of our waking lives, generating about 2,000 thoughts a day that are completely unrelated to the task at hand. "[Mind wandering is a] fundamental aspect of how we think," says Smallwood. That's why he, like Østby, takes a different view on mind wandering—one that sees it as an activity that is neither inherently good or bad, but dependent on the task at hand.

This same idea has fuelled much of neuroscientist Kieran Fox's research. He's fascinated by the relationship between mind wandering and creativity. Much of his work has centered on the idea that losing control of our thoughts is not only normal, but desirable.

Fox explains that, by and large, when our minds wander, they generate thoughts that are relevant and useful—at least to ourselves. We reflect on our actions from the hours gone by and ask questions about the days ahead. We think about our families and loved ones, our goals and personal challenges. And sometimes—if we're lucky—we come up with solutions that are truly original. "If you want to do anything different in your life," says Fox, "you need to create space for ideas."

Studies that connect mind wandering with creativity often center on the idea of the incubation period. The concept is simple: By taking a break from a difficult problem, we can give our minds time to work through our challenges unconsciously—to let our ideas "incubate"—while we focus on other things. When we finally return to the problem again, we often find that the solution has suddenly become obvious. Importantly, though, these incubation periods seem to be most helpful when they allow our thoughts to drift.

Indeed, many of history's most revered artists and inventors had daily routines that incorporated periods of mental rest. Frida Kahlo spent hours in her garden, drawing inspiration from the bright plants around her. James Joyce lay in bed "smothered in his own thoughts" for a full hour each morning, letting ideas come and go. Charles Darwin would declare at noon, "I've done a good day's work," and spend the rest of the day taking long walks, napping, and answering letters.

Fox, too, recommends creating space for some "mindful" mind wandering every day. "In our world right now, the idea of having dedicated space to think and unwind mentally is completely unacceptable," he says. "But if you start reading the sort of reports in the diaries of these creative people, they all say the same thing: Each day, prepare the field and plant seeds—study and think—but then let [the solution] come on its own. You never know when or where those seeds are going to grow."

As our interview comes to an end, I find myself lingering longer than usual, drawing out our conversation with small talk. After I finally click "Leave Meeting," I sit back, close my eyes, and let my mind drift. For what feels like the first time in months, I'm grateful to be alone with my thoughts again.

—*Alice Fleerackers*

First Impressions

I WAS HALF ASLEEP after a seven-hour boat ride when I pulled ashore at A'Ukre, a Kayapo village on the Fresco River in September, 2019. The Kayapo people live in small villages in Brazil along tributaries of the Xingu, the last major river flowing into the Amazon before it empties into the Atlantic. They're renowned for their colorful body painting mimicking rainforest animals, storytelling, and feared for ferocity in battle.

The boatman yelled, "We've arrived!" Instead of feeling like I was waking up, it seemed I'd entered a dream state that would last the three days I remained at the village taking pictures of war rituals they were performing. A small posse of girls along the shore eyed me attentively, stock-still as the tall trees in the jungle behind them.

Villagers chanted and shouted in a protest ceremony that day to warn newly elected president Jair Bolsonaro, who openly admits he wants to evict indigneous people from their land, that they would fight vigorously for native rights.

The tribal chief welcomed me and suggested that I refresh myself in the river. I took my camera along, weaving back and forth in the shallows, intent on capturing the beguiling children. A girl with an otherworldly haircut and painted skin approached, splashing me playfully with water. Through my guide she said her name was Nhakgogore. Kayapo people are used to naming people they meet, based on first impressions. Depending on who you meet, you can end up with several names. For her, I was Tepnomati, a fish that doesn't stay still.

— Dado Galdieri

PHOTOS BY DADO GALDIERI

The Flexible City

Life during the pandemic has shown us we can bend our cities into better urban designs

BY ANTHONY TOWNSEND

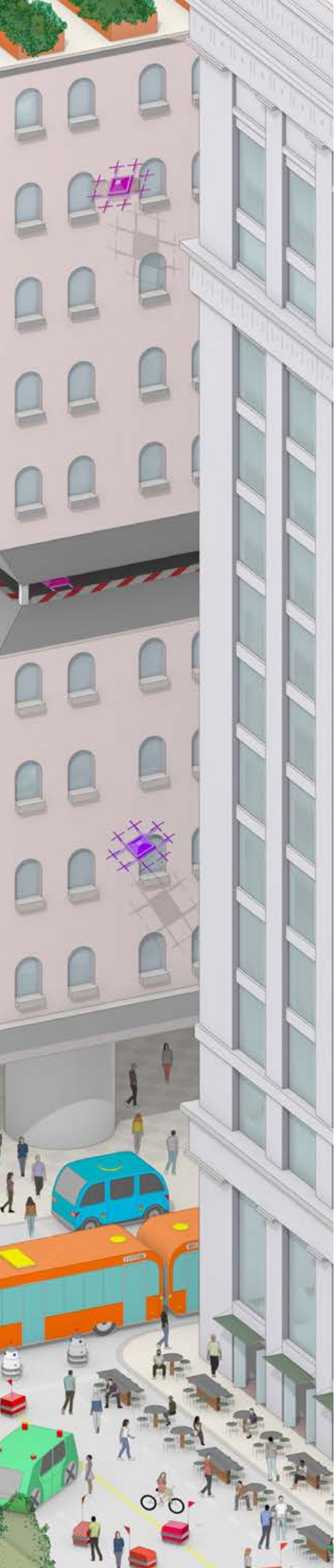
T**EN YEARS AGO THIS FALL**, Google gave us a glimpse of a new device unlike any it had ever built before—a computer-controlled car. It seemed such a strange thing for an Internet company to spend its time and energy on, a "moonshot" as the company's engineers called such massive efforts. But with a single blog post, the search giant promised to reinvent our cars, and our communities, too.

It was a big vision for a single invention to carry. And the details were scant. But we quickly filled in the blanks. Software was going to replace our dangerous, congested, sprawling roads with something utterly safe, seamless and organized. Humans would take the back seat in a new network of "ghost roads," as I call them. Ghost roads didn't demand a massive mobilization of government. The technology of autonomous driving would roll onto existing highways, invisibly weaving a new transportation system. Only this one would be modeled on the Internet. Computers would outnumber people. Code would call all the shots.

Google almost succeeded. The company's bold move spurred an arms race, drawing in the rest of Silicon Valley and automakers the world over. Hundreds of billions of dollars flowed into the quest to develop autonomous vehicles (AVs). Still in the lead, Google sister company Waymo now operates a limited self-driving ride-hail service in the Phoenix metro area.

But the future has a way of veering off the road. A generation in, fully automated driving has proven far more challenging than many thought. Some 15 years after university researchers aced the Defense Department's 2005 Urban Challenge, the first proof-of-concept of autonomous driving in populated areas, Google's robovans are still mostly confined to the modern subdivisions of the Sun Belt. That's because scant rainfall and wide, well-marked streets ease the engineering of split-second computer vision systems considerably.

SIKORKA / SHUTTERSTOCK



Never has a city flayed itself as deftly and visibly as New York City following the arrival of COVID-19.

Some experts now predict that we may *never* achieve the original dream of a reliable fully self-driving car. And even if we do, spreading the technology beyond the Arizona suburbs will require costly retrofits to add navigational hardware to existing roads. This is a non-starter in the post-pandemic age of austerity. Most state and local governments now struggle to merely maintain a much simpler, yet more fundamental technology for orienting both human and computer drivers—the painted markings that guide us along the pavement.

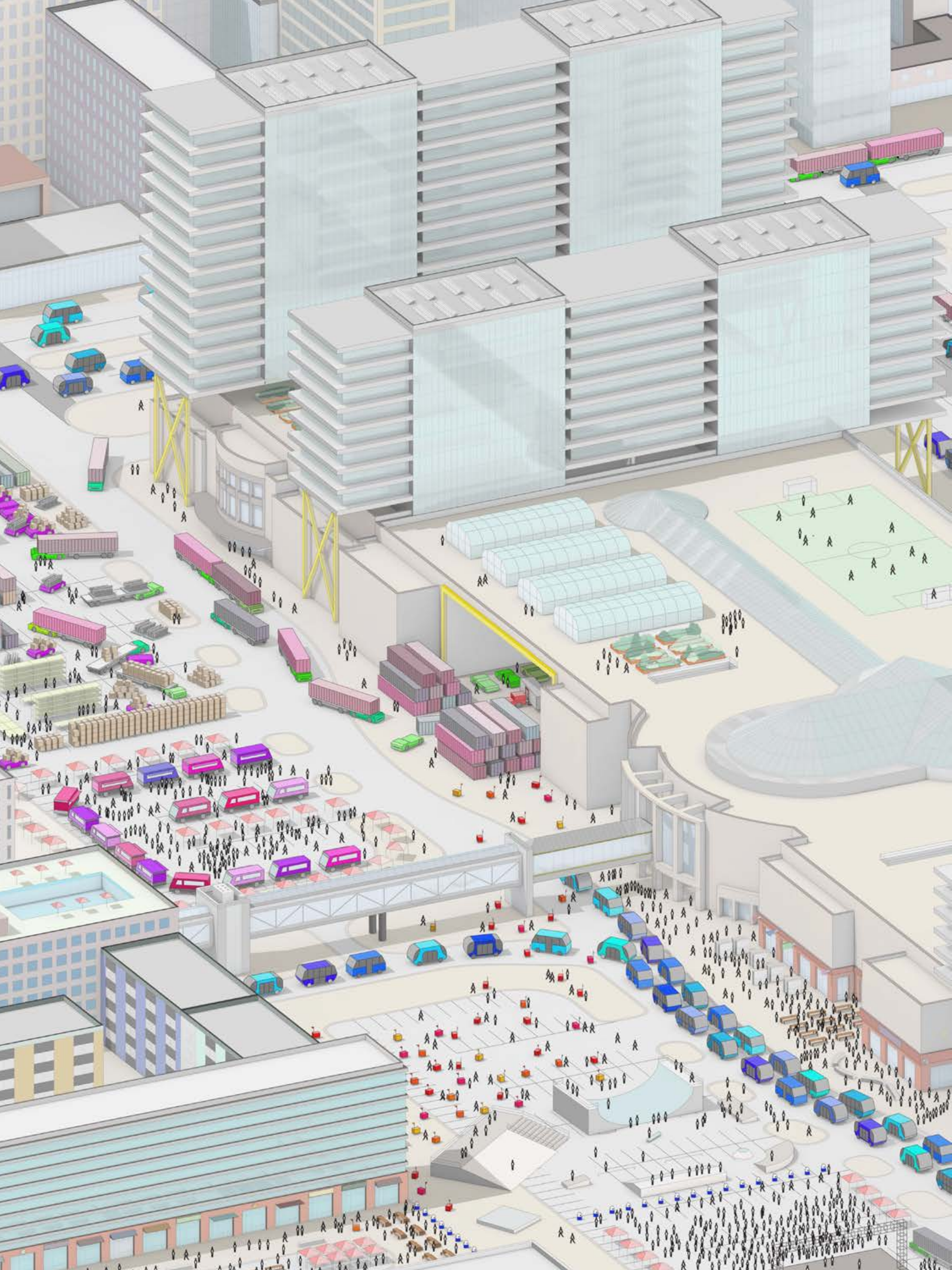
Meanwhile, as we've obsessed over driverless sedans and SUVs, the magic of autonomous driving has seeped into everything else on wheels. In 2019, University of Michigan urban technology professor Bryan Boyer and his students conducted a census of more than 80 commercially available robots and AVs designed for urban use. Unlike self-driving cars, these machines don't need AV-only ghost roads to operate. They're happy to mix it up with people, and defer to human supremacy on sidewalks, in bike lanes, and on streets.

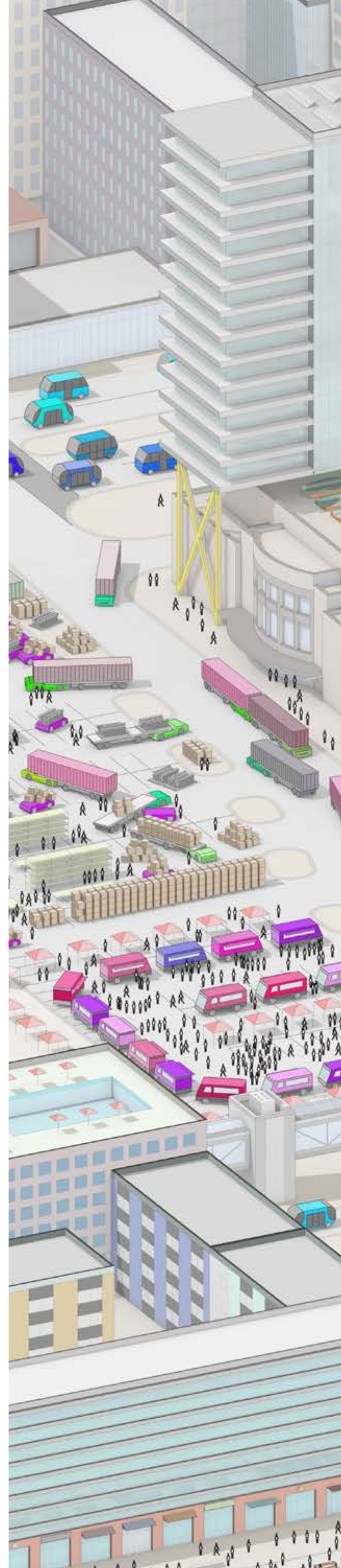
Flipping through the pages of Boyer's *Robot Survey 2019*, styled after the old Jane's guides to military equipment that filled my Cold War youth, the truth is hard to deny. The self-driving car was a red herring. An entire class of AV species, like the mammals once did, will replace the dinosaurs of the automotive age instead.

These strange silicon-powered beasts will arrive just in time. That's because—as we did when COVID-19 struck—spreading out and shutting down is going to be a tactic we'll employ over and over again to weather the shocks of the 21st century. How well we put these machines to use to ferry goods and people around in clever new ways, and tend to the dull, dirty, and dangerous work of municipal upkeep, will mean the difference between keeping our cities humming along or abandoning them altogether.

DASH MARSHALL


APARTMENTS





CITIES HAVE COME APART before when confronted with the outbreak of disease. But never has a city flayed itself as deftly and visibly as New York City following the arrival of COVID-19. In March and April alone, an estimated 420,000 people left the Big Apple. The majority fled into the surrounding suburbs. But resort communities and rural towns across a vast hinterland stretching from the Canadian border to the Virginia Tidewater absorbed many emigres. Tens of thousands fled as far as Florida and California.

Even 10 years ago, such a shift would have been unthinkable. But for these self-selected refugees—whiter, richer, and more likely to hold a job suitable for remote work—videoconferencing was a game-changer. Despite the unfairness of this urban exodus, new technology also improved conditions for many of those left behind. An array of services, digitally dispatched with a scale and precision never before seen, stepped in during lockdowns to bring food, medicine, and self-care supplies to the homebound. Delivery volumes doubled week on week, straining but never breaking down.

As the pandemic drama crawls toward denouement in the coming year—whether by deployment of an effective vaccine or a natural decline in transmission—we're left to wonder what, if anything, of this ad hoc dispersal will persist? Will the digital diaspora put down roots or return to the city? Will stores reopen and if so, will people go out to shop again?

Our ambivalence on these choices is palpable. Nowhere more so than in Silicon Valley, where the world's most powerful tech firms have given workers a free pass to work from home indefinitely—while also announcing massive plans for new downtown office quarters. Facebook moved early, committing to shift a big portion of its workforce to remote over the coming decade. Yet all along, the company continued to follow through on a pre-pandemic negotiation, signing a deal to lease the landmark Farley Post Office in New York City—a building whose considerable value comes from its proximity to the Pennsylvania Station commuter rail hub, North America's busiest. Since the start of the pandemic, despite touting work from home arrangements, Amazon, Google, Facebook, and Apple collectively expanded their New York City workforce by over 2,600 employees, more than 10 percent.

The tension of dispersal is grinding us down at home, too, despite high initial enthusiasm. Women have faced an especially turbulent set of new forces—freedom from commutes has given them new choices to manage work and family responsibilities, but the shutdown of schools and child care has further increased the already disproportionate burden of child care and housekeeping they bear. For all of us, the cost of prolonged isolation on productivity, recruitment, career development, creativity, and morale are all still largely unquantified. I suspect most organizations are in bad shape, but unable or unwilling to face it. At some point, they will be pulled apart. The failures could be sudden.

Stuck between a static condition that becomes more permanent with each passing week, and the gravitational field of human social networks slowly

DASH MARSHALL

reasserting itself—what's our next move? My hunch is that much like the tech giants, we should embrace the tension, and refashion our cities to be as good at spreading out during future emergencies as they are for crowding together during peacetime.

These new neighborhoods don't feel like the old ones though, as new ways of getting around take hold.

I call this approach "flexible density," and this kind of thinking is already visible in our responses to the COVID-19 pandemic. Restaurants shut down dining rooms but shift out into the street, colonizing curbside parking for "streateries" and expanding into the digital realm through multiple delivery platforms. Amazon adds over 1,000 local shipping hubs, slashing delivery times so much that shoppers stop thinking twice about going out to stores themselves. DJs have been locked out of dance clubs but promote live streams to backyard pod parties instead. Everyone discovers that doctor's visits by screen and prescriptions by mail beats waiting rooms full of sick people. While many of us will go back to the familiar old ways and places after the threat of infection subsides, these new offerings won't vanish completely when the pandemic does. A lot of them will stick around, and they'll be there for us again the next time the alarm sounds.

Until now, automation has lurked in the shadows of this transformation. Routing algorithms dispatch drivers. Conveyor droids race across warehouse floors fulfilling our just-clicked desires. Amazon has more than 100,000 conveyors already, toiling away around the clock in more than 100 town-sized shipping sheds. Inside, with humans pushed to the edges, goods-hauling AVs rocket down alleys too narrow for humans at three times the pace of a brisk walk. These robot-dominated interiors are truly inhuman. But extending these ghost roads out into the surrounding world may be the booster shot that's needed to bolster urban immunity for future crises. Amazon certainly seems to think so. The company bought Silicon Valley AV startup Zoox for $1 billion at the height of this spring's outbreak.

While automation is one powerful tool for flexible density, paving the way for automation through post-crisis cities can't be left to companies, however. Flexible density must be designed comprehensively into cities over the years and decades to come. We'll need buildings that are better suited to adapt when demands for space, security, energy, and ventilation change suddenly. Infrastructure must be pliable enough to extend to dispersed locations on short notice. And a wide array of essential services must be able to find and deliver to constituents and customers wherever they may be. Special attention must be paid to ensure that vulnerable and isolated groups are not left out of the new safety net. All of this will require new investments, new regulations, and new leadership. But as we belatedly start to price in the risks of human settlement in the 21st century, it may prove to be a bargain indeed.

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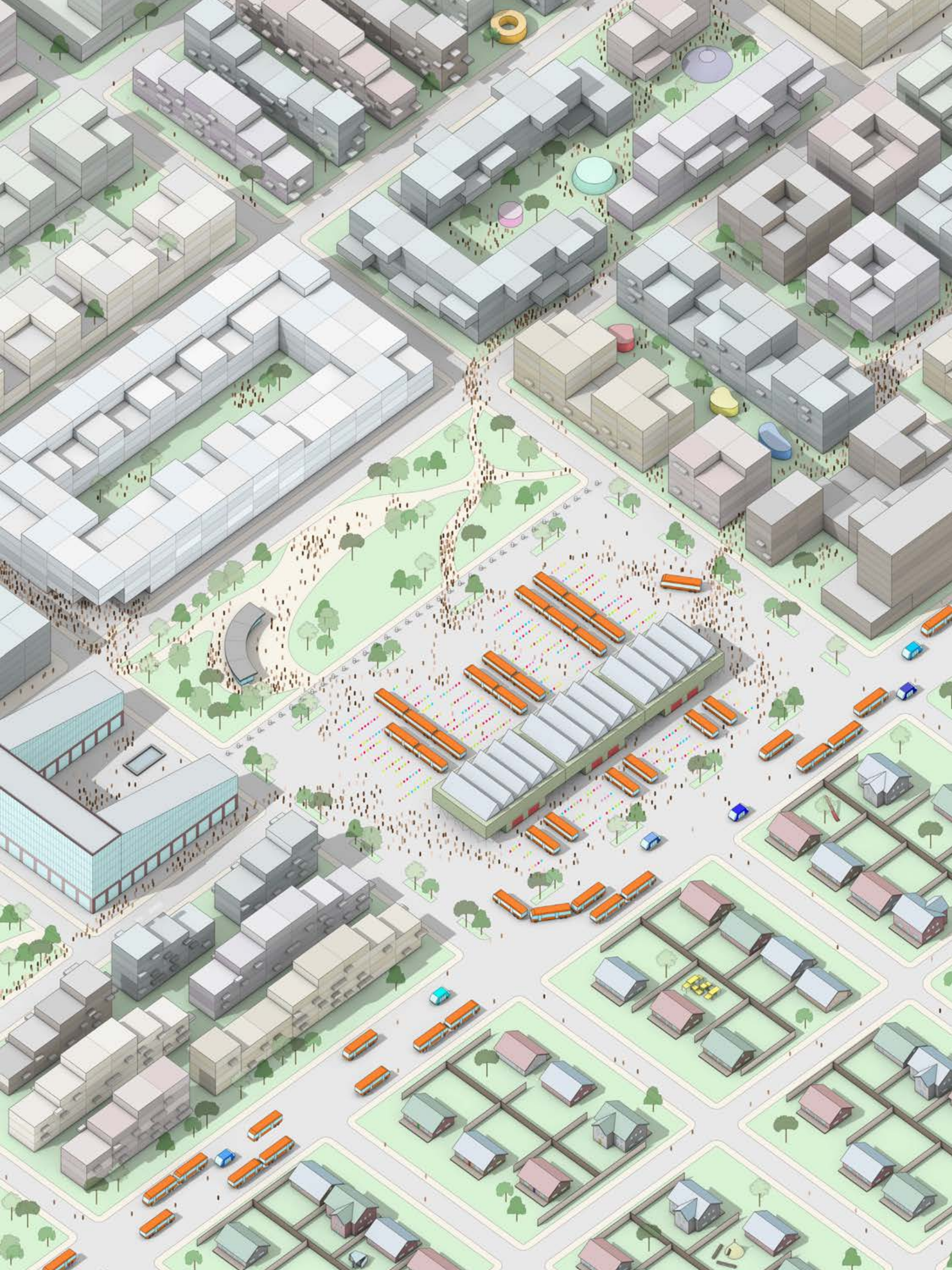

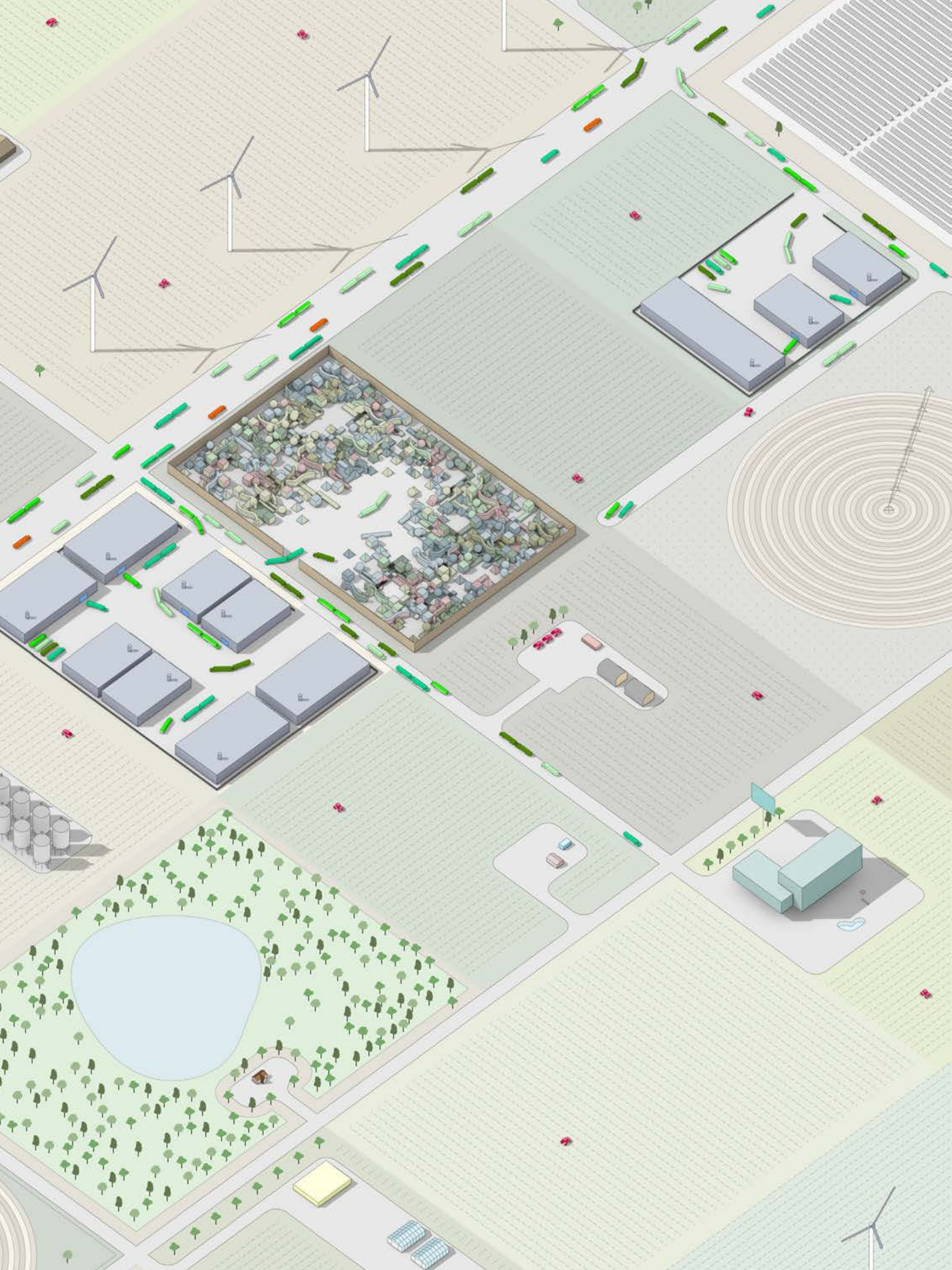

FAST FORWARD TO 2040, a world where iron-willed conservation and extreme adaptation go hand-in-hand. The big brush strokes that reimagine our world are painted with laser light, the scanning beams of helpful robots and automated vehicles feeling their way across the urban landscape. In New York City, they now outnumber people. For every one of some 10 million inhabitants, a half-dozen or more artificial ones have taken up residence. Yet while the city is more crowded than ever before, these machines make it possible to spread out even as we pack more tightly together.

The edges of the old city are where the most profound unraveling is underway. In the far reaches of Brooklyn and Queens a housing boom is in full swing. "Software trains" of automated buses—four and five coaches long, linked together only by a wireless connection—push at high speed along a vast new network of dedicated lanes. These transit-ready ghost roads are only a few feet narrower than the ones we used to lay out for human bus drivers, but with lateral gyrations limited by precise computer control, this belt-tightening makes it easier to squeeze them into a much wider range of city streets. Plowing effortlessly through neighborhoods the subway never reached or fully served, they're unlocking opportunities to up-zone entire swaths of the city for more apartments.

These new neighborhoods don't feel like the old ones though, as new ways of getting around take hold. Zipping around on "rovers"—a vast category of electric, automated runabouts that includes bikes, scooters, and even wheelchairs—is the way to go now. Summoned with a tap, they've crowded out pedal-pushers in the bike lanes, and even displaced cars and trucks from many local streets. Sporting minds of their own, these shared vehicles predictively swarm to where they're likely to be needed next—outside schools before dismissal, at the stop for an arriving bus, or by the pub at last call. Meanwhile, two-thirds of the stuff residents used to buy in person at local shops now gets delivered by a bewildering array of sidewalk-rolling, stair-climbing, and low-flying bots.

The collective impacts of these changes take some getting used to. Neighborhoods are bigger than ever, as rovers open up a range some five times what people can reach on foot. Snobs call it "microsprawl," but the people who live there don't seem to mind the abundance of affordable housing and open space that was always out of their reach in the old subway-centered districts. They adapt to the contradictions. Walking is passé, but cars have vanished, leaving more space for parks. Beloved shops on the high streets are long gone, but so too are most of the big box stores, which are now ball fields (at least the ones that weren't converted to distribution centers).

Despite all the new machine motion, on the streets people hardly take notice. That's because the cloud is a clever choreographer, who makes her most important curtain call late at night. Only then do the ghost roads of the city truly come to life. Heavy haulers are sent out, keeping the streets clear of big commercial loads during the day. Municipal robofleets are unleashed to do the dull, dirty, and dangerous work of urban upkeep.

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These new neighborhoods don't feel like the old ones though, as new ways of getting around take hold.

Wayward bikes and scooters scurry back to charging docks and disinfection baths. The cute eight-passenger shuttles that have replaced school buses moonlight as parcel vans. Bending time with technology, it turns out, is one of flexible density's secret weapons for sharing the city without overcrowding.

The hot, close salsa step of big city life isn't the only dance this city knows, though. Because when a crisis comes—be it pandemic, bombardment, flooding, or worse—it can shift stance to a spread-out, loose-formation waltz with ease.

For starters, this robot-powered metropolis is far more prepared to shelter in place. Municipal bots surge into hotspots—disinfecting, repairing flood barriers, extinguishing fires, or whatever the crisis calls for. And the same automated supply chain that powers e-commerce to our front door in peacetime is re-tasked in an instant to carry relief supplies.

When the situation worsens, though, and it comes time to evacuate, these machines prove their mettle. This city doesn't panic, it simply spreads out in an orderly fashion. Software trains change their routes to provide instant transit service out of the danger zone. Urban "ushers," roving street furniture with a mind of its own, close streets and direct evacuations. "Civic caravans," entire mobile buildings that house essential government services, pick up and crawl under precise, slow-motion computer control to higher ground overnight. Overhead, drones monitor the shifting scene and relay essential communications.

COVID-19 WAS A GENTLE WARNING compared to the stresses that will threaten cities throughout the 21st century. It also exposed striking inequalities in who will bear the brunt of these forces in large cities—migrants, racial, and ethnic minorities, the poor, women, and the elderly were all hit hard. The elite's preparations to flee are morally inexcusable. But simply hardening cities to ease the pain for those left behind is not enough. We need to shape cities in a way that both eliminates the need for such flight, yet bakes a more controlled, calculated version of it more deeply into the urban DNA.

Seen in this light, flexible density will be a shocking proposition for city builders and their advisors. For centuries, they've responded to pandemics by hardwiring social distancing into the urban fabric. After surviving the arrival of bubonic plague in Milan in 1485, Leonardo da Vinci sketched a series of unrealized designs for the city that included broader spaces for circulation. Four hundred years later, the early 20th-century modernists obsessed over windows and plazas in an effort to bring more sunlight and fresh air into buildings and neighborhoods. Because of their rigidity, however, these schemes didn't weather well. The permanent separation they baked in was too high a cost for city dwellers to bear. Over time, many drifted back to the old packed-in places that pre-dated the new ones. Those classic, tight-knit neighborhoods are still the places people love most. And they are our best models for sustainable, human-centered urban design. But they are not impervious to the shocks ahead.

Flexible density can help us navigate these tensions. It recognizes that dispersal is a strategy for resilience, but need not be permanent, or incongruent with the virtues of compact development. It recognizes the existential nature of the threats that cities face in the 21st century, and that the static way we've been thinking about resilience to date may not be enough. Yet it offers hope, too. It shows that even as the risks we face grow, so too do our capabilities. And it puts technology in its place, as a tool for boosting those capabilities. Flexible density highlights the potential for advances in automated mobility to unlock new design possibilities for buildings, infrastructure, and services—while not wholeheartedly re-organizing the future around their demands. There is much to be worked out about the details of how flexible density will work in the real world. But it is clear that we can and should challenge ourselves to peek over the horizon and imagine a tomorrow where flexible density is part of how we make ourselves at home on the other side of this very weird and unsettling present.

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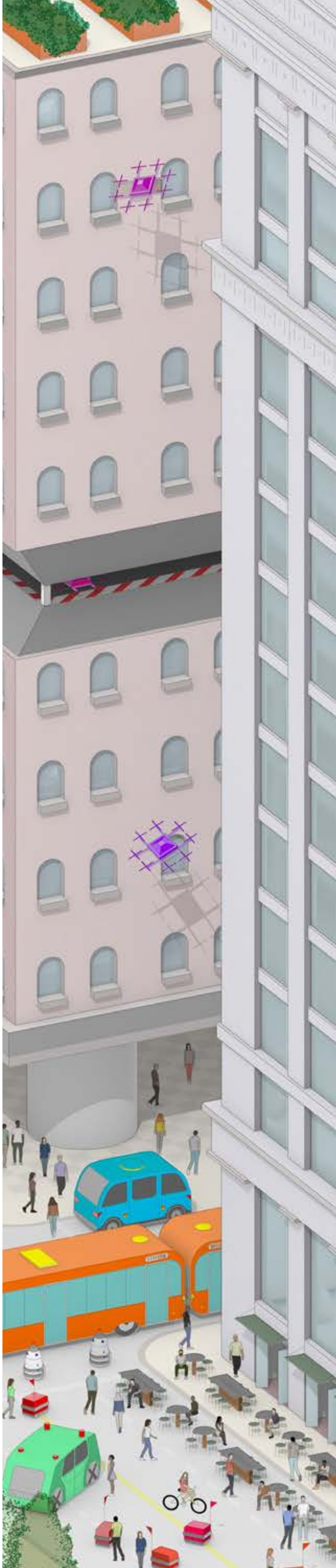
The illustrations that accompany this article were commissioned by the author to imagine concepts in his book, *Ghost Road*. They were done by the Detroit-based architectural design studio, Dash Marshall (dashmarshall.com).



The Human Error Darwin Inspired

How the demotion of Homo sapiens led to environmental destruction

BY AARON HIRSH

SINCE ITS PUBLICATION IN 1859, Darwin's *On the Origin of Species* has been read as a blow to the hubris of *Homo sapiens*. We aren't God's final and most perfect creation, after all, but merely one more product of the same evolutionary process that gave rise to apes, lampreys, and limpets. In his eulogy to Darwin, delivered in 1882, the German physiologist Emil du Bois-Reymond put it concisely: "Darwin seems to me to be the Copernicus of the organic world." Just as Copernicus had displaced man from the center of celestial orbits, Darwin had toppled him from the pinnacle of "animated beings." Du Bois-Reymond's analogy gained broad intellectual currency, and in fact it is often misattributed to Sigmund Freud, who appropriated it with just a wee bit of vainglory, adding psychoanalysis as "the third and most bitter blow" to humanity's "naive self-love."

Just for the record, since I am about to indict him: Huxley is among my heroes.

If the idea that Darwin humbled us has become canonical, what is less often observed is the fact that the newfound humility was, in certain important respects, misleading—and dangerously so. In the latter half of the 19th century, when small-scale artisanal methods were giving way to larger-scale industrialization in many areas of resource extraction and use, *Homo sapiens* was not, in fact, just another species, an organism like any other. To the contrary, *H. sapiens* was just embarking on a period of more sudden environmental transformation than any single species had ever achieved. *Homo sapiens* was, in fact, quite special.

It was a consequential error to think otherwise. In one important area of resource extraction—marine fisheries—we can trace the ramifications of Darwinian humility as it blinded powerful people to the unique and cataclysmic scale of their ecological impact.

Thomas Henry Huxley was a dear friend of Darwin's, a truly great zoologist in his own right, and the most important popular spokesperson on behalf of Darwin's ideas. Just for the record, since I am about to indict him: He is among my heroes.

From innumerable passages in Huxley's published writings and public speeches (which were transcribed and sold as pirated pamphlets by enterprising members of the crowd), it is clear that he viewed Darwin's theory as a broad argument against human pomposity, in favor of greater modesty. The very title of Huxley's magnum opus, published four years after *Origin*, points to a new perspective on the position of *Homo sapiens* in relation to the rest of the natural world: The book is called *Man's Place in Nature*. It is rare that a preposition is the most loaded and meaningful word in a book's title.

As a zoologist, Huxley contributed enormously to understanding the evolution of the primates, an order that Linnaeus himself had selected as the correct phylogenetic home for *Homo sapiens*. Compared with many other orders, the primates were rather easy to arrange on their evolutionary tree, thanks to well-preserved fossils, as well as relatively small yet well-defined gradations between living forms. This abundance of evidence allowed zoologists to include, in one great branch of the mammalian phylogeny, a wide range of species, extending from a lemur that looked a lot like a primeval shrew all the way over to *Homo sapiens*. Perceiving the philosophical implications of this speciose bough, Huxley wrote:

> Perhaps no order of mammals presents us with so extraordinary a series of gradations as this—leading us insensibly from the crown and summit of the animal creation down to creatures, from which there is but a step, as it seems, to the lowest, smallest, and least intelligent of the placental Mammalia. It is as if nature herself had foreseen the arrogance of man, and with Roman severity had provided that his intellect, by its very triumphs, should call into prominence the slaves, admonishing the conqueror that he is but dust.

The year these words were published, 1863, Huxley was appointed by the British government to be one of three royal commissioners investigating the state of marine fisheries. The commission had been formed to resolve a dispute between artisanal fishermen, who used hooks, lines, and crab pots, and trawlermen, who sailed larger ships, towing a net like a wide gullet, the lower jaw of which was a weighted cable that dragged along the sea floor. Over the previous two decades, the British trawling fleet had quadrupled in size, and artisanal fishermen thought the trawlers were not only extracting inordinate volumes of valuable fish, but also degrading the seafloor "garden" or "forest" that those fish relied on as habitat. Ship captains had been threatened, and their nets set ablaze.

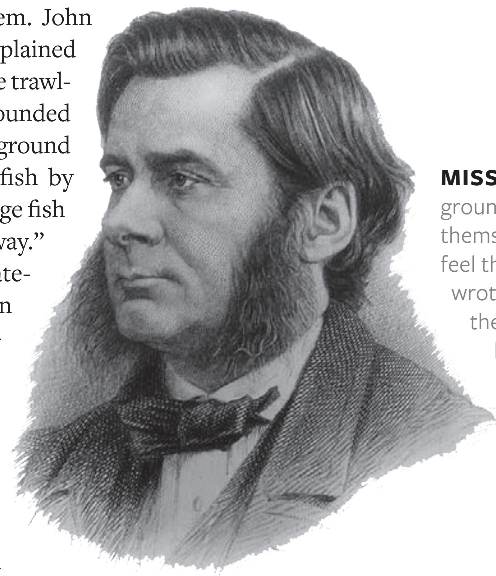
Twenty years later Huxley would serve again on a royal commission, this one prompted by the advent of yet another revolutionary advance in fishing technology, the steam trawl. Where before trawlers had traveled under sail and hauled their nets by manpower, now the steam engine enabled ships to swiftly and efficiently traverse every patch of seabed, and winches were turned with unprecedented ease and speed. Again the main objection to the new technology was that it destroyed the seafloor ecosystem. John Murray, an English fisherman, explained it during his testimony: Before the trawlers had arrived, "the ground abounded with small shellfish ... Now the ground is cleaned of this sort of shellfish by trawling, and now we have no large fish because their food is all taken away."

In both inquiries, Huxley's fateful inclination was to view human beings as he would any other species. Darwin, Huxley, and other naturalists had by this time understood the basics of natural population dynamics: As a prey species becomes scarce, the intensity of predation follows in decline. Elegantly, each regulates the other, and they may oscillate stably around an equilibrium. Huxley simply applied this insight to humans. "Any tendency to overfishing," he wrote, "will meet with its natural check in the diminution of the supply ... this check will always come into operation long before anything like permanent exhaustion has occurred."

That phrase—natural check—is one that Darwin had borrowed from Thomas Malthus, who had been thinking about human populations. Now Huxley was borrowing it back, taking ecological insights about other species and applying them to humans.

Huxley's influence is evident in the final reports from both commissions. His understanding of natural population regulation, for example, is reflected in the 1863 report:

> If any trawling ground be over-fished, the trawlers themselves will be the first persons to feel the evil effect of their own acts. Fish will become scarcer, and the produce of a day's work will diminish until it is no longer remunerative. When this takes place (and it will take place long before the extinction of the fish) trawling in this locality will cease, and the fish will be left undisturbed, until their great powers of multiplication have made good their losses, and the ground again becomes profitable to the trawler.



MISSED THE BOAT "If any trawling ground be over-fished, the trawlers themselves will be the first persons to feel the evil effect of their own acts," wrote Thomas Henry Huxley. Alas, the pioneering biologist missed the boat about humans' overwhelming ecological impact.

Huxley's fateful inclination was to view human beings as he would any other species.

Then comes the commission's startling recommendation: "We advise that all Acts of Parliament which profess to regulate, or restrict, the modes of fishing in the open sea be repealed; and that unrestricted freedom of fishing be permitted hereafter."

Tragically, Huxley had taken Darwin's great humbling of *Homo sapiens* a step too far. After all, a cod, when it is running short of prey, cannot suddenly double the width of its mouth, triple the speed at which it hunts, and venture deeper than any cod has ever gone before. Yet this is just what the trawler fleet could do. Steady increases in fishing capacity—larger nets, bigger ships that voyaged farther out to sea, new technologies for scraping the seabed—compensated for and thus largely masked precipitous declines in the abundance of fish.

By the turn of the century, however, it was undeniable: The effort required to catch a certain quantity of fish had multiplied by many times. Every accessible

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Tragically, Huxley had taken Darwin's great humbling of Homo sapiens a step too far.

square meter of the North Sea was being hit approximately twice per year by a trawl. Unlike the species he was fishing for, *Homo sapiens* had driven his prey so hard that—contrary to Huxley's humbled intuition—they would never bounce back. The ecosystem had been permanently transformed. By one species alone.

There is an inescapable and sad irony here. In its conception of humanity's relationship to other species, the Biblical account of the natural world, which Huxley had spent his career refuting and replacing with the new theory offered by Darwin, was in fact closer to reflecting accurately the new reality of industrialized civilization. According to Genesis, man held dominion over the rest of Creation. He was not at all just another species. He was distinctly more God-like. Under that view, it would not have been hard to imagine that humanity would one day bring even Leviathan to its knees, be they figurative or vestigial. It might have been wise for Huxley to hold on to one particular element of the Biblical account—its recognition of human dominion.

Or perhaps Huxley could have avoided his fateful error in another way: not by retaining an element of the old worldview, but by venturing further into the new, onward into a more thorough mortification of *Homo sapiens*. It is interesting to note that even Huxley had not taken the demotion of man to completion. Even as he argued that man ought to be humbled by his connection to the lemur, he placed man at the summit, the lemur on the lowly plain. The king might be reminded by the slave that he is but dust, but he is still the king. If Huxley had taken Darwinian humbling further, perhaps he might have wondered whether humanity was entitled to its sweeping extractive project. Or perhaps it would have occurred to him that the remarkable evolutionary trajectory of *Homo sapiens*, like those of several other species he had come across in the fossil record, might have rendered him vulnerable to extinction.

In view of the books Huxley read and the museums he worked in, we can be sure he was familiar with fossils of the Irish Elk, a species that labored under uniquely immense antlers until it fell into extinction around 8,000 years ago. In an odd coincidence, Thomas Henry Huxley's grandson, Julian Huxley, did his most important work in an effort to demonstrate that the antlers were not terribly out of proportion with the Elk's body. More recent research, however, suggests that sexual selection drove the evolutionary enlargement of the Elk's antlers, which subsequently taxed the species' energetic budget to such an extent that it became vulnerable to extinction. Perhaps, if Huxley had taken his humbling of man farther, he would have seen that evolutionary super-sizing of certain cephalic structures, whether antlers or brains, might prove dangerous in the long run.

AARON HIRSH is a writer and biologist with strong interests in education, evolution, and the environment. His first book, *Telling Our Way to the Sea*, won a National Outdoor Book Award for Natural History Writing and was a finalist for the William Saroyan International Prize. He is now working on another book about the history and fate of our planet. Aaron is also currently board chair for Ecology Project International.

The Fungal Evangelist Who Would Save the Bees

How mushrooms could solve colony collapse disorder

BY MERLIN SHELDRAKE

BEE HERE NOW Paul Stamets, a mycologist on a mission, wears a bee beard to promote honeybee health and funding for a Honey Bee and Pollinator Research Center at Washington State University.

SHELLY HANKS / WSU PHOTO SERVICES

I**F ANYONE KNOWS** about going fungal, it's Paul Stamets. I have often wondered whether he has been infected with a fungus that fills him with mycological zeal—and an irrepressible urge to persuade humans that fungi are keen to partner with us in new and peculiar ways. I went to visit him at his home on the west coast of Canada. The house is balanced on a granite bluff, looking out to sea. The roof is suspended on beams that look like mushroom gills. A *Star Trek* fan since the age of 12, Stamets christened his new house Starship Agarikon—agarikon is another name for *Laricifomes officinalis*, a medicinal wood-rotting fungus that grows in the forests of the Pacific Northwest.

I've known Stamets since I was a teenager. Every time I see him I'm met with a flurry of electrifying fungal news flashes. Within minutes his mycological patter picks up speed, and he leaps between bulletins almost faster than he can talk, a ceaseless torrent of fungal enthusiasm. When Stamets was a teenager, he suffered from a debilitating stammer. One day, he took a heroic dose of magic mushrooms and climbed to the top of a tall tree, where he was trapped by a lightning storm. When he came down, his stammer was gone. Stamets was converted. Since his influential work on psilocybin mushrooms in the 1970s, he has grown into an unlikely hybrid between fungal evangelist and tycoon. His TED Talk— "Six Ways that Mushrooms Can Save the World"—has been viewed millions of times. He runs a multimillion-dollar fungal business, Fungi Perfecti, which does a roaring trade in everything from antiviral throat sprays to fungal dog treats (Mutt-rooms). His books on mushroom identification and cultivation—including the definitive *Psilocybin Mushrooms of the World*—continue to provide a crucial reference for countless mycologists.

> *"Oh my god." Stamets woke up. "I think I know how to save the bees."*

In Stamets' world, fungal solutions run amok. Give him an insoluble problem and he'll toss you a new way it can be decomposed, poisoned, or healed by a fungus. Fungi are veteran survivors of ecological disruption. Their ability to cling on—and often flourish—through periods of catastrophic change is one of their defining characteristics. They are inventive, flexible, and collaborative. With much of life on Earth threatened by human activity, are there ways we can partner with fungi to help us adapt? Stamets and a growing number of mycologists think exactly this. Many symbioses have formed in times of crisis. The algal partner in a lichen can't make a living on bare rock without striking up a relationship with a fungus. Might it be that we can't adjust to life on a damaged planet without cultivating new fungal relationships?

One of the ways fungi might help us is by helping to restore contaminated ecosystems. In "mycoremediation," as the field is known, fungi become collaborators in environmental clean-up operations. We have recruited fungi to break things down for millennia. The diverse microbial populations in our guts remind us that in those moments in our evolutionary history when we haven't been able to digest something by ourselves, we've pulled microbes on board. Where this has proved impossible, we've outsourced the process using barrels, jars, compost heaps, and industrial fermenters. Human life hinges on many forms of external digestion using fungi, from alcohol, to soy sauce, to vaccines, to penicillin, to the citric acid used in all fizzy drinks. This sort of partnering—in which different organisms together sing a metabolic "song" neither could sing alone—enacts one of the oldest evolutionary maxims. Mycoremediation is just a special case.

Fungi can transform many common pollutants in soil and waterways that endanger lives, whether human or otherwise. They are able to degrade pesticides (such as chlorophenols), synthetic dyes, the explosives TNT and RDX, crude oil, some plastics, and a range of human and veterinary drugs not removed by wastewater treatment plants, from antibiotics to synthetic hormones. And yet decomposition is only part of the story. Heavy metals accumulate within fungal tissues, which can then be removed and disposed of safely. The dense meshwork of mycelium can even be used to filter polluted water. Mycofiltration removes infectious diseases such as *E. coli* and can sop up heavy metals like a sponge—a company in Finland uses this approach to reclaim gold from electronic waste.

WHEN I SHOWED UP at Starship Agarikon, I found Stamets sitting on the deck fiddling around with a mason jar and a blue plastic dish. It was the prototype for a bee feeder he had invented. The jar dribbled sugar water laced with fungal extracts into the dish, and bees crawled through a chute to get to it. Even by Stamets's standards, this project was a big headline. His 2018 study, co-authored with entomologists at the Washington State University bee lab, had been accepted by the journal *Nature Scientific Reports*. He and his team had shown that extracts of certain fungi could be used to reduce bee mortality dramatically.

About a third of global agricultural output depends on pollination from animals, particularly honeybees, and the precipitous decline in bee populations is one of the many pressing threats to humanity. A number of factors contribute to the syndrome known as colony collapse disorder. Widespread use of insecticides is one. Habitat loss is another. The most insidious problem, however, is the varroa mite, appropriately named *Varroa destructor*. Varroa mites are parasites that suck fluid from bees' bodies and are vectors for a range of deadly viruses.

Wood-rotting fungi are a rich source of antiviral compounds, many of which have long been used as medicines, particularly in China. After 9/11, Stamets collaborated with the U.S. National Institutes of Health and Department of Defense in Project BioShield, a search for compounds that could be used to fight viral storms unleashed by biological terrorists. Of the thousands of compounds tested, some of Stamets's extracts from wood-rotting fungi had the strongest activity against a number of deadly viruses, including smallpox, herpes, and flu. He had been producing these extracts for human consumption for several years—it is largely these products that have made Fungi Perfecti into a multimillion-dollar business. But the idea of using them to treat bees was a more recent brainwave.

ANITRAM / SHUTTERSTOCK

"Wake Up": An Interview with Paul Stamets

What is "evolutionary intelligence"?

Evolution is the evolution of intelligence. And one could make a very good argument we're not acting very intelligently now. We're destroying the very ecosystem that gives us life and will sustain our species for the future. The whole concept of evolution is that it spreads our genetic material into the future and preserves us as a species. Are we preserving ourselves as a species now? Are these pandemic zoonotic diseases emblematic of our intelligence or emblematic of our ignorance?

If you're aware of your environment, you're responsive to changes in your environment. You strategize to succeed and you protect your genomic destiny—that's the lesson of evolution and the underpinnings of evolutionary intelligence. Once you live with the symbiosis of nature, you have a deeper wisdom and appreciation. I think it's spiritual. I'm not religious, but I think there is a convergence of science and spirituality. Who could not become more spiritual by following astronomy? We have hundreds of billions of galaxies. Who cannot be deeply affected by the enormity and the expansiveness of the universe?

(*continued on p.42*)

The effects of the fungal extracts on the bees' viral infections were unambiguous. Adding a one percent extract of amadou (or *Fomes*) and reishi (*Ganoderma*) to bees' sugar water reduced deformed wing virus eighty-fold. *Fomes* extracts reduced levels of Lake Sinai virus nearly ninety-fold, and *Ganoderma* extracts reduced it forty-five-thousand-fold. Steve Sheppard, a professor of entomology at Washington State University and one of Stamets's collaborators on the study, observed that he had not encountered any other substance that could extend the life of bees to this extent.

Stamets told me how he had come up with the idea. He was daydreaming. All of a sudden, separate lines of thought came together and hit him "like a lightning bolt." If fungal extracts had antiviral properties, then maybe they'd help reduce the viral load of bees—and yes, in fact, he remembered that in the late 1980s, he had watched bees from his hives visiting a pile of rotting wood chips in his garden, moving the chips aside to feed on the mycelium underneath. "Oh my god." Stamets woke up. "I think I know how to save the bees." It was a big moment, even for someone who has spent decades dreaming up fungal solutions to obstinate problems.

Stamets' narrative style is straight out of an American blockbuster movie. Many of his accounts feature fungal heroes, poised to save the planet from almost certain doom. But will antiviral compounds produced by wood-rotting fungi really save the bees? Stamets's findings are promising, but it's too early to say whether the fungal extracts will translate into fewer collapsed colonies in the long term. Viruses are just one of many problems that bees face. Whether the fungal antivirals perform equally well in other countries and contexts isn't known. More important, to save bee populations, Stamets's solution has to be widely adopted, a feat he hopes to accomplish by recruiting the efforts of millions of citizen scientists.

I TRAVELED DOWN to the Olympic Peninsula in Washington State to visit Stamets's production facility. Headquarters is a cluster of large hangar-like sheds, surrounded by woods, several kilometers off the beaten track. This was where Stamets grew and extracted the fungi used in the study. It was where production was soon to be ramped up to bring a product to market for

(*continued from p.41*)

We suffer from scientific myopia. Understanding that we're one form of a molecular configuration among a sea of molecules that's reforming and disambiguating, and reforming constantly, gives solace when I consider death. I return to that from which I sprang.

Do you think nature is sending us a message?

Well, you find the answer to that question in your journey. Many people who've had what's called the hero's dose of psilocybin mushrooms have come through that experience gratified, informed, happier, more creative, more compassionate, more satisfied with the concept of life and death. It comes with this oceanic feeling that you're in this giant ocean of existence, and that life is a celebration. Organisms are singing out to us with praise but also deep concern. We've gotten here today because of biodiversity and the collaboration of other citizens and species on this planet. As we destroy biodiversity, we are removing citizens, and the democracy of nature is being undermined by human activity. Ultimately, nature will revolt against the species that is harming its foundation. It's time for us to wear our responsibility as a species, as a good

Give Paul Stamets an insoluble problem and he'll toss you a new way it can be decomposed, poisoned, or healed by a fungus.

widespread use. In the few months after the bee study had been published, he had received tens of thousands of requests for the BeeMushroomed Feeder. Unable to keep up with demand, Stamets plans to open-source the 3-D printed design in the hope that others will start to manufacture them.

I met one of Stamets's directors of operations who had agreed to show me around. There was a strict dress code: no shoes, a lab coat, and a hairnet—beard nets were also provided. We kitted up and passed through a special set of double doors designed to reduce the inflow of contaminant-filled air from outside.

We entered the fruiting rooms, which were warm and damp, the air thick and cloying. There were ranks of shelves lined with clear plastic growing bags stitched solid with mycelium sporting all sorts of startling protrusions, from woody reishi mushrooms with their shiny chestnut scalps, to lion's mane tumbling out of the bags like delicate cream-colored corals. In the reishi fruiting room, the air was so thick with spores I could taste their soft, damp bitterness. After just a couple of minutes my hands were dusted a cappuccino brown.

Humans were going out of their way to divert tons of food into fungal networks. A global crisis was turning into a set of fungal opportunities. Like the challenge faced by *Pleurotus* mycelium paused at the edge of a puddle of toxic waste, radical mycological solutions are less about inventing than remembering. Somewhere in the *Pleurotus* genome there is probably an enzyme that will do the job. Perhaps it has done the job before. Perhaps it hasn't but can be repurposed to serve a new cause. Similarly, somewhere in the history of life there may be a fungal ability or relationship that can inspire a new old solution to one of our many dire problems. I thought of the bee story. Stamets's eureka moment happened when

citizen within the biosphere. We've been not paying our dues. We've been extracting resources at the expense of biodiversity and not replenishing and re-supporting the foundation that have given us those resources.

How much does a psilocybin consciousness continue to inform you about the natural world?

I only journey on average about twice a year. But they inform me every single day that I re-remember my experience. I believe psilocybin mushrooms have made nicer people, more intelligent people, more creative people. These are Einstein molecules. How many Einsteins are we losing every day? And how many Einsteins would we not be losing every day if psilocybin mushrooms and psychoactive substances were incorporated into part of our mental health well-being?

Hallucinogen therapy in clinical settings has been successful in helping people treat PTSD, depression, and addiction. How does that compare to tripping outside?

I'm not going to pretend I have all the answers. But I want to be out in nature on a cliff in Big Sur, which is where I had my first experience, seeing the ocean, hearing the wind and the birds, and to have that expansiveness feeling. Other people feel safer being in a hospital setting, with a mask, and listening to music, and having a highly controlled therapeutic setting. I think both are perfectly good approaches. I think the hospital setting is an easier entrance for people who are concerned about not having the strength, or the conviction, to feel they can

(*continued on p.44*)

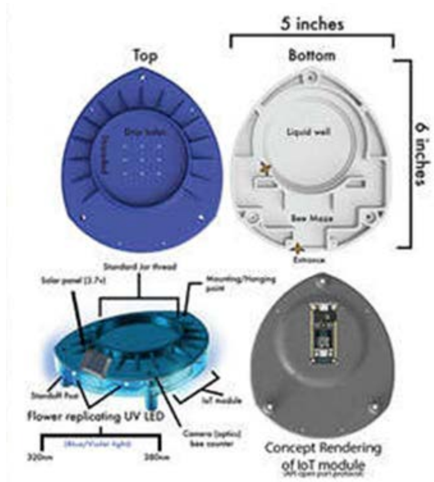
(continued from p.43)

weather this experience. But then they might use that as a stepping stone for doing it in nature, which is much more beneficial.

Most people look at the stars in the sky as a two-dimensional plane. But when you're on these psychedelics, you can see that Betelgeuse is bigger than Arcturus, you can see which is closer and which one is farther away. You experience the three-dimensionality of the universe. The air breathes. Rocks shimmer. Rocks speak. It just gives you a whole different perspective we'd never have with goggles, listening to music with headphones, at a hospital. But both avenues are justified. Psilocybin mushrooms are coming to us at a time when we need to have a paradigm shift in the evolution of the human species, and the medical science is rapidly catching up to this concept and supporting it.

You've written psilocybin can literally expand our minds. How so?

Psilocybin analogs, many of which are legal, like baeocystin and norbaeocystin, excite neurogenesis. Our studies were the first to show the proliferation of neurons from stem cells grown in vitro. We compared this growth to brain-derived nerve-growth, and discovered that baeocystin and norbaeocystin excite neurons over and above baseline, providing a proliferation of neurons within 12 days, up to 22 percent over controls. It's thought by many that dementia is a slow slide, and is non-reversible, as is Alzheimer's. Unfortunately this is the degeneration of synaptic junctions and the inability of growing new neurons. We all face this. But we are showing that these mushrooms stimulate neurogenesis.



SELF-MEDICATION
The BeeMushroomed Feeder, co-designed by Paul Stamets, delivers a mushroom mycelium extract to bees, key to restoring their health and reviving their colonies.

HTTPS://FUNGI.COM/PAGES/BEES

he remembered something that he had seen decades earlier—bees appearing to medicate themselves using fungi. Stamets didn't discover the idea of curing bees using fungi. Bees did, we presume, during a biochemical squabble with viruses in a damp corner of their shared history. Somewhere deep in the psycho-spiritual compost heap of his dream world, Stamets metabolized an old radical mycological solution into a new one.

I walked into the growing rooms, packed with shelving units three meters tall. Thousands of bags charged with soft blocks of furry mycelium filled the space. Some were white, some off-yellow, some a pale orange. If the fans filtering the air had stopped, I felt that I might have heard the crackling of millions of miles of mycelium running through its food. Upon harvest, the bags of mycelium were extracted in large barrels full of alcohol to produce the cure for the bees. Like so many radical mycological solutions, it is still uncertain; the first tender steps toward the possibility of mutually assured survival, symbiosis in its earliest infancy.

MERLIN SHELDRAKE is a biologist and author of *Entangled Life: How Fungi Make Our Worlds, Change Our Minds, and Shape Our Futures*. A keen brewer and fermenter, Merlin is fascinated by the relationships that arise between humans and more-than-human organisms. Find out more at merlinsheldrake.com, and follow him on Twitter @MerlinSheldrake or Instagram @merlin.sheldrake.

You've said you're just one voice in a long history of voices about the power of mushrooms. What do you mean?

There's been mycological experts going back tens of thousands of years. But the problem with studying mushrooms is that unlike other plants and animals, which can be in your view for months or years, mushrooms can come up and disappear in four or five days. Some can feed you, some can heal you, some can kill you, some can send you on a spiritual journey. Then they disappear and you don't see them for four or five years. Something that's so powerful but so ephemeral speaks to the cognoscenti in certain cultures. They were the mushroom specialists, the mycologists. I am just one voice in a continuum of voices, calling out for nature, from nature, for people to wake up.

—Mark MacNamara

The Greening of Antarctica

Few have witnessed the impact of global warming more closely than this scientist

BY MARISSA GRUNES


OLEKSANDR UMANSKYI / SHUTTERSTOCK

IF ANTARCTICA HAD A VOICE, it would be Jim McClintock. The marine biologist has been narrating the story of the changing continent for the past 30 years. A professor at the University of Alabama, McClintock studies the tiny marine invertebrates and crustaceans in the oceans around Antarctica. This research has taken him to Antarctica since the 1980s, when he first showed that Antarctic marine life has developed its own unique chemical defenses, some of which have medical applications in fighting AIDS, cancer, MRSA, and other human diseases.

McClintock has followed his far-reaching curiosity into marine ecology, climate change, and biomedical research. The small, strange creatures he studies—corals, sea sponges, sea butterflies, and other animals that form the basis of Antarctic ecosystems—are especially vulnerable to rising water temperatures and acidification as the Southern Ocean absorbs carbon dioxide from the atmosphere. McClintock has seen firsthand the impact of climate change on the oceans, glaciers, and marine life, a story he tells in his book *Lost Antarctica: Adventures in a Disappearing Land*. He has taken his storytelling approach all over the country, meeting with faith groups, campaigning for conservation organizations, and leading educational cruises to Antarctica for over a decade. Harrison Ford was so taken with McClintock's book that he recorded a reading with the E.O. Wilson Biodiversity Foundation.

During a phone call from our respective home offices, McClintock shared his experiences of watching Antarctica transform—and turn green. He is especially familiar with the West Antarctic Peninsula, the northern-most tip of Antarctica that is one of the most rapidly warming places in the world, and is often seen as a "canary in the coal mine" for climate change. McClintock has done research on icebreaker ships, as a scuba diver, and at Palmer Station, along with leading cruises along the coast.

Palmer Station, the northernmost of the U.S. Antarctic Program's three research stations, is located on Anvers Island along the peninsula that stretches up toward South America. It is home to the Palmer Station Long-Term Ecological Research (LTER) program, where McClintock's colleagues have continuously studied changes in the surrounding ecosystem since 1990. The LTER program is critical to understanding changes occurring in the region, the impact on wildlife, and what we can expect to see in the future. McClintock speaks of his time along the peninsula with exuberance: He shares his mentor E.O. Wilson's infectious generosity and passion for his work—and for the fragile world of Antarctica.

When you hear the term "the greening of Antarctica," what comes to mind for you?

Wearing less clothing when you go outside! I think in the big picture it's another term in the West Antarctic Peninsula to describe climate change and warming.

What kind of "greening" have you noticed in your 20 years traveling around the peninsula?

When I lead climate change cruises, we go up to the Antarctic Sound at the tip of the peninsula, and then turn around and sail back through Shetland Islands, working our way down to Palmer Station. The moss in

THE ANTARCTICA WHISPERER
Says marine biologist Jim McClintock: "What I've noticed is that the surface of the glacier has changed. The ice is crustier. And the thing that really struck me is: I began to hear it. To me, that running water is part of the climate change story."

COURTESY OF JIM MCCLINTOCK

some of these places is taking over. It's just amazing. In the places that we've stopped and gone to shore over the last 11 or 12 years—gosh, some of them have really greened up. You'll see a big rockface, and it has gone from a light covering of green moss, to this dense emerald green. And people on the cruise say: "Wow, look at that! Are we in Antarctica?"

I suppose given all the ice and marine life there, the "greening" of Antarctica isn't always visibly *green*. What other sorts of large-scale changes have you been seeing?
There's this massive glacier right behind Palmer Station on the peninsula that's always on everyone's mind: Marr Glacier. When I first got down there 20 years ago, Marr Glacier would calve a big chunk of ice into the bay next to the station maybe once a week. And it was a big deal. I remember people actually pushing past each other to get down the hall to look out into the bay, to watch the waves from a big calving. But now—say in the last 10 years—the glacier is going crazy. This last time I was down there in early 2020, it was calving three, four, sometimes five or six times a day. I'd say bigger chunks are coming off, too. And the behavior of people there has changed—they don't really react. It's just a constant backdrop. Everybody's aware that it's changed. It's indicative of the 80 percent of the glaciers on the West Antarctic Peninsula that are receding. That's the biggest physical factor that has struck me over 20 years at Palmer.

What do researchers believe is causing West Antarctic glaciers to become unstable and break apart like that?
It's due to a combination of sea water temperature and air temperature warming. There's also more rainfall than there used to be, which affects the glacial conditions. Midwinter air temperatures have increased about 10 degrees Fahrenheit in the last 50

ICE BREAK Antarctica's massive Marr Glacier has been going crazy, calving up to six times a day, says Jim McClintock. "It's indicative of the 80 percent of the glaciers on the West Antarctic Peninsula that are receding. That's the biggest physical factor that has struck me over 20 years at Palmer Station."

BETH SIMMONS

or so years. This past year, just north of Palmer Station there was a record air temperature in the 60s Fahrenheit! As a result, you see a lot more crevassing in the glacier, so you see these big crack lines coming down the glacier, and the big chunks break off where the cracks are.

There's something else about the glacier, too. At Palmer, one of the things you do to get away is go for a hike. That's really important, because you're stuck in this little station and there aren't a lot of places to go. So inevitably, every season, everybody hikes up to the top of Marr Glacier, at least once a month, sometimes every week. What I've noticed—particularly in the last five to 10 years—is that the surface of the glacier has changed. The ice is crustier. And the thing that really struck me is: I began to hear it. I began to hear channels of water trickling from the meltwater underneath the surface of crusty ice. You could hear running water. I thought: "I should come up with a microphone and record it!" To me, that running water is part of the climate change story.

How have the changes in Antarctica affected you?
When you live somewhere and see, year to year, if not month to month, changes in the environment around you, it's revolutionary. It just blew my socks off. As I came back each year to Palmer Station, the glacier had noticeably retreated. Penguins are disappearing around the peninsula. I personally witnessed climate change. I wasn't a climate change scientist. I was a marine biologist who was living and working in a place surrounded by change.

How important is Antarctica in the climate change story?
Polar environments are the barometers of change because a small increase in temperature can have a huge impact on the ecosystems in the ice. I think the fact that Antarctica is one of the first and foremost regions of the world—along with the Arctic—to be impacted makes it especially important, because it tells us what's coming elsewhere.

I give a lecture called "From Penguins to Plankton: Dramatic Impacts of Climate Change in Antarctica."

Ocean acidification is happening now. You don't have to wait for your grandkids.

After I've spoken about Antarctica, I show how Antarctica affects the place I happen to be lecturing—whether I'm in New York or Alabama. I'll say: "How is it affecting us here at home?" If you look at the Circumpolar Current that goes around Antarctica, for instance, it's the biggest ocean current on our planet. And it heads north and splits into the Pacific and Atlantic sides of the northern hemisphere. This means Antarctica has a huge impact on the climate of the rest of the world—a lot of people don't realize that. And then of course the melting of the ice is affecting sea levels here on the coast of Alabama. Antarctica might be far from us, but it's very much a part of our world—in some ways almost like a critical organ.

What does your own research on ocean acidification and marine invertebrates tell us about Antarctica?
Well, one thing we noticed this year, which I had never really seen before, is the huge number of salps. Salps are these gelatinous organisms that float around in the water. They can be solitary or colonial, traveling in chains. They look kind of like jellyfish. This last season when I was down there in February and March, I was helping on a research dive, and I looked down in the water and just saw chains of salps going by everywhere. But this has been one of the predictions: that salps are going to move down the peninsula and dominate the ecosystem. The downside of salps is that they are little tiny feeding machines. They eat *everything*. And where the salps are getting really abundant, the krill aren't as common, and the food web is slipping from this krill-based state to salp-based. But salps are like lettuce, their nutritional value is extremely low.

Does that mean fewer large predators like penguins and seals can survive in a salp-based ecosystem?
Exactly. I've been peering into this water for 20 years and I've never seen anything like this. And the divers came up, saying "Wow, that was a salp dive!"

Salps aren't really green, I guess.
No, not so much greening as jellyizing.

Along with jellyizing, how do you see wildlife changing along the peninsula?
The biggest wildlife factor that I became deeply aware of when I first got to Palmer is ecologist Bill Fraser's penguins, the Adèlies. They're out on these little islands in front of the station. Twenty years ago there were significantly more than there are now. There were 16,000 breeding pairs when Bill first went down there in 1974. Every year Bill's team does counts, and I go by the birding hut and ask, "What are you at this year?" The last count I heard was 1,100. So 90 percent of them are gone. In my book I call them "Ghost Rookeries"—there are so many empty rookeries. It's hard to believe that they may be gone eventually. Bill thinks they will be, at least from the West Antarctic peninsula.

This reminds me of something I heard: Antarctica's "greening" is making it a less uniquely polar environment, and more like an "ecological world suburb"—more temperate, more like the rest of the world.
Increasingly the peninsula has a warmer, humid, more sub-Antarctic climate. And you're finding species moving in that wouldn't have survived in a traditional polar climate. A case in point would be the Gentoo penguins and Chinstrap penguins. They're warmer-weather penguins that are extending their range down the peninsula as it's warming. Meanwhile the Adèlies, which are more specifically polar penguins, are disappearing.

Is there anything that can be done to slow the greening? How do you envision the West Antarctic Peninsula looking in 50 to 100 years?
Rising ocean temperature and rising ocean acidification are both significant challenges to Antarctic marine life. They're happening *now*. You don't have to wait for your grandkids. You can go to the Southern Ocean today and pick up a little shelled sea butterfly

ICE STATION The Palmer Station sits on the edge of Antarctica's Anvers Island. The station is home to scientists in the Long-Term Ecological Research program, critical to understanding changes occurring in the region, the impact on wildlife, and what we can expect to see in the future.

in your hand and you can see that the shell is dissolving—there's actually etching on the aragonite that forms the shell. It's urgent, it's happening. People have asked me, "What can we do about the poor Adèlies?" The answer is we'd have to do something about burning fossil fuels. That's the bottom line. You can't separate Antarctica from the bigger picture of what carbon dioxide is doing to the Earth's atmosphere. We can slow the trajectory if we get to business, move to an economy based on renewable energy. But when I envision the peninsula in 50 years, we're looking at very little sea ice and less krill offshore. Some species are better able to cope than others. The Gentoo penguins will be doing great, and the Adèlies will largely be gone.

In your biomedical research, you've argued that these ecosystem changes will affect humans more directly, right?

At Palmer, my colleague Chuck Amsler and I work with a chemist named Bill Baker, who studies marine chemical ecology. We extract chemicals from Antarctic sponges and soft corals to look for potential cures to human diseases. We have found chemicals in Antarctic sponges and tunicates and some algae, that have garnered attention as potential drugs. One of them is a tunicate that has a compound that is active against melanoma skin cancer, another is a compound in an Antarctic sponge that's active against MRSA—the Methicillin-resistant *Staphylococcus aureus* that everybody dreads getting in the hospital because it's antibiotic-resistant. That's

DUKE MARINE ROBOTICS AND REMOTE SENSING LAB / UNDER PERMIT BY ACA

I don't believe anybody can go to Antarctica and come back the same person.

caused quite a bit of interest because the compound we found is the first chemical to penetrate a biofilm. You can imagine a surgeon putting in a knee replacement, and the replacement gets a film of mucus and proteins and different things growing on it; the MRSA can hide underneath it like a blanket, and drugs can't reach it. This compound from an Antarctic sponge was the first chemical that had activity against MRSA under a biofilm. My point is: This is an ancient seafloor community that's been isolated a long time. It's got fairly high species diversity, and we've just touched the tip of the iceberg in terms of the potential medicinal value to humankind. We've got a resource for the future of humankind that we're potentially going to squander because of climate change.

What do you say to folks who want to go down to Antarctica but are worried about contributing to the damage?

Cruises to Antarctica are definitely an environmental issue. I'm concerned about the carbon footprint of cruises, I'm concerned about people dropping litter, I'm concerned about people getting too close to the wildlife. I'm concerned about the fact that Antarctica is a growing tourist industry. I try to push things like carbon offsets for the cruise industry, or getting rid of two-cycle engines for the Zodiac boats, and replacing them with cleaner and quieter four-cycle engines. And I do get asked by people, "Is it worth it? Should we be going down to Antarctica as tourists?" It's difficult. But after 13 years of leading cruises, I've seen the impact on these guests who witness climate change—who become ambassadors for Antarctica after visiting this amazing place. I honestly believe it changes you. I don't believe anybody can go to Antarctica and come back the same person. I don't say that lightly. Antarctica is in its own right a spiritual kind of experience.

MARISSA GRUNES is a postdoctoral fellow at the Harvard University Center for the Environment, where she is at work on a book about Antarctica.

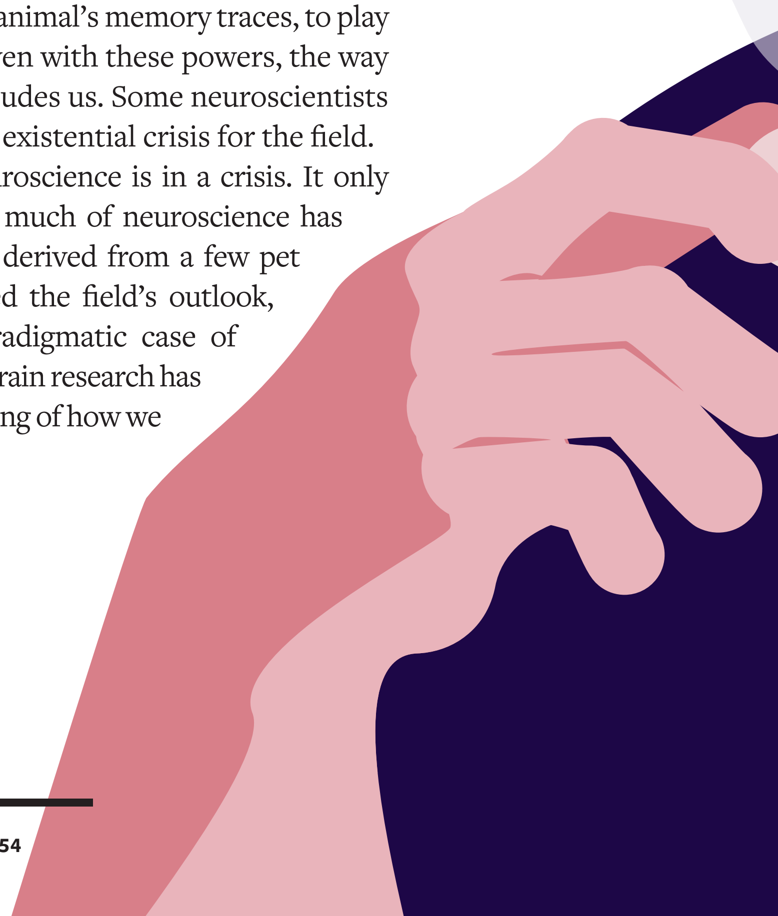
Our Mind-Boggling Sense of Smell

How your brain identifies an aroma from its minute molecular traces is a marvel

BY ANN-SOPHIE BARWICH

YOU MIGHT SAY the brain is our most photogenic organ. We are, thanks to modern neuroimaging, living amid an explosion of brain data. Just consider: We can zoom into the brain's connectivity to the most minute, molecular level. We can trace individual cells as well as entire cell populations. We can turn neurons on and off just like a light switch. We can even genetically engineer our way through an animal's memory traces, to play with its behavior. And yet, even with these powers, the way the brain ultimately works eludes us. Some neuroscientists are tempted to see this as an existential crisis for the field.

Still, I wouldn't say neuroscience is in a crisis. It only seems that way because too much of neuroscience has focused on favorite theories derived from a few pet systems. And this has limited the field's outlook, quite literally. Take the paradigmatic case of vision. Most of 20th-century brain research has been built on our understanding of how we see. This wasn't an accident.



TATIANA STULBO / SHUTTERSTOCK

What if we broadened our theories to include the workings of less popular parts of the brain?

The captivating beauty of the visual system is its apparent display of logic. The visual system gives us specialized areas in the brain that create and process our perception of particular sensory features. These include orientation, movement, shape, and color. It's almost as if you can map the physical world onto discrete and orderly neuronal structures.[1] This brain-map principle was found in other senses, too, including audition. Tonal frequencies line up in the auditory cortex, similar to the keys of a piano.

Perhaps this feature now proves to be a bug for general theories of brain function. The difficulty in mapping other physiological and mental functions—such as interoception, reward and motivation, or conscious awareness—onto discrete neural structures is that, unlike vision, not all of these activities represent spatial structures by default. They might instead represent a relational measure that connects an organism's constitution with fluctuating information from the world.

Mapping is, without a doubt, a notable characteristic of many sensory and cognitive systems. However, it might just be one of many material expressions, not the ultimate principle by which the brain organizes its neural activity. What if we broadened our theories to include the workings of less popular parts of the brain?

As I argue in my new book, *Smellosophy: What the Nose Tells the Mind*, an obvious choice is olfaction. Our sense of smell offers an intriguing challenge to the mapping paradigm in vision. The nose is tailored to measure an unpredictable chemical array in our environment, allowing the brain to evaluate when minute molecular traces shift behavioral meanings to signal pleasure, danger, or novelty.

Ramón y Cajal, a founding father of neuroscience, had already recognized this first when, at the turn of the 20th century, he drew attention to the sense of smell as an exemplary model to learn how the brain makes sense of the world.[2] Though olfaction, to most scientists during Cajal's time, looked to be a capricious and quirky sense without much sophistication—and so of little interest to studies of cognition and its biological basis—Cajal believed understanding smell would grant us better insight into other sensory systems.

The reason why has to do with an intriguing feature specific to the olfactory system. That is, it takes only two synapses for information to travel from the air, through your nose, and to the core cortex, deep in the brain. To put this into perspective: Two synapses won't get you out of the *retina* in the visual system. You cannot find a more direct route bringing the brain in touch with the world!

This closeness to the world does not imply that our sense of smell is simple. The complexity of smell is mind-boggling. The chemical composition of your surroundings—and we're talking hundreds and hundreds of molecules—is changing constantly and rapidly. Your nose picks up volatile airborne compounds that interact with your olfactory receptors (situated on the cilia of the sensory neurons in the nasal epithelium) in a combinatorial fashion.[3] This means that different receptors detect different parts of different molecules, and that one molecule interacts with various receptors via different features. The function of the olfactory system is not to map chemicals discretely in space. Instead, it tracks and computes the statistics of a changing chemical environment: How many, in what concentration, and how often do chemicals co-occur as a molecular cloud?[4] (Our nose is tuned to detect blends of different chemicals—coffee aroma, for example, consists of 800 different compounds.) Simply consider the system's mind-boggling capacity: If you calculate all possible combinations of structure-receptor interactions in smell (with one molecule hypothetically activating 100 receptors), you'd end up with a number higher than atoms in the galaxy.

Neuroscientists did not pick up Cajal's advice until the late 20th century.[5] There was a certain pragmatism for this. Smell has always been notoriously hard to investigate. As many people can personally attest, the experience of scents is inherently variable. Things can smell different not just between different people but also for the same person.

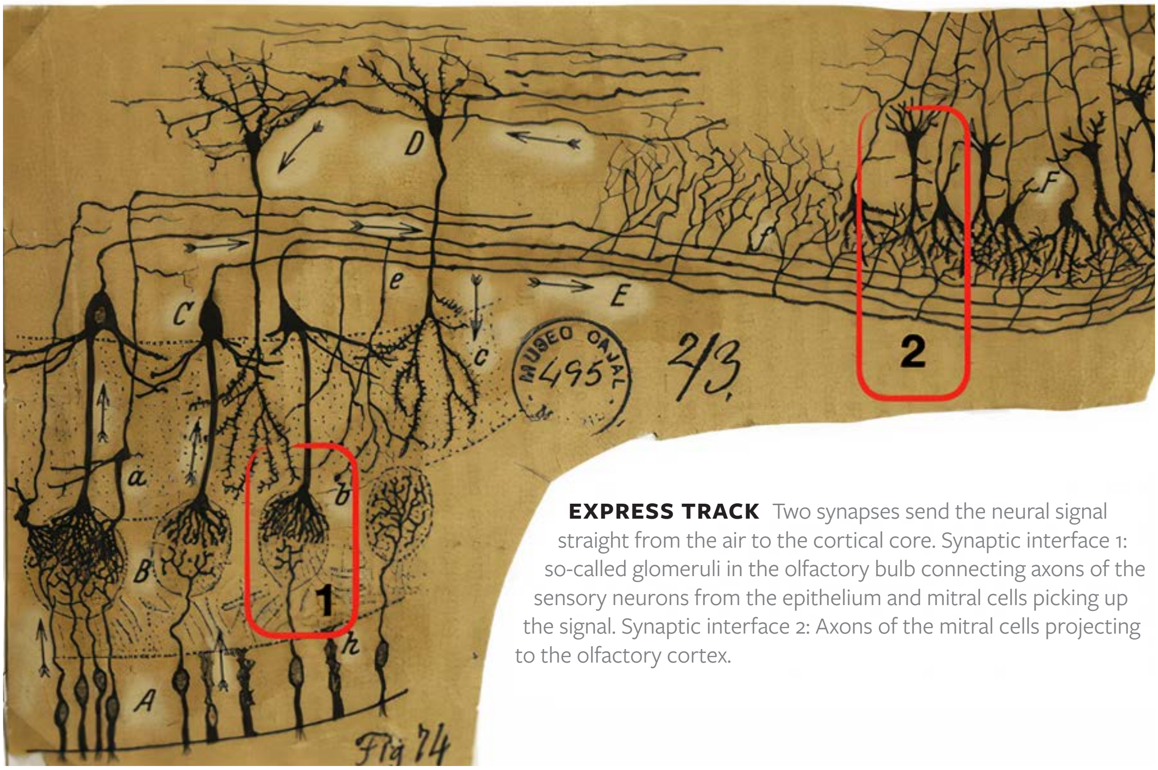
When you experience a glass of red wine, for example, you may enjoy its dominant cherry aroma—until someone comments on a strong vanilla note in the same glass of wine. Suddenly the cherry moves to the backseat of your conscious awareness, while the vanilla aroma pops into focus—even though you had not noticed it before. How do you turn such ephemeral and transient nature of odors into a measurable, stable, and comparable object of scientific study?

Linda Buck and Richard Axel set scientists on the path to answering that question with the discovery of the olfactory receptors. The olfactory receptors happened to be the most structurally diverse and sizable member of the largest multigene family of protein receptors in the mammalian genome (so-called G-protein coupled receptors—or GPCRs in short). Their striking diversity and sheer size—olfactory receptor genes have more "genetic storage" than the immune system, occupying about 4 percent of the mammalian genome—caught the attention of scientists interested in mechanisms of gene recombination and the evolutionary diversification of biological processes. How did some biological entities, like proteins, evolve to facilitate a variety of functions? The superfamily of GPCRs orchestrate numerous fundamental biological processes, including vision, the detection of neurotransmitters in the brain, and the regulation of immune responses.

The brain is not simply a projection screen. It is fundamentally a pattern-recognition device.

These receptors turned out to be a genetic goldmine for which, along with other work on the organization of the olfactory system, Buck and Axel received the 2004 Nobel Prize in Physiology or Medicine. Olfaction, long the Cinderella of the senses, was thrown into the limelight of the scientific mainstream. As a result, smell emerged as a promising molecular model to think about GPCRs—the target of about half of all drug studies—and the causal principles governing their functional interactions.[6]

For example, how broad is the tuning of these proteins? Do some receptors respond to a wider array of molecular features than others, and might this suggest a genetic difference? How do genetic differences between receptors link to the wiring of the brain (receptor genetics is a fundamental driver in the neural development of the olfactory system[7])? What's more, what combinations of molecular features may block or even enhance the response of these proteins? How these proteins execute a vast variety of functions remains a site of ongoing discovery.



EXPRESS TRACK Two synapses send the neural signal straight from the air to the cortical core. Synaptic interface 1: so-called glomeruli in the olfactory bulb connecting axons of the sensory neurons from the epithelium and mitral cells picking up the signal. Synaptic interface 2: Axons of the mitral cells projecting to the olfactory cortex.

IMAGE MODIFIED FROM CAJAL'S DRAWING OF THE OLFACTORY PATHWAY.[2] COURTESY OF THE CAJAL INSTITUTE, CAJAL LEGACY, SPANISH NATIONAL RESEARCH COUNCIL (CSIC), MADRID, SPAIN.

With only two synapses straight into the cortex, a full understanding of the olfactory brain looked imminent. Yet the apparent simplicity of the olfactory system soon proved deceptive. Today, three decades after the receptor discovery, the mechanisms of odor perception continue to flummox researchers. Rather than close in on a full understanding, we merely started to appreciate the hidden complexity with which the brain makes sense of scents.

Neuroscientists were wrong to rely on vision as a guide to how the brain works. Arranging smells in a map-like way may sound like a nonstarter. Jasmine scent over here and coriander aroma over there? But this approach soon reveals its limits. By what features would you map potentially more than a trillion odor chemicals in neural space? Are ketones, for instance, placed next to aldehydes, or closer to esters? And where do you put indole, an unpleasant smelling crystalline organic compound found in coal tar and feces?

Recent research on the olfactory system reveals such a visual system-inspired design is mistaken. The olfactory cortex is not organized in a logical spatial manner, like other sensory cortices are. Instead of a map, you face a seemingly random and complicated mosaic of signals. In contrast with color vision and sound, the stimulus in olfaction is multidimensional, not low-dimensional. Color perception is based on the visible spectrum of electromagnetic waves of light and auditory perception is based on the frequency of pressure waves of air, which can be mapped linearly to neural correlates. But odor quality is linked to structurally highly diverse chemicals. These chemicals have about 5,000 molecular features, not correlated in any straightforward manner to odor quality, that olfactory receptors (of which humans have about 400 types) pick up on to identify them.

How the human brain ought to use neural space to organize this plethora of non-spatial chemical information is, as yet, unresolved. In a way, how your brain processes the complex chemistry of smells is closer to doing mathematics than mapping.

Recall the capacity of combinatorial coding by the receptors. Odors are computed from a widely

I wouldn't say neuroscience is in a crisis. It only seems that way.

distributed mosaic of signals: All the brain "sees" (for a lack of a better term) is what receptors light up, how many of them, for how long, and in what combination and ratio. With about 400 types of receptors participating in a combinatorial coding of 5,000 molecular parameters, this turns out to be a rather sophisticated task.

The real question we must ask is: What kind of sensory information is picked up and interpreted via the olfactory system that can be linked to neural correlates? What characterizes olfactory encounters "in the wild" (outside the discrete administration of simple stimuli in the laboratory) is the inherent unpredictability of the chemical stimulus in its environment and its interaction with the sensory interface. This point has implications for our general understanding of how the brain works.

The olfactory system does not require a map mirroring some fixed physical features in the world because its chemical stimulus is constantly in flux. The brain, drawing on memory, recognizes patterns in the chemical composition of the olfactory stimulus. This is one way for the olfactory system to foreground novelty, meaning the introduction of unknown (and potentially behaviorally relevant) compounds into an otherwise constant environment. A similar enough principle of novelty detection in pattern recognition applies to other sensory systems that aren't strictly mappable, either. Consider interoceptive systems, which regulate processes within an organism like heart rate to hormonal changes.

Paying attention to the brain's peculiarities can, in other words, be insightful, not counter-productive. Such idiosyncrasies, like the weird complexity and variability of smell, now turn out vital to understanding the brain—how it maneuvers an organism through a landscape of fast-changing molecular combinations. The processing behind this is highly dynamic and radically prompt in answering how, what, and when to choose. The brain is not simply a projection screen. It is fundamentally a pattern-recognition device. Tracking the chemical statistics of an ever-changing environment needs a simple solution to a complex problem—an overly specialized map may even be disadvantageous here. Our brains evolved from our bodies, after all, not the other way around.

ANN-SOPHIE BARWICH is a cognitive scientist and empirical philosopher. She is the author of *Smellosophy: What the Nose Tells the Mind*. Follow her on Twitter @smellosopher.

FOOTNOTES

1. A series of breakthrough experiments on the visual cortex of the cat, by Torsten Wiesel and David Hubel, cemented the explanatory primacy of a mapping approach to brain function in sensory systems. Hubel and Wiesel's ideas were informed by prior research on the motor system—Wilder Penfield's "homunculus" from 1937 (with specific regions of the motor strip on the cortical surface representing particular parts of your body), and the discovery of cortical columns by Vernon Mountcastle in 1957 (where neighboring cortical cells responded to similar input).

2. y Cajal, R. Croonian Lecture: La fine structure des centres nerveux. *Proceedings of the Royal Society of London* **55**, 444–468 (1894).

3. Malnic, B., Hirono, J., Sato, T., & Buck, L.B. Combinatorial receptor codes for odors. *Cell* **96**, 713-723 (1999).

4. Cleland, T.A. & Sethupathy, P. Non-topographical contrast enhancement in the olfactory bulb. *BMC Neuroscience* **7**, 7 (2006).

5. With exceptions such as Edgar Adrian in the 1940s and Gordon Shepherd in the 1970s proving the rule.

6. Barwich, A.-S. What is so special about smell? Olfaction as a model system in neurobiology. *Postgraduate Medical Journal* **92**, 27-33 (2015).

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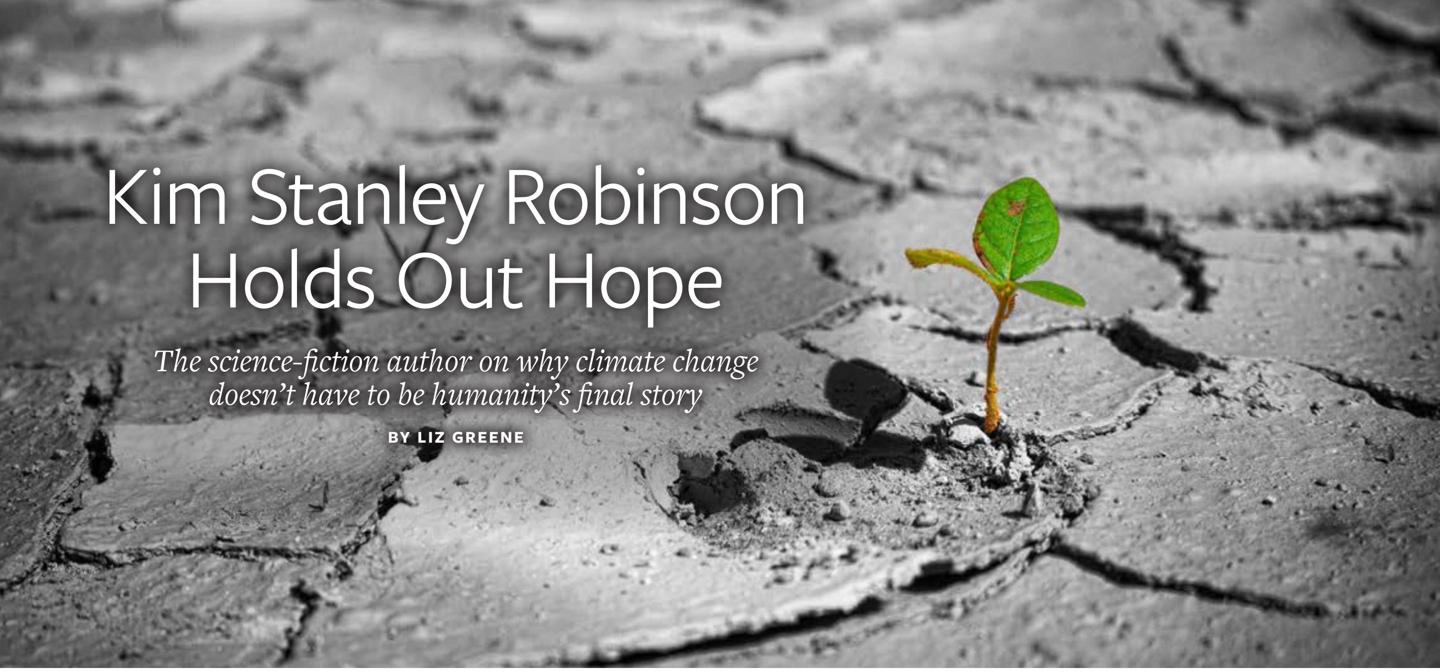


Kim Stanley Robinson Holds Out Hope

The science-fiction author on why climate change doesn't have to be humanity's final story

BY LIZ GREENE

THERE'S SOMETHING ABOUT STORIES. We cherish them. Teach them. Pass them down to the next generation. Stories create a sacred space that humans have always respected. And science fiction takes us one step further. It gives us the space to imagine what we could be, could do, could make. And sometimes these stories give us an all too real vision of what may yet come to be in our own world. They are a warning.

In his new novel, *The Ministry for the Future*, Kim Stanley Robinson paints a picture of a global temperature that's been allowed to keep rising unchecked, and the harsh results of humanity's inaction. In the book, the Ministry for the Future is a United Nations agency that was formed to mitigate climate change and consider climate equity. This is, of course, an impossible task for a toothless agency, so the members have to get creative. But we're not left without hope. When it comes to climate change and its discontents, Robinson says, "We could deal with it better or worse. And so I wanted to describe how we could deal with it better."

Polls show climate change is getting more important to people. But there's still this dissociation where it feels far away, like someone else's problem. Do you think fiction can help make climate change more of a palpable emotional issue that people can feel in their gut today?
Yes. But I'd also make the assertion that everybody who's paying attention is aware that climate change is happening and it's a big problem. You would have to deliberately shelter your mind from the general onslaught of information, and some people do that, for sure. If you only watch Fox News, you might not be as concerned about climate change. But I think general awareness of climate change is all over now and people are aware it's a problem.

Climate change is a global story. It will last for centuries. It will affect everyone.

What I've been doing in my climate fiction is try to point out the ramifications that aren't fully taken on by the culture that are really important to think about. And that's been a way to sort out which story I want to tell. Climate change is a global story. It will last for centuries. It will affect everyone. So which story do you tell of all those literally billions of stories for billions of people? I've been trying to pick the stories that aren't yet on the radar.

RATTANASAK KHUENTANA / SHUTTERSTOCK

***The Ministry for the Future* opens with a horrible, incredibly deadly heatwave. How likely do you think it is that we'll see this in real life soon?**

I think it's all too likely. I'm terrified that it can happen in the 2020s. This wet bulb 35 temperature—the combination of heat and humidity together that's fatal to humans if they're not in air conditioning—is already striking a few times a year around the world. And it's coming faster than the scientific modeling had predicted because the world's heating up at the worst case scenario speed.

There was a certain complacency in the social sciences or academic community, the think-tank community. People were saying the world was going to heat up, there's nothing we could do about it, we just have to adapt, blah, blah. They hadn't considered that just another 1 degree Celsius rise in global average temperature is going to end up being fatal for humans. And we can't adapt to fatal heatwaves. They'll simply kill us.

And that, I think, changes the game. It increases the intensity of the need to decarbonize. Say we have to decarbonize fast and everybody admits it, because of a heatwave like the one I describe, how do you do it? What would happen then? That's what the novel explores.

What do scientists who've read your fiction say to you about it?

I've heard from literally hundreds of them. They say science "is harder than you thought." "How come you didn't tell me there was more math in this one?" "When I was a kid, I read your book and I became a geologist and now I'm in over my head and it's all your fault." So it's not altogether just happy-happy. A lot of scientists read science fiction when they're young, that's for sure. And then they get into real science and become disenchanted with science fiction.

I think what they like about my work is that it takes the scientific world seriously as a story space, where you can tell interesting stories without having light sabers—even if they have quibbles about the things that I left out or got wrong, which they love to point out, and sometimes helpfully so. I've taken scientists' comments on my work and fixed the texts in subsequent printing. In the Mars trilogy, there are literally scores of corrections that scientists pointed out to me. Until you get to the 18th printing of *Red Mars*, you don't have the final text.

My work takes the scientific world seriously. You can tell interesting stories without having light sabers.

What role can fiction play in the world of science?

Science is all about modeling and trying to extrapolate from current conditions into the future, so that you can then do something about it. Fiction, and especially science fiction set in the future, is easily taken in by the scientific community as a kind of a modeling exercise that is personalized, speculative, and useful for its examination of interlocking and interfering effects. It's also useful for the personal aspects and human factors—what some people have called thick texture. Fiction has the thick texture of a speculation that in science might just be a single sentence.

At what point do you think we won't be able to save Earth from ourselves? Is it already too late?

It's never too late, it's only better or worse. We can't dodge climate change, we're already in it. But we could cope with it well if it becomes civilization's main project. If instead of profit we focused on sustainability, which has to do with justice, full employment, and the carbon coin paying people to do the right things rather than the wrong things. This has to do with agriculture, with ranching, with the entirety of the way we run civilization. If we were organized around decarbonizing and getting into a good relationship with our biosphere, we could, by the end of this century, have a quite prosperous and successful long-term civilization, a carbon-negative civilization. So not only is it not too late, it's never too late. What we do in the next decade or two will make a huge difference.

LIZ GREENE is the managing editor of *Nautilus*.

WANNAPONG / SHUTTERSTOCK

Los Angeles Is Gone

In an excerpt from his new novel, the author drowns La La Land

BY KIM STANLEY ROBINSON

I **WAS IN MY APARTMENT** in Sierra Madre, which is a little town lined by tall palm trees, wedged between Pasadena and Azusa, set right at the foot of the San Gabriel Mountains, which tower over that part of LA like a brown corrugated wall, pretty ugly if you ask me. It was kind of a blessing when the smog got so thick you couldn't see it, which could happen even from only three miles away. None of the ring of mountains backing LA are good-looking. But they do form quite the wall, as we found out that day.

Water is a force of nature, you can't resist it if it gets you.

ROMIEL MASIH

Luckily I was an active kayaker before I broke my arm, and I still had my kayak. My apartment was a granny flat over a garage, its separate entrance something I valued a lot, as I didn't have to bother my landlord going in and out, and he usually never saw me and thus never got a chance to scam on me. It was kind of a mercy rental on his part, or so I thought before his intentions became clear, as I couldn't afford Hollywood anymore, no doubt obvious when I gave him my clichéd young-aspiring-actress-currently-waitressing shtick. And he let me store my big stuff in his garage below my studio, which was really just a storage shed with a bathroom in it, tacked onto the flat roof of his garage. So when the atmospheric river hit, I was one of the few people in the city with watercraft on hand.

It rained hard all that first night, the timing was part of the problem—by the time everyone woke up things were already bad, and it just went downhill from there. Literally so for the water, and therefore everything else. But it wasn't your ordinary flood, or maybe it was, I don't really know, but in our case, the water came roaring down off the side of the San Gabriels onto us. It was terrifying to see what the dawn revealed that day. The mountains are ten thousand feet high over Sierra Madre, and they were catching all that rain, which was falling as hard as in a hurricane or something, and then it was all rushing down those vertical ravines onto the streets that poked up into the ravines, now all of them whitewater rapids brown with mud, and filled with boulders and shrubs and pieces of all the houses that were coming apart farther up the street.

I looked out my front door and saw cars floating down the street on a brown wave about three feet high that covered everything. I could see the water was already coming into my landlord's house, and rushing hard toward the 210. Everywhere I looked was a big sheet of brown water! I shouted to my landlord but he had already left without informing me, very typical. In fact I couldn't see anyone anywhere except for a family on top of their SUV, getting taken for a sideways ride and looking desperate.

HANS BRAXMEIER / PIXABAY

I got down my outside stairs and sloshed through brown water to the garage side door. Inside I found the power had gone out, of course, so it was a struggle to get the big garage door open. I managed to pull it up from the inside, and a sloosh of water flowed into the garage, a little wave about a foot high. But there was my kayak and I grabbed it and the paddle off the wall, wriggled into the skirt and got into the kayak and took off into the street.

That was a crazy moment, realizing the streets were all flooded and my kayak was the only way for me to get around. So much water! And brown as hot chocolate. And it was still raining cats and dogs too, so it was hard to see very far, and hard to believe what you could see. Later I heard the whole LA basin was flooded, all the way from the Hollywood Hills down to San Clemente, past Irvine where I grew up. Orange County was just as bad as LA, which makes sense given they are the same coastal plain with the same backing mountains. Of course there are some high points here and there on the plain, as everyone found out that day. Palos Verdes sticking up near Long Beach of course, and a few inland neighborhoods on lines of low hills like Puente Hills and Rose Hill, and back where the freeways meet around San Dimas. But for the most part LA is just one big coastal plain, and on that day, a big brown lake. In lots of places the elevated freeways were the only flat surfaces that stuck up out of this new lake, so, with no other place to go, the freeways were where people went. There were still some cars up there, but none of them were moving, and as the need for space to accommodate people got greater, a lot of cars were shoved over the side into the drink.

A whole river network was being revealed or half-revealed by currents in the streets.

I kayaked under the 210 through a very scary underpass, and paddled around getting people off roofs and over to the freeway, where onramps served as boat docks. A lot of people were zipping around on motorboats they had kept in their driveways, also some kayaks like mine. We were doing all we could to help, some people were really desperate, especially if they had kids, and it was hard to keep them from tipping my kayak over in their panic. My arm started to hurt where it had broken, and I kept feeling a sense of unreality that this could all be happening at all, it was too much like a cheesy disaster film, but whatever, I must have gotten cast at last, and besides the fear on people's faces and in their voices kept reminding me that no, this was real no matter how weird it was. And my arm hurt, kayaking is just very bilateral, you can't do it one-armed, but I just kept saying Fuck it and kept paddling.

One thing about the LA basin being so huge was that even though the whole thing was flooded, it was never flooded very deep. Lots of taller rooftops stayed above the flood level, although many other buildings had collapsed into the water. Most palm trees were knocked down, it was a shock to see and a danger to navigation. One of many! Sometimes I had people hanging on to the back of my kayak and the current would take us toward a floating tree or a car and I

The entire city of Los Angeles is going to have to be replaced.

would have to paddle insanely to get away from them, my arm hurting and the people hanging on and not always kicking in the most helpful ways. And all the old washes crossing the plain were now revealed again as fast places in the flow, it was spooky to see those currents, dangerous too, and it was never obvious which way water would be moving on any given street, because it depended on where the nearest wash was, since the water got sucked toward those, and the streets were almost flat. A whole river network was being revealed or half-revealed by currents in the streets, north south east west, they could be running in any direction. Orange Grove Avenue was on enough of a tilt to be like a water slide running south, then the old sunken part of the Pasadena Freeway just west of it ran in the other direction, it was crazy. Sepulveda was scary fast, I was told, the other kayakers all said Stay off Sepulveda, it's like class 8! And the rain kept pounding down on us. Hard rain, in LA, for hour after hour? It was like Noah's flood! And it looked like it could go on for forty days and forty nights too, why not?

So, ten million people stranded on all the high points left sticking out, and no food to speak of. Rain pounding down for hour after hour. Lots of little boats but nothing big, and nothing organized. All the freeways packed with very wet people. It was never colder than about seventy degrees, although

KELLY SIKKEMA / UNSPLASH

that feels cold when you're wet and it's windy, but cold wasn't the issue. Nor was the flood like some do-it-right-now-or-die emergency, where you get an hour of total danger followed by relief. That became clear as it went on. So, not like a movie, not at all. Which was impressing me more and more. Here I was helping people, all of us wet and scared, and my right bicep just screaming, and I kept thinking This is real, this feels good, why again are you trying to be a fucking actress? Oh sure, some people had gotten caught somehow and drowned, it was inevitable given the number of people and the power of water, water is a force of nature, you can't resist it if it gets you, but for the most part people were on rooftops or on the freeways, and it was more a matter of evacuating everyone before they starved than anything else. If you didn't get drowned right away then it was just a matter of holding on and waiting for relief.

So as the day wore on I joined a crowd on the roof of a restaurant and they fed us spaghetti. They had broken through the roof and were using the restaurant's food supplies and big pots from its kitchen, and cooking over an open fire a group of men were tending, set on a big sheet of corrugated metal they had pried off of something, with another sheet as a roof over them to keep the rain off. Chances seemed good they would burn that restaurant down, but on the other hand they could always take their roof sheet away and the rain would drench any fire that wasn't nuclear, it was still pouring down so.

After a while there my arm felt better and I went back on the water, fueled up and ready to help more people. There were fewer of them in the later afternoon, people were either dead or had gotten to a high point of some kind. So I joined the other boaters and we made some street sweeps. It was really fun to ride down Orange Grove Avenue, I have to say, running the brown flow almost as fast as a car, but you had to stay sharp, because sometimes an easy flow would head under a freeway bridge or the like and it could quickly become desperate getting out of that current before you got sucked down and killed. People shared knowledge of these danger zones, that's how I heard about Sepulveda, no one's phone was working but some people had GPS devices with maps saved on them, and they were happy to share their orienteering news, and a lot of people out had local knowledge as well, so we paddled around and the motorboats zipped around, often wasting gas without thinking that they weren't going to be able to refill anytime soon, but after a while they remembered, if they didn't run out, and so most of the action as the sun went down was kayakers and a few rowboats and the like, even some sailboats with their sails down and people in them paddling along awkwardly. Little flotillas like human water bugs on the great lake of LA.

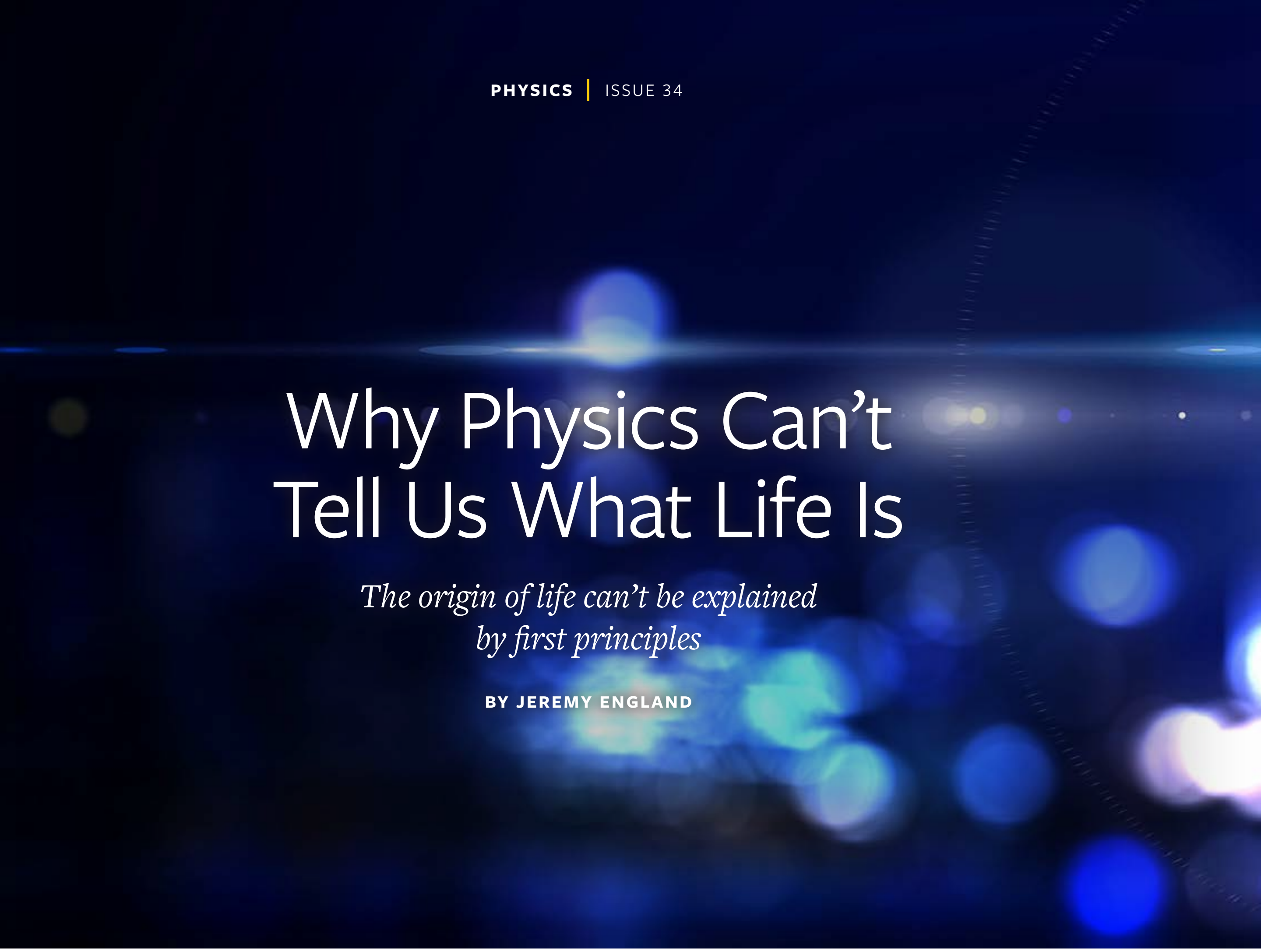
And what was occurring to me over and over again as all this was happening was, Hey: I hate LA. I was born here and I know it well, and have even read or been told some of its history in school, and I really do hate it. The truth is, after World War II this place went from a sleepy little spread of villages to the ten million people here now, and during that time the developers were getting rich making ticky-tack suburban neighborhoods, that and putting in the freeways, which cut the plain into a hundred giant squares, and all of it crap. No plan, nothing good, no parks, no organization, no plan of any kind. Just buy some orange grove and subdivide it and tear out the trees and build a bunch of plywood houses, and then do it again, over and over. It happened in a snap of the fingers, and it was never anything but stupid. And that's what we've been living in ever since! And more than a few of us trying to live out a remake of the movie *La La Land*. It was double stupid.

So as we were paddling around in our kayaks, people were saying to each other, This whole fucking place is gone! Everything is going to have to be torn out! *The entire city of Los Angeles is going to have to be replaced.*

Which was great. Maybe we could do it right this time. And I myself am going to find a different job.

KIM STANLEY ROBINSON is a *New York Times* bestselling author and winner of the Hugo, Nebula, and Locus awards. He is the author of more than 20 books, and he works with the Sierra Nevada Research Institute.

Excerpted from *The Ministry for the Future* by Kim Stanley Robinson. Reproduced courtesy of Hachette Book Group.



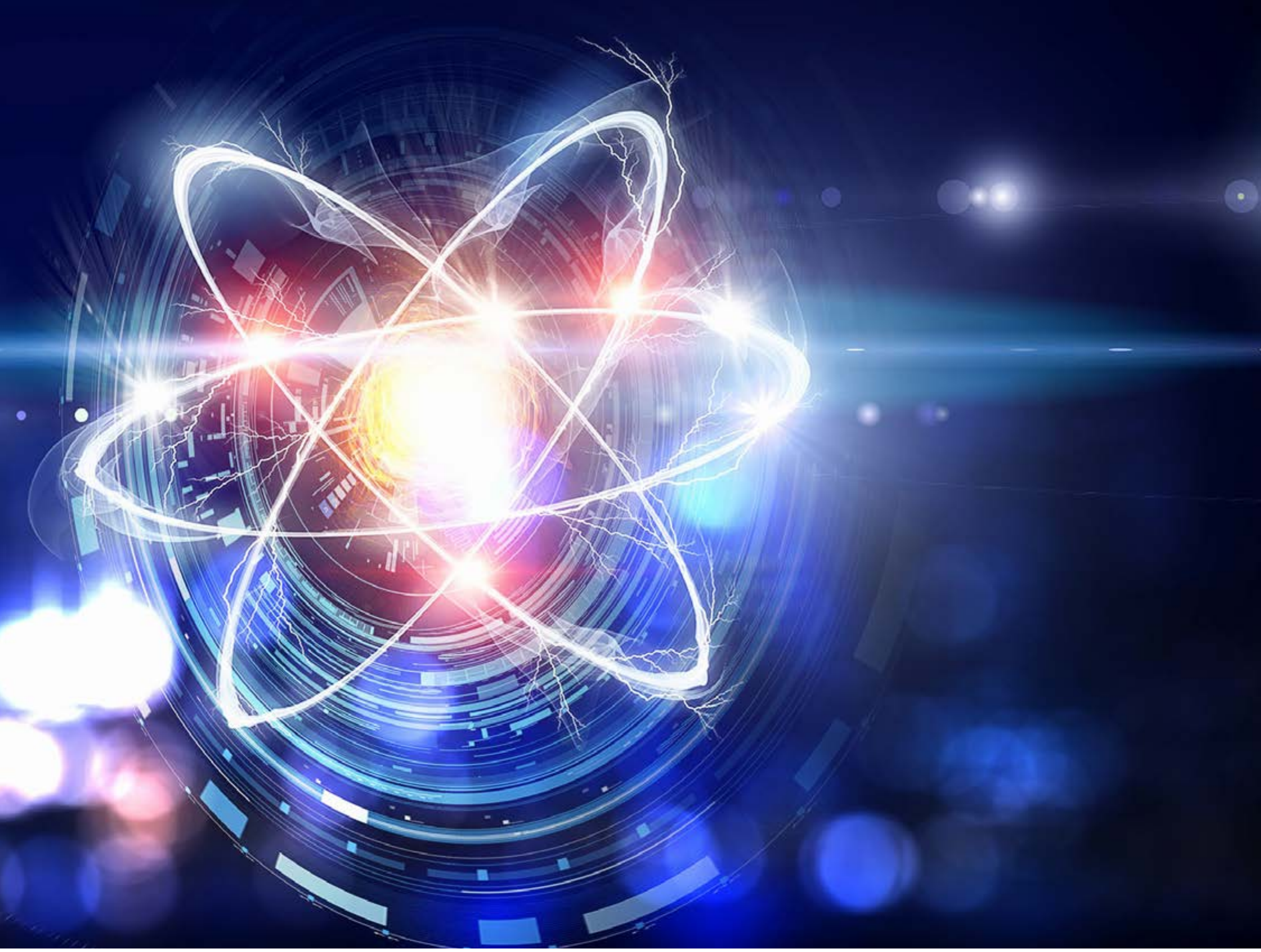
Why Physics Can't Tell Us What Life Is

The origin of life can't be explained by first principles

BY JEREMY ENGLAND

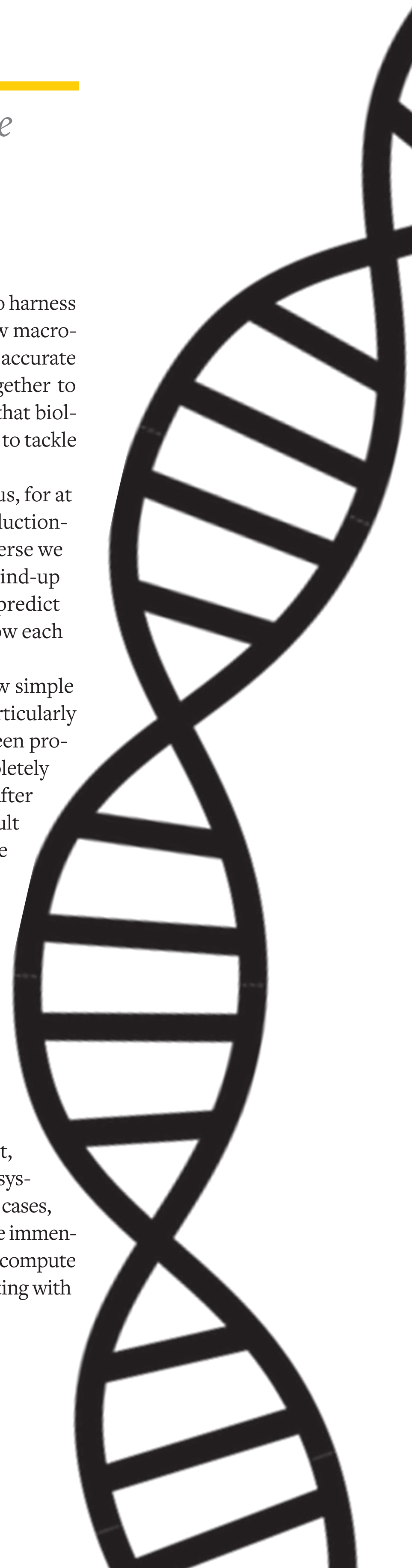
THERE IS JUST SOMETHING obviously reasonable about the following notion: If all life is built from atoms that obey precise equations we know—which seems to be true—then the existence of life might just be some downstream consequence of these laws that we haven't yet gotten around to calculating. This is essentially a physicist's way of thinking, and to its credit, it has already done a great deal to help us understand how living things work.

SERGEY NIVENS / SHUTTERSTOCK



Thanks to pioneers like Max Delbrück, who crossed over from physics to biology in the middle of the 20th century, the influence of quantitative analyses from the physical sciences helped to give rise to mechanistic, molecular approaches in cell biology and biochemistry that led to many revolutionary discoveries. Imaging techniques such as X-ray crystallography, nuclear magnetic resonance, and super-resolution microscopy have provided a vivid portrait of the DNA, proteins, and other structures smaller than a single cell that make life tick on a molecular scale.[1]

We did not know any physics when we invented the word "life."



Moreover, by cracking the genetic code, we have become able to harness the machinery of living cells to do our bidding by assembling new macromolecules of our own devising. As we have gained an ever more accurate picture of how life's tiniest and simplest building blocks fit together to form the whole, it has become increasingly tempting to imagine that biology's toughest puzzles may only be solved once we figure out how to tackle them on physics' terms.

But approaching the subject of life with this attitude will fail us, for at least two reasons. The first reason we might call the fallacy of reductionism. Reductionism is the presumption that any piece of the universe we might choose to study works like some specimen of antique, wind-up clockwork, so that it is easy (or at least eminently possible) to predict the behavior of the whole once you know the rules governing how each of its parts pushes on and moves with the others.

The dream of explaining and predicting everything from a few simple rules has long captured the imagination of many scientists, particularly physicists. And, in all fairness, a great deal of good science has been propelled forward by the hunger of some researchers for a more completely reductive explanation of the phenomenon that interests them. After all, there are things in the world that can be understood as the result of known interactions among various simpler pieces. From the rise and fall of ocean tides with the moon's gravitational tug, to the way that some genetic diseases can be traced to molecular events arising from the altered chemistry of one tiny patch on a protein's surface, sometimes the thing we are studying looks like a comprehensible sum of its parts.

Alas, the hope that all scientific puzzles would be conquered through reductionism was more popular with physicists before the 20th century rolled around. Since then, multiple Nobel laureates in physics (and countless others as well) have written lucidly about how and why reductionist thinking often fails.[2] You cannot use Newton's laws or quantum theory to predict the stock market, nor to predict even much simpler properties of "many-particle" systems, such as a turbulent fluid or a supercooled magnet.[3] In all such cases, the physical laws supposedly "governing" it all are swamped with the immensity of what we do not know, cannot measure, or lack the ability to compute directly. Physics still works on such systems, but not solely by starting with fundamental equations governing the microscopic parts.

The second mistake in how people have viewed the boundary between life and non-life is still rampant in the present day and originates in the way we use language. A great many people imagine that if we understand physics well enough, we will eventually comprehend what life is as a physical phenomenon in the same way we now understand how and why water freezes or boils. Indeed, it often seems people expect that a good enough physical theory could become the new gold standard for saying what is alive and what is not.

However, this approach fails to acknowledge that our own role in giving names to the phenomena of the world precedes our ability to say with any clarity what it means to even call something alive. A physicist who wants to devise theories of how living things behave or emerge has to start by making intuitive choices about how to translate the characteristics of the examples of life we know into a physical language. After one has done so, it quickly becomes clear that the boundary between what is alive and what is not is something that already got drawn at the outset, through a different way of talking than physics provides.

TO SOME DEGREE, a hopeful inclination toward reductionism is expressed in the very asking of the question of where life comes from. We look at a living organism and cannot help but wonder whether such breathtaking success in form and function could simply be the result of a bunch of more basic pieces bouncing off of each other like simple and predictable billiard balls. Is there something more in the machine other than all its dumbly vibrating parts? If there isn't, shouldn't that mean we can eventually understand how the whole thing fits together? Put another way, wouldn't any proposed explanation for the emergence of life have to break it all down into a series of rationalized steps, where each next one follows sensibly and predictably from the last? If so, how is that not the same thing as saying we want to reduce life to a choreographed performance directed by a simple, calculable set of known physical rules?

It must be granted that physicists have already identified some rules that prove to make highly accurate predictions in systems that once seemed hopelessly and mysteriously complicated. Thanks to the ideas of people like Kepler and Newton, the motion of heavenly bodies is now an open book, and our ability to compute where these bright lights in the sky go is such an unremarked banality that it is now possible to get an extensive education in physics at many a great university without ever delving into the specialty sideshow of rigorous orbital mechanics. Imagine, though, being a brilliant natural philosopher at any point during most of human history, and marveling at the seemingly intractable complexity of how the sun, moon, and stars seem to continually rearrange themselves in the firmament as the days and years pass. The idea that a terse pair of equations describing gravitation and motion under force could bring distant galaxies, the wandering planets, and boxes dangling by coiled springs all into one comprehensive theoretical frame must have been inconceivable even to the greatest genius of every

Biology is most certainly not founded on mathematics in the way that physics is.

era for thousands of years. The scope and significance of the revolution that started with Newton and his contemporaries are hard to overstate.

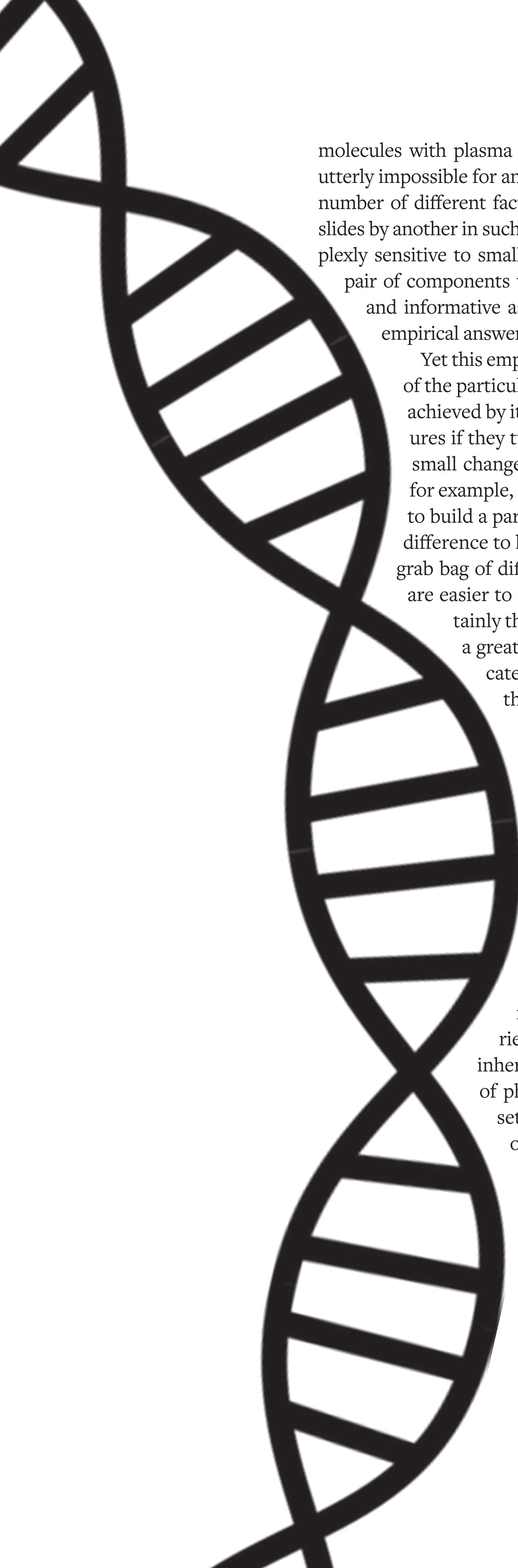
And then came the 20 century! Einstein began with contemplating the equations that describe the motion of light, and through sheer force of insight ended up reimagining the origins of gravity, so as to finally explain the last remaining puzzle of planetary motion that Newton could not touch (namely, Mercury). Meanwhile, Erwin Schrödinger's quantum mechanical wave equation unlocked the atom, providing an elegant quantitative explanation for the colors of light emitted from various types of electrified gases. This was a bizarre, unintuitive theory of the mathematical inner workings of objects too small to be seen or touched, yet it could still match experimental measurements with stunning accuracy. In the wake of these grand scientific victories, one might forgive the odd scientist or two for feeling like all unpredictability might eventually be swept away as newer and ever more brilliant theories arrived.

On closer inspection, however, this hit parade of wins for reductive theoretical science reveals some bias. What these and many other examples of successful physical theories have in common is that they perform best when trying to predict a well-isolated piece of the world described by a relatively simple mathematical formulation involving a few different things one can measure—the one-planet solar system, the single, solitary hydrogen atom, and so on. In each of these cases, the theory succeeds by filtering out the rest of the universe and focusing on a few equations that accurately describe the relationships among a small number of physical quantities.

The fact is, there are many ways in which the extreme reductionist, armed with a powerful supercomputer, is going to miss the mark by miles when trying to compute the behavior of the whole directly from the simple rules obeyed by its parts. As physics Nobel laureate P.W. Anderson once famously wrote: "More is different."[4] And while we may well succeed at coming up with very good physical theories of things like freezing crystals or viscous fluids, it will not be because we have started by perfecting our detailed models of the atoms or subatomic particles out of which these things are built.

THERE'S NO QUESTION that molecular biology has its own long and venerable history as a hard science in its own right. Thanks to countless experiments on molecules, cells, tissues, and whole organisms, it is now abundantly clear that the marvelously diverse functional capabilities of a living thing all have sound bases in the physical properties of their material parts.

However, this is not to say that reductionism reigns; on the contrary, the "more is different" idea of emergent properties rears its head everywhere in the study of how life works. Blood, for example, is a liquid that flows through veins and carries oxygen, and its biochemical capacity to absorb and release oxygen is well understood in terms of the atomic structure of a protein on red blood cells known as hemoglobin. At the same time, though, a quantity such as the viscosity of blood (which in theory results from mixing water



molecules with plasma proteins and many other components) would be utterly impossible for anyone to predict precisely from first principles. The number of different factors contributing to how a given cell or molecule slides by another in such a heterogeneous mixture is so particular and complexly sensitive to small differences in the interaction properties of each pair of components that there will never be a computation as reliable and informative as just doing the experiment to measure what the empirical answer is.

Yet this empirical answer is important! Life thrives in the realm of the particular, where quite specific and precise properties are achieved by its components that could trigger catastrophic failures if they turned out differently. We cannot assume that any small change to how sluggishly blood slides through a vessel, for example, or to the DNA sequence that instructs the cell how to build a particular protein, will necessarily only make a small difference to how the living thing functions as a whole. Life is a grab bag of different pieces, some of whose physical properties are easier to predict mechanistically than others, and it is certainly the case that at least some of the factors that matter a great deal to how a living thing works will fall into the category of highly non-universal emergent properties that are impossible to derive from first principles.

At base, this challenge will always keep popping up, because talking in physical terms is never the same thing as talking in biological ones, and so biologically important questions are not picked for their physical tractability. Instead, biological and physical ways of talking ground themselves in very different conceptual spaces.

Physics is an approach to science that roots itself in the measurement of particular quantities: distance, mass, duration, charge, temperature, and the like. Whether we are talking about making empirical observations or developing theories to make predictions, the language of physics is inherently metrical and mathematical. The phenomena of physics are always expressed in terms of how one set of measurable numbers behaves when other sets of measurable numbers are held fixed or varied. This is why the genius of Newton's Second Law, $F = ma$, was not merely that it proposed a successful equation relating force (F), mass (m), and acceleration (a), but rather that it realized that these were all quantities in the world that could be independently measured and compared in order to discover such a general relationship.

The extreme reductionist, armed with a supercomputer, is going to miss the mark by miles.

This is not how the science of biology works. It is true that doing excellent research in biology involves trafficking in numbers, especially these days: For example, statistical methods help one gain confidence in trends discovered through repeated observations (such as a significant but small increase in the rate of cell death when a drug is introduced). Nonetheless, there is nothing fundamentally quantitative about the scientific study of life. Instead, biology takes the categories of living and nonliving things for granted as a starting point, and then uses the scientific method to investigate what is predictable about the behavior and qualities of life. Biologists did not have to go around convincing humanity that the world actually divides into things that are alive and things that are not; instead, in much the same way that it is quite popular across the length and breadth of human language to coin terms for commonplace things like stars, rivers, and trees, the difference between being alive and not being alive gets denoted with vocabulary.

In short, biology could not have been invented without the preexisting concept of life to inspire it, and all it needed to get going was for someone to realize that there were things to be discovered by reasoning scientifically about things that were alive. This means, though, that biology most certainly is not founded on mathematics in the way that physics is. Discovering that plants need sunlight to grow, or that fish will suffocate when taken out of water, requires no quantification of anything whatsoever. Of course, we could learn more by measuring how much sunlight the plant got, or timing how long it takes for the fish-out-of-water to expire. But the basic empirical law in biological terms only concerns itself with what conditions will enable or prevent thriving, and what it means to thrive comes from our qualitative and holistic judgment of what it looks like to succeed at being alive. If we are honest with ourselves, the ability to make this judgment was not taught to us by scientists, but comes from a more common kind of knowledge: We are alive ourselves, and constantly mete out life and death to bugs and flowers in our surroundings. Science may help us to discover new ways to make things live or die, but only once we tell the scientists how to use those words. We did not know any physics when we invented the word "life," and it would be strange if physics only now began suddenly to start dictating to us what the word means.

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FOOTNOTES

1. Watson, J.D. & Crick, F.H.C. Molecular structure of nucleic acids. *Nature* **171**, 737–738 (1953); Wüthrich, K. Protein structure determination in solution by NMR spectroscopy. *Journal of Biological Chemistry* **265**, 22059-22062 (1990); Rust, M.J., Bates, M., & Zhuang, X. Sub-diffraction-limit imaging by stochastic optical reconstruction microscopy (STORM). *Nature Methods* **3**, 793 (2006).

2. Laughlin, R.B. & Pines, D. The theory of everything. *Proceedings of the National Academy of Sciences* **97**, 28–31 (2000); Anderson, P.W. More is different. *Science* **177**, 393–396 (1972).

One should say that both Anderson and Laughlin do not mean to argue that systems with many components are wholly unpredictable; on the contrary, they both made their careers discovering predictability in such devilishly complex systems. However, what often happens in the so-called world of hard condensed matter (i.e., metals and more exotic solid-state materials) is that the way of cutting through the multitudes and seeing order in the whole is to realize that the collective behavior must be governed by some very specific symmetries of the system at hand.

This can get quite mathematically rarefied, but for a simple example imagine a flat, planar lattice of arrows pointing every which way in the plane. Suppose that each arrow's energy is lower to the extent that it points in the same direction as its neighbors. Clearly, the energy is therefore lowest for the collective when all the arrows point in the same direction. Yet symmetry tells us that the lowest energy state should not exhibit an average bias to point in any one direction, because the overall way we determine the energy of the system looks exactly the same when we rotate our perspective. The resolution is to realize that there are infinitely many equivalent lowest-energy states, with all arrows aligned with each other, but with each collectively aligned state pointing in a different direction.

3. It is worth stating specifically why one might have ever imagined something so outlandish as the idea that quantum theory could be used to predict the stock market. The point is that, from the perspective of a physicist, all the people and documents and computers and phones and factories and mines and forests and winds (and everything else) that act to determine the price of a stock are made of atoms. The way these atoms bind together into molecules is described quite well by known equations that govern the interaction of electrical charge, light, and matter on the tiniest of scales. So why do we not try to predict stocks (and indeed, all the events of the world influencing the stocks) using these equations? Not only does the sheer scale of the computation required to represent such fine details put the task far beyond reach, but we also have little way of knowing most of the numbers that would serve as input to the model. Accordingly, much the same way that the shareholders may not easily get to know all that is ailing a publicly traded company, we also, by default, know very little about exactly what each atom or molecule on the planet is doing. Instead of trying to measure every one of those details, we are much better served making predictive models that paint a simpler picture of the thing we are trying to model (for example, by just positing that prices are determined by a balance between supply and demand).

4. Anderson, P.W. More is different. *Science* **177**, 393–396 (1972).

The Physicist's New Book of Life

Jeremy England says religious ideas can inform our scientific quest for the origin of life

BY MICHAEL BROOKS

W**HO IS JEREMY ENGLAND?** There are many answers to that question. He is a biochemistry graduate who became an MIT assistant professor in physics when he was 29 years old. He is an ordained rabbi. He is the grandson of Holocaust survivors. He is a descendant of the first life-form on Earth. He can also be described as an assemblage of atoms that exhibits complex, lifelike behavior. England might describe himself as one of the many dissipators of energy in the universe—this, he says, seems to be a useful way to answer the question that humans have asked for so many millennia: What is life, and how did it arise?

This question—and England's answer—form the basis of his new book *Every Life Is on Fire: How Thermodynamics Explains the Origin of Living Things*, which explores the idea that burning up energy is the base activity of life. But England has no simple, neat tale to tell: This is a complex, multilayered subject, and must be treated as more than a scientific issue, he says. That's why *Every Life Is on Fire* daringly brings ideas from the Hebrew Scriptures and uses them to unpack the science. Cultural and religious traditions have long been exploring this territory, he says, and can complement scientific angles on the question of where we ultimately came from. If we really want to understand ourselves, he suggests, we'll need more than science.

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KATHERINE TAYLOR

BOTH SIDES NOW

"I always wanted to do physics because I liked the predictive power of simple principles," Jeremy England says. "At the same time, I was fascinated by the form-function relationships of biology. So I was always trying to do both."

How did you get into combining physics and biology to come up with ideas about life's origins?

I always wanted to do physics because I liked the predictive power of simple principles. At the same time, I was fascinated by the relationships between form and function in biology—especially when you see that it's still there when you get down to the molecular level. I started out working in a structural biology and a cell biology wet lab, and was very bad at that! By the time I was finishing undergraduate school, I was working in a theoretical lab looking at protein folding. So it feels natural for me to be drawn to this set of questions.

Does it matter that no one has come up with a watertight definition of life?

Not really. We get the notion of what life is. You can do plenty of great science while saying, "Let me accept that there is a category of things where fish belong to it, and trees belong to it, but rocks don't belong to it, and ice doesn't belong to it." We can continue to use the word while admitting that we don't really have a scientific pedigree for where the development of the word came from. And yes, there will be some difficult cases such as viruses. But we can accept the category as given, and study, to the best of our ability, the properties of the things in that category that are of interest to us.

Part of the quest involves seeking out life-like behavior in inanimate things too, doesn't it?

In a way, yes. We had a paper in *Physical Review Letters* a few years ago about a simulation of a bunch of balls and springs, just jiggling and the springs were hooking and unhooking from the balls. Then you wiggled one of the springs at a certain frequency and it all jumbles and hooks together in a different way. Now you have a resonator that's better at absorbing energy from the frequency that you're wiggling the ball at. Learning to harvest energy better from its surroundings is a feedback process that sounds lifelike. On the other hand, if you held it up to someone and said, "Look at this jiggling mass of balls and springs, it's alive," they would just laugh at you, and rightly so.

That I can talk about a person as a collection of atoms should not supplant the fact that I can also talk about that person as a moral being.

So it's clear that this is a territory where there's going to be a lot of different arguments. Some might say, "Well, the fundamental thing about life is that it does X." And someone else might say, "Well, the fundamental thing about life is that it does Y." What I find is that when I focus on any one of those properties, you can always find examples and counter-examples. If you were loose enough in your understanding of what it means to copy yourself, for instance, then a spreading fire is a self-copying phenomenon. But to call a fire alive is a really contentious extension of the domain of that word.

What we term life is this multifarious bundle of all these different things together: You're good at self-replication, energy harvesting, and so on. When you study each one of those things on its own, it's a physical phenomenon that has more primitive examples. But those examples are where we have a chance of understanding the fundamental principle better.

A lot of physicists' efforts to understand life seem to invoke ideas from thermodynamics, such as entropy. To me, that feels uncomfortable, because thermodynamics was developed for another purpose entirely. Are you wedded to a thermodynamics approach?

It's necessary to talk about entropy for historical reasons, and if we are conservative enough about how we use the term, it can still be useful as a shorthand. What I advocate for now is that we try to make theories that talk about the probability of things happening. And yes, it's true that entropy, which is counting the number of ways something could happen, is part of what weighs on the scale in determining probabilities—but it is not the only thing that impacts probability. So trying to talk about whether entropy should increase becomes very distracting. I think a better way to talk about it is more to consider what is the likely outcome, given the starting point, given the way the system is being driven, and given the sources of fluctuation in the system. Entropy will be one of the things that matters there, but not the only one.

You say that life seems to demand an explanation. Do you think that you've found one?

The focus of my line of research is more about whether we can develop the capability to bring about the different aspects of what I would call "lifelikeness" in experimental settings, with control and with theoretical principles that can be clearly articulated. We may not know exactly how our particular

Subjected to the right kinds of patterns, naive matter can exhibit computing and learning behaviors.

example of life got put together, but we start to see how one puts a bunch of things together in general. The starting point for that is to break things apart into these different phenomena like energy-harvesting, self-replication, et cetera. With each of those, we've made some progress. There's more to do, but we can start to see how a story might come together.

Energy harvesting is central to your ideas. You suggest a key aspect of life's emergence is down to structures that adapt to their environment by dissipating energy. Can you elaborate on that?

Imagine I have a collection of matter under the influence of an environment. The environment is essentially sources of energy that are kicking the matter and knocking into it and allowing it to change shape. I'm interested in which configurations of that matter will be likely to exist at some point in the future. That likelihood depends, in part, on how much extra energy was absorbed and dissipated on the way. Over the course of the whole history of the system, highly dissipative histories are going to lead to highly likely outcomes.

What's an example of a likely outcome?

An example might be a self-copying bacterium that eats some sugar. It uses the sugar to build another copy of itself. Now I have two of them and they eat the sugar even faster, and then they make four of them, and then they eat the sugar even faster. So the chemical dissipation is accelerating toward a likely outcome, which is that I have more bacteria in my future than I had in my past. The balls and springs work that way as well. It's a positive feedback process where you're exploring a space with combinations of matter. There's an energy source. And the flow of energy through the system is leading to a positive feedback relationship where you find a better energy absorber and it helps you absorb even more energy, then you find another even better energy absorbing state.

What's the general idea of dissipative adaptation?

There's a feedback process that's positive: I end up in a particular place because I was in a state in my past that was good at absorbing energy and it carried me irreversibly in a certain direction that I can't go back from. It left its mark. So the general idea with dissipative adaptation is that the current state of the system holds the signature of how I had to be in some special state in my past to absorb a lot of energy. That helped me change my shape in consequential ways. Sometimes that leads to growing energy absorption over time, and sometimes it leads to extinction of energy absorption over time. And both of those things can leave very noticeable fingerprints that are different aspects of lifelike behavior.

And can we see this in biological experiments?

I haven't been able to apply these ideas rigorously to anything like living cells yet—certainly not in experiments, but also not even with theoretical models. It's much messier and more complicated to try to get things done in the biological context. But I don't think that doing that kind of experiment is a long way away. Usually if I show a biologist a living cell and I say, "Look, it's behaving in this way where it's being very smart in how it's reacting to something its environment is doing," the default assumption is, "Well, there's something you don't understand yet about the biology, and that's the explanation to what you're seeing." The design of experiments will have to be done very carefully.

If you can't yet use biology, what can you use to explore these ideas?
There are membrane-less droplets, for instance, that self-organize into cells under different conditions. They seem to have very plastic and flexible properties to help the cell respond to different functional needs. A biologist might say, "Oh, well, it has all of these evolved abilities that come from eons of natural selection, making it better and better at what it does." But it's starting to be hard to imagine that every kind of response like this has its own separate program, as though it's all been learned from the past. There's a growing list of experimental biologists who are interested in these kinds of emergent adaptive behaviors in biological systems.

What kind of experiments are you doing along these lines?
We've been working with primitive abiotic examples. The place we're looking is called "active matter." It can involve proteins chewing through chemical fuels and binding and unbinding from each other. But you can also do it with larger objects. I have a collaboration at Georgia Tech where we do this with robots swarms. There are also examples of "colloidal particles" that have special coatings on their surface—they're like little chemical jet packs. And they already exhibit really interesting collective behaviors. Active matter is a nice experimental base camp. You don't have to try to make sense of the living cell, where in addition to everything else you have all of the impacts of natural selection at the level of the organism. We can just study the collective behavior of things that are like soups of interacting proteins that are more primitive.

***Every Life Is on Fire* is still not the long-sought origin of life story, though?**
It's true: There is a lot more to fill in. I'm sure there are people who will read this book and say, "Well, you've talked about different kinds of life-likeness and how they might emerge, but that's not the same thing as a full story from start to finish of how life as we know it gets put together." Maybe we can understand how self-replicators might start to emerge, how predictive mechanisms that respond to the patterns in their environment by accurately predicting their surroundings or their behavior might emerge. And maybe energy harvesting is something whose emergence we can understand. So that certainly recalibrates our sense of how to imagine a prebiotic situation and think about what's difficult or easy to accomplish

You can't describe the interesting phenomena of the world if you just start with Coulomb's law and the Schrödinger equation.

with what would be lying around. But, no, it is not the same thing as telling a blow-by-blow story. I'm sure anyone who's looking for that level of detail in a story that is convincing and testable will have to wait a while. Doing forensics on that kind of distance to history is pretty difficult.

What's the next stage in trying to get a handle on the origin of life?
For the short term, it's going to be about how far can we push this idea that, subjected to the right kinds of patterns, naive matter can exhibit computing and learning behaviors. I'm trying to do that right now with some of my collaborators—Dan Goldman at Georgia Tech and others who are part of this effort to control robot swarms. We want to push that envelope and show a smoking gun for that kind of an effect, creating something that can be tested and proven empirically in the laboratory. That will put the physical principles on a very firm footing. The more we can achieve impressive results in that way, the more we are going to be able to redouble our efforts to understand wider implications of the theory and tie it back into other things. To be honest, the broader question of how we start to talk about how life comes together is something I find more difficult to predict: I don't claim that I can see which way that goes yet.

One thing that makes your book particularly interesting is that it is not entirely focused on science, but weaves religious narratives—in particular, the story of Moses from Hebrew scripture—into the scientific narrative. What made you want to do that?
Talking about the origin of life, or the boundary between what's alive and what isn't, involves broader questions that aren't in the narrow domain of what you can understand scientifically. I didn't want to stick my head in the sand about that. I want to understand how things work if I reason about them scientifically. But I am also a human being with other interests. I'm a practicing religious Jew—I'm an ordained Orthodox rabbi—and I care very deeply about these things. So I would feel foolish putting the scientific ideas out there but not making my own comment about a larger conversation that includes more perspectives on what some of this could mean. When I decided to write this book, I quickly realized I wanted to go and look in the Torah and see if I can find a commentary that responds to what I'm already thinking about with the science. I certainly think that it's possible to contemplate the boundary between life and not-life from that perspective, and the text, I would argue, clearly contains such a contemplation.

Do you think that including all these different perspectives is important in our quest to make sense of ourselves?
It's clear that the question of what happened in the past is not a low stakes question. You see that in how people argue about history and in the very emotional disputes people end up having about the prehistoric, or about cosmology. Ultimately, and this is something I learned from the Torah, how you describe the past is not ideologically neutral. The way you talk about

who we are, and where we come from, matters to people—partly because it makes some people powerful, and enables them to convince others to do certain things. So I certainly don't want to eliminate any frameworks of meaning that we need for talking about the past—we can't just have frameworks that involve concepts like fundamental fields or prebiotic chemical reactions.

I sometimes think fundamental physicists gin up the notion that when we're done we'll just talk about strings and that will be everything. But we already know you can't describe the interesting phenomena of the world if you just start with Coulomb's law and the Schrödinger equation. It doesn't work. You need different languages. We certainly shouldn't be trying to have fewer of them. The difference between physics and biology is that they are different languages for talking about the same world. It's a mistake to be trying to look for one language that will replace or subsume all others. The fact that I can talk about a person and see them as a collection of atoms should not supplant the fact that I can also talk about that person as a participant in an economy, or a moral being, or a participant in a relationship. These other frameworks of meaning are important, and we should grab them and hold on to them and insist on them.

Is it more important to wrestle with issues around our origins than solve them?

This is not a conversation that we should be hoping to exhaust. People who think that we're done sorting it out are misguided in one way or another. People need to keep talking respectfully, with intellectual honesty, and in different languages, and sharing those languages with each other in order. That's how we'll progress in our understanding.

MICHAEL BROOKS holds a Ph.D. in physics and is the author of *The Quantum Astrologer's Handbook*.

Are We Wired to Be Outside?

A neuroscientist searches for the roots of feeling innately connected to nature

BY GRIGORI GUITCHOUNTS

HIKING THE FRANCONIA RIDGE LOOP is an intimidating proposition. The trail, in the heart of New Hampshire's White Mountain National Forest, is close to 9 miles long, and peaks at over 5,000 feet above sea level. The ridge connects several of New Hampshire's highest peaks and offers stunning views of the surrounding mountains. The ridge itself is a ragged, narrow path flanked by alpine tundra, with low-standing bushes and virtually no trees.

My partner and I found ourselves on the Franconia trail on a recent Sunday morning, our backpacks full of trail mix, sandwiches, and hot tea, our minds ready to take on the arduous hike. We entered the forest and discovered a path covered on all sides with beech, birch, and fir trees. Ferns littered the forest floor, while moss covered downed trees like a short but scraggly beard. The path zigzagged across streams and waterfalls. Tree roots and boulders—some as small as sneakers, others as big as cars—hogged the trail unapologetically. The path appeared to ascend into infinity, like the Penrose stairs.

JORM S / SHUTTERSTOCK

MOUNTAIN MAJESTY
On a hike in New Hampshire's White Mountains, the author, a neuroscientist, took this photo, and asked himself, "What happens in a human brain during a walk through a forest?"

The hike was a welcome escape from the city, and as we walked, the conversation turned to the power of nature. Walking through a forest, climbing a mountain, watching ocean waves: These activities have for millennia awakened something raw in humans. Even as we collectively barrel toward destruction of nature, humans seem to have an innate connection to it. It's a connection that deepens when we consider the magnitude and irreversibility of extinction. But what's the essence of that connection? What happens in a human brain during a walk through a forest, when watching the mesmerizing licks of a campfire or the undulations and ripples of rapids in a stream?

As a neuroscientist, I spend my days thinking about how brains orchestrate behavior and synthesize perception. I ask questions about how brain cells allow us to experience the world and set up laboratory experiments to answer them. A number of basic questions crossed my mind as we scrambled up the path. How do our legs adapt from walking on a paved road to scrambling up rocks? Animals have no trouble but few machines are this acrobatic. How do our eyes lock on to the optimal path across the jagged terrain? Machines struggle with visual recognition, too, while humans and other animals do not. Even more intriguing are the wondrous effects nature has on our emotional states. How does one begin to examine the nebulous neuronal roots of our fascination with nature?

THE EVOLUTIONARY EXPLANATION for human connection to nature is a colossal safari through the African savanna, where our ancestors fought, fed, and frolicked for millions of years. The biologist E.O. Wilson speculated on this story in *Biophilia*, a slim volume on human attraction to nature. Wilson defined biophilia as an "innate tendency to focus on life and lifelike processes." He argued that if other animals are adapted to their environments and are best-suited to the environments in which they

PHOTO BY GRIGORI GUITCHOUNTS

evolved—for example, a thick white coat serves the polar bear well in its native cold and snowy Arctic—then is it possible that humans too, despite our ability to live anywhere on this planet, are best adapted to the particular environment in which we evolved?

"The more habitats I have explored, the more I have felt that certain common features subliminally attract and hold my attention," Wilson wrote. "Is it unreasonable to suppose that the human mind is primed to respond most strongly to some narrowly defined qualities that had the greatest impact on survival in the past?" Those qualities include the savanna's sprawling grasslands, sparse trees, cliffs and other vantage points, as well as bodies of water, which provided resources. Wilson cited human tendencies to build savanna-like environments where they are not found naturally, as in malls or gardens; open-concept architecture seems to have hit on our love of vast spaces, too.

It's satisfying to think being in nature is pleasant because this is the environment to which our minds are best adapted. The trouble with such stories is they are experimentally untestable. We can't wind back the evolutionary clock. We can't transform Earth into a lab and run an experiment with half of humanity evolving in the savanna and the other half in the desert. Would the desert group evolve to prefer desert-like environments over the savanna? Despite the fact that our ancestors spent thousands of generations in the savanna, wouldn't it be logical for a primate to prefer a resource-rich, low-danger environment if given the choice? Couldn't the preference for the savanna be due as much to a careful consideration of pros and cons—using one's brain—as to an evolutionary instinct?

As people spend time in nature, they're thinking less about their to-do list and more about being in the moment.

Still, given our minds evolved in nature, it's reasonable to conclude that spending time in human-made environments—houses, offices, towns, cities—crosses some primal wiring. Some psychologists have run with this idea and now tout nature as a health intervention, a miraculous cure for everything that ails the modern human. Chief among these ideas is Attention Restoration Theory, developed by the psychologists Stephen and Rachel Kaplan, who argue that nature's health benefits are due to its ability to relieve stress and fatigue and restore focused and productive attention. I was skeptical to believe the hype of such studies, but I couldn't deny that being in nature is a pacifying experience I cherish. Evolutionary psychology stories are grand, but even if true, they do not explain how nature envelops our emotions. To understand why nature energizes us, the focus must pivot to the core of the matter: the brain.

THE DESERT OF SOUTHERN UTAH is a mesmerizing landscape of red sandstone mesas and canyons. The sheer scale of the place evokes a sense of deep time: These wonders have been forming for millions of years and will continue to change long after the last human eyes behold their beauty. People come here to hike, rock-climb, camp, and to find any number of ways to unplug. That's why this may be the last place one would expect to find machines for measuring brain activity. For Rachel Hopman, Sara LoTemplio, and other graduate students mentored by David Strayer, a psychologist at the University of Utah, bringing such tools to the desert was the logical next step in their efforts to understand the brain on nature.

"We packed all of our equipment up and basically recreated a lab out in the desert," Hopman, now a postdoctoral fellow at Northeastern University, told me. "The first time around didn't go as smoothly as planned." The researchers wanted to begin understanding the neural mechanisms associated with a phenomenon they call attention restoration, one of the many mental benefits of nature psychologists like the Kaplans have documented. They turned to the electroencephalogram (EEG), a method that measures the coordinated rhythmic oscillations of millions of neurons across the surface of the brain known colloquially as brain waves.

Hopman, LoTemplio, and others in Strayer's lab designed an experiment in which they measured brain waves in volunteers before, during, and after a five-day hike in Southern Utah, hypothesizing that unplugging from the stresses of city life and technology for several days would have some noticeable impact not only on people's mood and mental well-being, but also on brain waves.

"I am against this anthropomorphic approach to science," he said. Neurons do not understand faces or toilet brushes.

"Our brains are not evolved to deal with the number of different channels competing for our attention in the modern environment, with computers, phones, streets, cars," LoTemplio hypothesized. "A natural environment is more suitable to the way our attentional systems operate."

The idea that some physiological change in the brain had to be associated with the feelings accompanying nature immersion is a given: Any feeling, percept, movement, or thought must have an underlying neurological signature (unless you believe in souls). The question was what exactly happens in the brain after several days in the desert.

Scientists wishing to measure brain activity face a frustrating tradeoff. If they wish to understand the role individual neurons play in a certain behavior, they have to measure those neurons in animals, where bioethical rules allow them to use invasive tools like micro-wire electrodes implanted in the brain. Those wishing to study the complex mysteries of human cognition must be satisfied with more opaque devices like EEG and fMRI. EEG gathers its data with several dozen electrodes temporarily glued to the scalp, which measure fast changes in the coordinated activity of thousands of neurons close to the surface of the brain. On the other hand, fMRI measures slow changes in blood flow—which correlates with neuronal activity—in millimeter-sized chunks all over the brain. (In limited cases, scientists record from individual human neurons using electrodes in neurosurgical patients.)

To set up an EEG lab in the desert, Hopman bought enclosures—"sports pods"—to keep the subjects and the equipment safe. After a day of hiking, the participants would climb into the clear plastic pods, which were set up along a riverbank. With a cap full of EEG electrodes over their heads, they would proceed to have their brain waves recorded.

What Hopman and colleagues found was a prominent decrease in the strength of the alpha rhythm in the time spent in nature compared to either before or after. The alpha rhythm is a brain wave with a frequency around 10 hertz and is typically associated with attentional processes. Closing the eyes results in a large increase in the strength of the alpha rhythm in visual cortical areas in the back of the head. In physiological studies, increased alpha power has been correlated with inhibition of cortex. Physiologists have taken the findings to mean that low alpha power has something to do with outward attention and cortical activation. Conversely, increases in alpha have been associated with inward attention and mind-wandering.

"What we think that means is that as people spend time in nature, they're less engaged in internal narratives and internal kinds of conversation or thinking about their to-do list or ruminating on future plans. They're more likely to be aware and in the moment," Hopman said. "We have also studied this through cognitive tasks and people's ability to perform different cognitive tasks. It has pretty consistently shown that nature can improve performance, but that does vary in certain ways. People have a different ability to attend to information based on their environment. So, nature provides this kind of increased awareness of your external environment," Hopman said.

In terms of attentional restoration, it is not clear if the effects of the hiking trip are due to nature rather than the myriad confounding variables. "There's a lot more work that needs to be done to definitively qualify it as a nature-specific effect," LoTemplio told me. Perhaps the effects are due to what she called a vacation effect; in that case, a trip to Las Vegas would have the same effects, despite being a radically different environment from the desert. Likewise, the important effects may be due to the fresh air, physical activity, or social connectedness rather than to nature per se.

The EEG results too, while intriguing, are hard to interpret because the experimenters did not control for the scene the subjects were looking at during the recordings. On the other hand, the fact that decreases in the power of alpha waves persisted when the subjects had their eyes closed points to the effect being real, if difficult to understand.

Another reason that the finding that nature reduces alpha power is hard to interpret is that previous studies have found the opposite. In a study from 1981, Roger Ulrich, then a professor of geography at Delaware University (now at Chalmers University of Technology in Sweden), found increased alpha power for subjects viewing images of nature compared to human-made scenes. Likewise, Richard Taylor, a physicist at the University of Oregon, reported increases in alpha power in subjects viewing images of increasingly complex fractal patterns, which mimic the complexity of nature scenes.

Reading through EEG studies on nature soon became a dizzying experience. I could almost feel my own alpha rhythm jump off the charts, chaotically trying to keep up with the contradicting data and interpretations.

Besides, it was hard to understand what the brain waves really meant in terms of what the neurons in the brain were doing. When I asked LoTemplio what kinds of things she would want to learn by looking at the brain, she admitted that "some might argue you don't even need to look at the brain if you're just observing these kinds of cognitive improvements." However, showing brain data would strengthen the case for any possible policies regarding nature therapy, she offered.

The confusing EEG data notwithstanding, the results on attentional restoration reminded me of E.O. Wilson's interpretation of the effect of nature on the human mind. "The naturalist is a civilized hunter," he wrote in *Biophilia*, without ever consulting an EEG machine. "He goes alone into a field or woodland and closes his mind to everything but that time and place, so that life around him presses in on all the senses and small details grow in significance. He begins the scanning search for which cognition was engineered. His mind becomes unfocused, it focuses on everything, no longer directed toward any ordinary task or social pleasantry."

Still, I was curious how Wilson's personal observations might look from the inside of a skull. How do neurons behave when their owner lets them out into nature? It's a vexing question. The simpler question of visual perception—do visual cortical neurons respond differentially to nature scenes compared to human-made ones?—seemed to be more approachable. To answer it required a trip back to the early days of neuroscience.

ONE OF THE CHALLENGES of science is understanding complex relationships among large numbers of uncontrolled variables. This is especially problematic for neuroscience, where the variables—an animal's neurons and the environment outside its brain—number in the billions. Understanding how neurons in brains interact with each other and the entire world outside the brain is a problem akin to predicting the movements of all celestial bodies in the galaxy, if those bodies were also juggling each other while being driven by toddlers in bumper cars.

In order to make headway, neuroscientists often simplify the problem by placing animals in a laboratory, where they control the environment much better than in the wild. In the case of visual perception, this has, historically, involved presenting artificial stimuli to restrained or anesthetized animals, while recording neuronal activity in the visual cortex with electrodes.

Using this approach, David Hubel and Torsten Wiesel discovered in the late 1950s that neurons in the visual cortex are highly sensitive to oriented bars, with each cell responding best to a particular angle. The discovery was serendipitous. The physiologists were flashing dots on a screen while recording disappointingly weak responses from a neuron in the visual cortex of an anesthetized cat, when a slide jammed on its way into the projector. The stuck slide cast a shadow on the screen, which excited the neuron beyond anything the two had previously observed. Since then, edges, bars, or gratings have become the stimuli of choice.

YOUR BRAIN ON NATURE
Psychologists from the University of Utah put test subjects in pods and measured their brain waves while they gazed on the beautiful landscape.

UNIVERSITY OF UTAH APPLIED COGNITION LAB

"When you use very simple stimuli like gratings, you can have absolute control," Gabriel Kreiman, a professor of neuroscience at Harvard, told me. "There are two or three variables that you need to worry about: There is a contrast; there is a spatial frequency; and then maybe if you're very courageous, you can add movement." Using simple parametric stimuli makes it easier to understand the relationship between stimulus and neuronal response; the disadvantage is that no animal's natural visual world consists solely of bars, which makes it difficult to extrapolate findings to real-world situations. On the other hand, real-world images have a lot going on in them.

In the 1990s, Russian-American artists Vitaly Komar and Alexander Melamid conducted a survey to determine the elements of a painting that Americans preferred and then painted a work that blended the elements. It featured a lot of blue—the sky, mountains, a lake—gentle brown woods, hikers, deer, and George Washington. They called the painting *America's Most Wanted*. It had a satiric bite to it but the late art critic and philosopher Denis Dutton, in his book, *The Art Instinct*, wrote the painting shouldn't be written off as worthless, "for it did reveal one stunning fact: People in very different cultures around the world gravitate toward the same general type of pictorial representation: a landscape with trees and open area, water, human figures, and animals." And George Washington.

Could the landscape painting tell us something about a hardwired connection to the outdoors? To understand if scenes of nature activate the visual cortex in some special way that other stimuli do not, one would have to spend eons observing a neuron's activity because "the universe of possible images is essentially infinite," Kreiman said. If a particular nature scene excited a neuron less than a particular non-nature scene, how many scenes would you test before reaching a general conclusion about the neuron's preference?

The mesmerizing Utah desert of red sandstone is the last place one would expect to find machines for measuring brain activity.

Of course, this conundrum applies to all images, not just those of nature scenes. And neuroscientists have been finding neurons that respond to all sorts of things, not just oriented gratings, but objects, faces, as well as geometric shapes and scenes. Some such discoveries came serendipitously, too. In the 1970s, Charlie Gross, a neuroscientist at Princeton University, discovered neurons in monkey cortices that respond to hands when, in exasperation to a poorly responding neuron, he waved his hand in front of the monkey's face. His team later described face-preferring neurons, as well as those that responded to an oval toilet brush that had an uncanny resemblance to the faces of the lab members, who happened to all be bearded white men.

Kreiman feels strongly about such discoveries. "I am against this anthropomorphic approach to science," he said. The problem, as he sees it, is that neurons and people speak different languages. Neurons do not understand faces or toilet brushes; they speak only in spikes, electrochemical impulses sent to and received from other neurons. So why should an individual neuron respond best to something with a human-language label of "face" or "nature scene"?

Kreiman's solution is to take the human experimenters out of the loop and replace them with a computer model. Such an approach is better than "a human comfortably sitting in an armchair and saying, I think that faces are cute. Let's try faces. I think that hands are important. I think from an evolutionary standpoint, we need to study color," he said. "These are all anthropomorphic constructs. Having a more quantitative, unbiased method, in terms of experimental design, is a good thing."

Collaborating with Margaret Livingstone, a professor of neuroscience at Harvard, Kreiman showed that computers can make decent stimulus generators. In a 2019 paper, they described an algorithm they named XDREAM—"EXtending Deep-Dream with Real-time Evolution for Activity Maximization in real neurons"—which compares the responses of one of a monkey's visual neurons to a set of synthetic stimuli; it then takes the stimuli that elicited the highest responses, mutates them randomly, and presents the new stimuli again. "The neuron is swiping right, swiping left, saying, 'I like this picture. I don't like that picture,' " Kreiman said. "Basically, we have a closed loop, and generate better and better images."

Over several generations of such evolution, the algorithm has found stimuli that elicit much higher responses in visual neurons than do normal hand-picked natural stimuli. In this case, natural refers to photographs of real-world items such as a chair, an airplane, or body parts. Non-natural stimuli in this case would be parametric stimuli like oriented bars, while natural would include both the savanna as well as something human-made like a hydrant. The XDREAM stimuli that elicited the highest responses could be said to be hyper-natural: mishmashes that evolved algorithmically from random textures and often look like Cubist depictions of monkey faces or body parts. Still, statistically speaking, these images show complex patterns and textures, and evoke a vague sense of animacy. "If we construct stimuli in the right way, we could generate images that look funky and strange, but that still respect properties of natural image statistics," Kreiman offered.

When I mentioned E.O. Wilson's idea, from *Biophilia*, that because our brains evolved in nature, they may respond more robustly to objects found in nature, Kreiman agreed that this is possibly true. But he wants to discover this through an unbiased, human-free way, rather than imposing it through anthropomorphic hypotheses. "I'm hoping that by constructing rigorous computational models, we will discover the biophilia; we will discover that that neurons are tuned to these kinds of statistical regularities in the world."

Meanwhile, we are left pondering what it means for a visual neuron in a monkey's brain to be most active when presented with Kreiman's hyper-natural images. (Perhaps Cubists like Picasso or Georges Braque intuited that their transformations of commonplace objects tickled the cortex in some hyper-natural way.) "Perhaps the simplest interpretation is that natural stimuli are so much richer, that they sort of tap into a larger repertoire of neurons," Kreiman said. While I could not find concrete data for this idea, there are several factors that support it: The distribution of angles at which edges are oriented is more diverse in scenes of nature than in human-made scenes, which are dominated by horizontal and vertical lines. Since neurons in the primary visual cortex prefer edges of a particular orientation, it is possible that many of them are chronically understimulated in human-made environments. Kreiman agreed that this is possible, though speculative.

Another piece of evidence comes from neurological patients with damage to specific areas of cortex, usually due to a stroke, who suffer from visual agnosia, or the inability to recognize specific objects. "These are very messy natural experiments," Kreiman explained, since strokes do not follow clean brain region boundaries. One category of agnosia is for animate versus inanimate objects. A patient with this condition may, for example, be incapable of naming animals or plants, but unimpaired at naming human-made objects. This points to the possibility that representation of natural objects takes up a separate portion of cortical space. If this is true, then a person deprived of nature scenes may be depriving

BY POPULAR DEMAND Artists painted this landscape based on elements people said they preferred in a painting. Psychologists have asked whether the preferences are innate.

KOMAR & MELAMID, *AMERICA'S MOST WANTED*, 1994. PHOTO BY D. JAMES DEE.

those neurons of activity as well. Of course, with both of these examples, I am making an equivalence between higher neuronal activity and pleasant feelings; this need not necessarily be true. Whatever the true neural basis for our love of nature is, it is likely more complex than we currently know or can easily describe.

AFTER A THREE-HOUR ASCENT along the Falling Waters Trail, my partner and I reached the peak of Little Haystack Mountain, the first of three summits along the trail. The sun was blasting, the wind was shoving us side to side and filling up the soundscape. We were hot in the sun, and cold in the wind. We were soaking in sweat from the arduous climb and shivering from the cold at the same time. We were hungry but almost too awestruck to eat. Only a cloud or two punctuated the clear sky. The horizon above the still-green mountaintops shone light azure but darkened into an ultramarine directly overhead.

With green crests and valleys undulating into the vast space in front of us, I couldn't help but think that there seems to be no way of avoiding being a player in climate destruction, short of off-the-grid living. It seems inevitable humans will continue to destroy nature for a long time. I worry about the thousands of species dying off, and the millions of humans whose lives will be upended by changing weather patterns, lower crop yields, and political shifts. I worry too for the charismatic species—elephants, whales, dolphins, the great apes—whose habitats are being plundered. These animals are intelligent enough to suffer emotionally from this destruction, but not intelligent enough to escape it.

It's satisfying to think being in nature is pleasant because this is the environment to which our minds are best adapted.

Knowing that nature is dying ignites in me a preemptive nostalgia and the urge to stock up on outdoor experiences, like canned beans in a pandemic. Perhaps future studies of human connection to nature will focus not only on basics like visual perception but on complex feelings like grief. For now, the science on human connection to nature is in its infancy. The psychology and brain studies are endlessly captivating and important for understanding basic physiology, but it's nearly impossible to say what they mean for personal experience in nature.

As a neuroscientist, I believe my research and that of my colleagues will continue to unlock important secrets of human life and health, perception and experience. But at the same time, I have come to appreciate that science can fall short of delivering a satisfying account of our experiences. I can only hope that if neuroscience ever does come up with the tools to explain something as ineffable as our love of nature, there is still nature left to love.

As we continued the ascent—from the summit of Little Haystack Mountain, up along the ridge to Mount Lincoln and the highest peak, Mount Lafayette—our legs grew increasingly wobbly and the sun dipped into the horizon. It felt wondrous that our muscles could keep carrying us forward, even when taking the next step felt like an impossibility. On the mountain's western slope, exhausted but fulfilled, we stopped by a lakeside hut to refill our water bottles and rest in the chilly twilight. By the time we reached the bottom of the mountain, it was already pitch dark.

GRIGORI GUITCHOUNTS is a neuroscientist.

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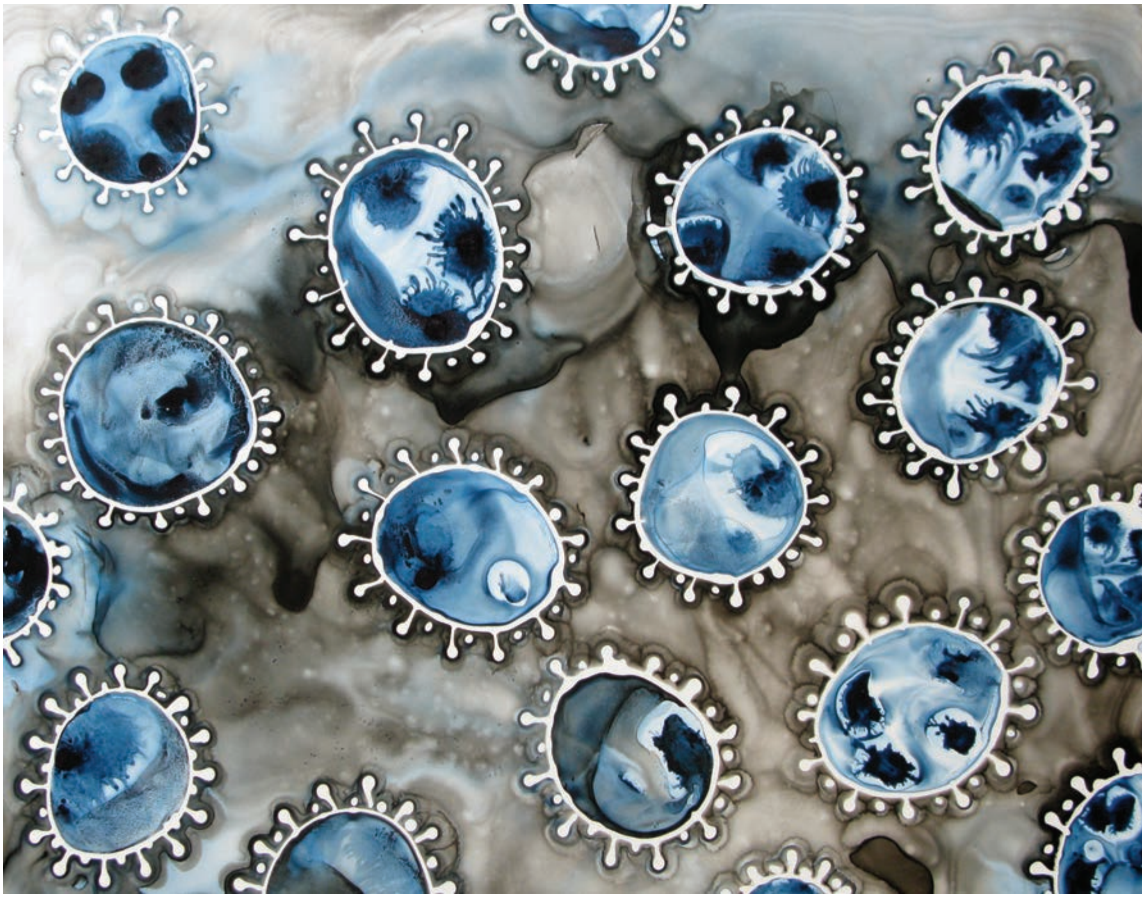

MICHELE BANKS, *Indigo Coronavirus,* 2020, ink on Yupo paper, 12 x 16 inches.

COVID-19

Creative Response Questionnaire

Please share your projects, your stories and your inspiration during this difficult time

Cultural Programs of the National Academy of Sciences has created a questionnaire to collect information about creative responses to the coronavirus pandemic. Collaboration and integrative ideas are critical now more than ever. Please help us collect information as we generate a time capsule of creative responses. Share your creative projects or add projects that have inspired you.

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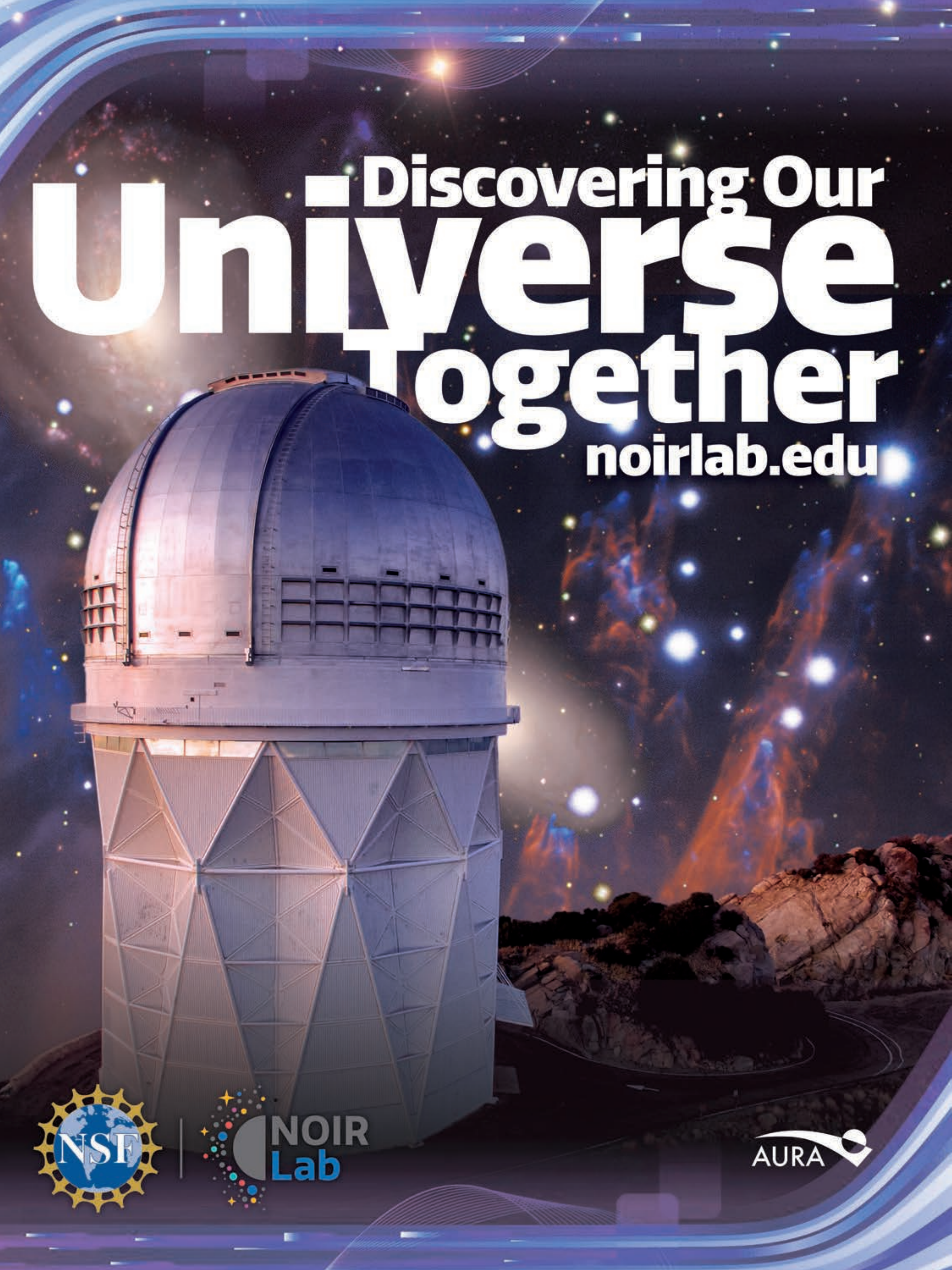

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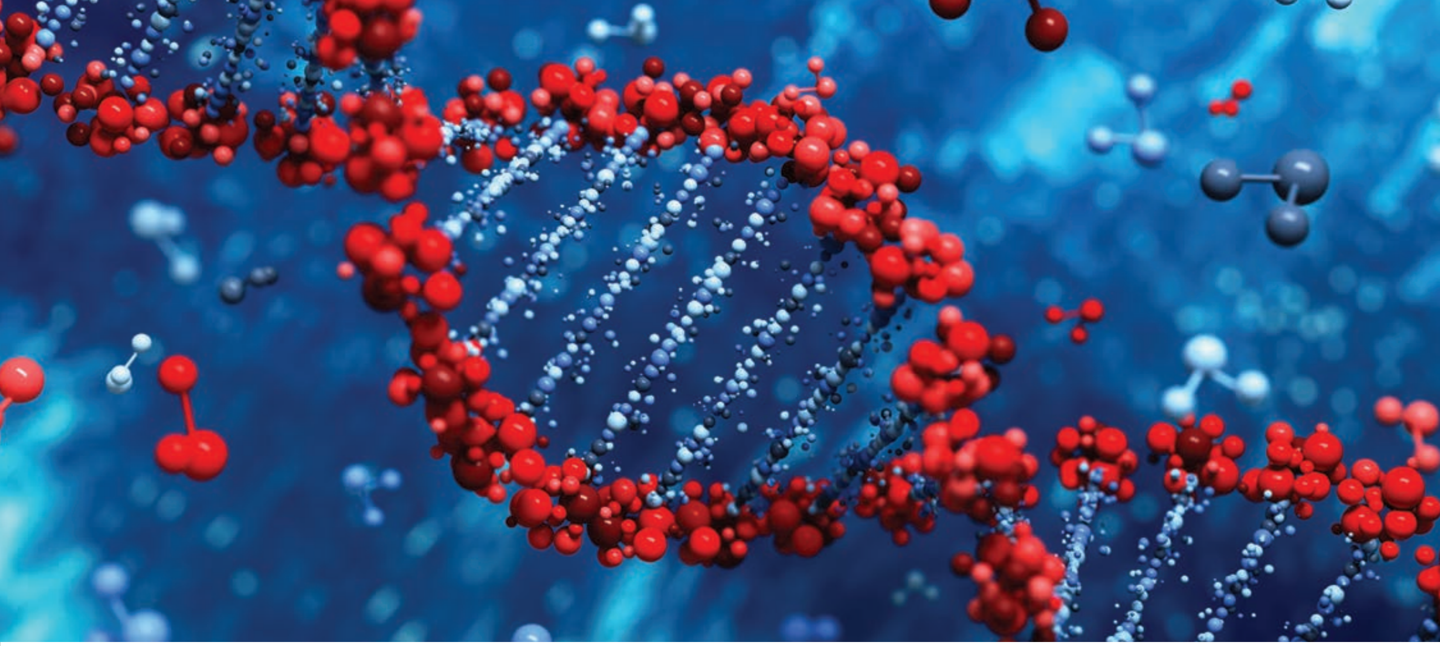

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Ashley Whillans

The behavioral scientist on how to think about time

INTERVIEW BY BRIAN GALLAGHER

TIME IS ON YOUR SIDE

We're indoctrinated with this idea that money and productivity are the path to greater happiness and success. But my data shows this is not necessarily the best way by which to measure the satisfaction, productivity, and meaningfulness of your life. Consistent evidence reveals that people who feel time-affluent, and in control of their schedules, report greater happiness, less stress, better health. They're less likely to get divorced, more likely to choose satisfying jobs. Time is not money, but happiness.

SACRIFICING TIME NOW

You might have more time in the future. But maybe that future never comes. Maybe something happens before you get to reap the five years of glorious retirement that we're all banking on. Maybe you're never able to get out of this cycle of getting rewarded for high-quality performance, with more money making you want more money, continuing this cycle, which research is pretty strongly suggesting happens to many people who go after money for prestige and external factors.

ALWAYS ONLINE

We're constantly fragmenting our leisure into small buckets of time that are less enjoyable by working on our phones, text messaging, or going to social media and doom-scrolling. This task switching not only feels unpleasant, it also pulls us out of the moment, and leads to one of the major causes of time poverty—goal conflict: You could be trying to engage in a conversation, and then think about the things that you could or should be doing instead. For example, if you ask randomly assigned parents to turn off their email notifications while they're at a science museum with their kids, they enjoy the activity more than when they had their alerts on. When they have the alerts on, they start thinking about the opportunity cost of that leisure, undermining enjoyment of the present moment.

TIME BIAS

We think we'll have more time in the future than we do in the present. Meaning, I don't care that much about having two hours a week from now, or three months from now, because I think I'll be less busy than I am right now. We also undervalue time because we account for small losses of money more so than time. We're used to tracking money because of the market economy. It takes huge losses of time—10 months, 12 months on a project—to pay attention to it. But it doesn't take much money to pay attention to losses.

ACCOUNTING FOR TIME

Write out your time-affluent activities like volunteering, socializing, outsourcing. Then write out time-poverty producing activities, like how often you spend researching for a small deal on the Internet over consumable goods—one way we all waste time. Arguably we waste more time on that during COVID than we did before. I quantify the value of that time-saving into "happiness dollars," the income equivalent of the happiness you get from making a time-related choice. Shifting your mindset from money to time produces the happiness benefit of making about $4,400 more of household income per year.

BEING TIME-SMART

Think about how you can incorporate more time for better social relationships, fitness, hobbies, or volunteering. Don't defer these decisions into some hypothetical future. Tomorrow might not come.

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