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THIS EPOCH SHOULD BE NAMED HELIOCENE P.20

ISSUE 32 Science Connected **NAUTIL.US**


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Features

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Galileo Journalism

BY KEVIN BERGER

IN JULY, writing in *The New York Times*, John Barry, author of *The Great Influenza,* about the 1918 flu epidemic, explained in one incisive line why the United States has failed to halt the COVID-19 pandemic. "When you mix science and politics, you get politics." Politics, stemming from the White House, has infected science and poisoned the national response. Jason Beaubien of NPR opened the window on the tragedy wider. The four countries with the most cases globally—the U.S., Brazil, India, and Russia—Beaubien reported, have leaders who espouse "anti-science views."

Ultimately science will light the way out of the darkness. Molecular biologists will bring us effective tests and vaccines; computer data analysts will refine tracking to rein in the contagion. But the benefits of science need the will of the people to bloom across the political landscape. That some politicians and citizens have stymied science during the pandemic, putting their individual beliefs above the public's welfare, is incredibly frustrating. You want to throw up your hands and storm out of the room. But futility is no solution.

In this issue of *Nautilus*, Mario Livio, an astrophysicist, writes that science communication done right can overcome prejudice. Livio roots his perspective in the actions of a scientist who bore the lash of political authority like few others. Galileo was a "relentless advocate for what science could teach the rest of us," Livio writes. "He was a master in outreach and a brilliant pioneer in the art of getting his message across." Galileo switched from publishing his scientific findings in Latin, the custom of the time, to the Italian vernacular, the speech of the common people. Galileo was determined to distribute telescopes to people. He wanted us to see what he did—craters and mountains on the moon, dark spots on the sun, and the vast number of stars that make up the Milky Way.

Psychologists and sociologists tell us science lights up people's minds when they experience it in their personal lives. Those experiences aren't limited to the quotidian benefits of science but to experiences there's no harm in calling spiritual, such as those Milky Way stars. I like to believe Galileo's conviction that science can excite everybody is realized in every issue of *Nautilus*. As we see it, science communication is an article through which science comes alive in the personality and humanity of the writer.

That kind of writing, epitomized in this issue's cover story, draws people into the heart of science. As journalists, that's our goal. We can never tell how our articles will be interpreted. We don't know if they will reroute political currents, change people's minds, help them overcome prejudices about science. All we can do is keep taking our cue from Galileo and putting out articles that, as the astronomer wrote, "propose great things for inspection and contemplation by every explorer of Nature."

Readers Respond

Comments and letters about stories from print issue 31.

“WE ARE THE ENVIRONMENT”

Very interesting article (as always) that puts things in perspective. Let’s hope that humans will be able to acquire through this experience an increased understanding that will make them live in balance with the rest of the natural world. Keep up the good work of spreading awareness. Thank you.

—*Thanos Zakopoulos*

“GAIA WILL SOON BELONG TO THE CYBORGS”

The article offers a beautiful but perhaps naive mysticism about the future of life. There are things to be skeptical about. 1. Carbon has capacities that silicon does not—which is why evolution originally chose it. 2. The absence of evidence about extraterrestrial life is not very good evidence for the absence of such life—it’s such a big universe, and many good arguments have been made pointing out that we have barely begun the search. 3. Perhaps more significant, however, is the reality of what it takes to go extraterrestrial. We have not even begun to imagine the rigors of space travel in terms of time, energy, distance, and harsh conditions.

—*George Gantz*

“GUIDED BY PLANT VOICES”

There is so much we do not know. So much we do not know how to measure. Perhaps the world was hijacked, and perhaps we will be on the long arduous journey to return, perhaps with more consciousness, to where we started. I am glad this scientist is looking at the world in this way. I hope this perspective grows, and that we can learn to sort through the subjective and the objective so that all may experience more joy in living. Isn’t that what we are after? The careful use of psychedelics is just the tip of the iceberg in our understanding and sensitivity to the world that we inhabit.

—*Leumas.1*

Although she talks about science a lot, her motivation and method are not scientific. She doesn’t demonstrate to herself or anyone else that the plant knowledge she acquires is indeed from a plant consciousness. She rejects the interviewer’s alternative hypothesis that the knowledge could have come from her own mind, and she does so on the basis of her belief, not on the basis of something demonstrable to other people.

—*Erberberk*

“THE UNINTENDED BEAUTY OF STARLINGS”

Love this article with its mix of the poetic and shall we say “behavioral” angles. Knowing more about the things we see (some of us) each day, and how our human perception structures phenomena, in a way so different than the creatures involved in the action, helps us start to break down the barriers between species. One of the new frontiers.

—*Barbara Roether*

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

CONTACT

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

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We need racial justice to achieve climate justice

NRDC

Photo: Mike Von

Preludes

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ALIENS

The Trouble with Counting Alien Civilizations

YOU MIGHT IMAGINE that in the midst of a global pandemic and all of its social and economic fallout that our minds would be laser-focused on immediate, earthly woes. But apparently not entirely. A case in point is the recent virus-like spread of news headlines to the effect that there should be "at least 36 alien civilizations" in our galaxy. Not 10, not a thousand, or a billion, but 36. There you have it, three dozen other sets of intelligent life dotting our cosmic neighborhood, so stick that in your pipe and smoke it.

It's at times like these that you can almost hear the collective sigh from astronomers and astrobiologists who realize that they have to roll up their sleeves to gently, politely, carefully try to explain why these headlines are, shall we say, of the same nature as the matter that emanates from ruminant digestive systems.

Right now, in science, the question of whether we are alone in the universe or not is crying out for some kind of answer. There is a confluence of reasons for this sense of urgency. For one thing we now know that planets are fantastically abundant in the universe and are potentially the best incubators of the complex chemistry associated with life as we understand it. We're also getting closer to being able to evaluate some of these other worlds with a fidelity of data that could reveal rudimentary signatures of life, through its chemistry and the changes it wreaks on a planetary environment. Simultaneously there is a resurgence of interest in the quest to look for evidence not just of life but of technological life; either emitting structured information in radio waves or laser pulses, or sculpting its surroundings in ways that reflect intent and sophistication.

Consequently, many scientists are actively looking for ways to incorporate even the tiniest hints or clues that come from new data or insights to see if we can't come up with statistically meaningful statements about the likelihood of life elsewhere—be it microbes or civilizations. In that sense (and I count myself in this category), we are the kids shaking the nicely wrapped presents to see if we can tell what we're getting. The problem is that the wrapping may not come off for a long time, and that all of our guesses rest on fundamental assumptions—on prior knowledge or expectations that are themselves possibly highly biased and unusual.

It is those assumptions that gets us back to the headline-grabbing statements about 36 alien civilizations. These headlines are based on a new study by two respectable scientists, Tom Westby and Christopher Conselice. What these researchers actually say is that, based on a very specific calculation, there is an argument to be made for the possible existence of anywhere

The question of whether we are alone in the universe or not is crying out for some kind of answer.

between about half a dozen to over 200 civilizations capable of communication in our galaxy.

Arriving at those figures involves a number of steps. Some are to do with a detailed astrophysical analysis to evaluate the likely number of stars and planetary systems of particular ages and elemental compositions. But other steps involve assumptions that are extremely tricky to justify, and highly contentious. This is not to unduly criticize the study, because it is entirely open and honest about these assumptions and is a stimulating contribution to these questions. Nonetheless, the assumptions are the weak link.

In this case two "principles" are suggested: a Weak Astrobiological Copernican Principle and a Strong Astrobiological Copernican Principle. The weak one is a scenario where, because of what we witness on Earth, it is assumed that planets only form intelligent life after they reach an age of 5 billion years. The strong one says that intelligent life has to form between 4.5 and 5.5 billion years into a planet's existence, as it seems to have on Earth. The justification for choosing these figures is that if Earth is not special (as the modern form of the Copernican Principle would have it) then we would expect other life-bearing worlds to follow suit on average. The estimated number of alien civilizations derives from these constraints, after combination with the computed statistics of exoplanets and their properties.

This is also precisely where scientific feathers get righteously ruffled. The most direct technical rebuttal to these proposed assumptions and principles is that we on Earth suffer from powerful "winner bias." If, for example, intelligence came along much earlier or much later it would look at its history and also select its time of existence as "the most likely."

That's a thorny problem. But we already knew it was a problem, and there has been sophisticated work done to deploy the tools of so-called Bayesian probability to try to account for precisely this kind of bias. The results tell us that we are truly, quantifiably ignorant about life's most probable trajectory, and that our Earth-based data points have very limited discriminatory power.

The other rebuttal, that is in many ways far more interesting, is to do with our impressive ignorance about the very nature of life itself, and the nature of the phenomenon we blithely call "intelligence." Because of that ignorance, charting the development of civilizations as a simple function of the age of life on a planet seems positively ludicrous.

What we do have is an emerging sense that life and its planetary environment are inextricably entwined. Every piece of Earth's deep environmental history is a complicated story of the interactions and interdependencies of life and planet; of geochemistry and biogeochemistry. As a result, the trajectory of life here may only be partially reproducible anywhere else in the cosmos.

The nature of intelligence, or technological capacity, also tends to be conflated with the idea that life, on average, seems to become more complex over time. It has been posited that the improvements of prediction that complexity enables is one item at the root of this tendency. If an organism can guess the future better it ought to survive better. But, of course, there are living forms, from bacteria to plant life, that have remained largely unchanged for hundreds of millions, even billions, of years. If something works in biology there seems to be little need for it to change. The impetus of life toward intelligence over evolutionary time is, at best, a hypothesis.

In short, any assumptions about properties like intelligence or agency that we make based on what we currently know about life on Earth are on exceedingly shaky ground. To import those assumptions to quantitative analyses of the likelihood of civilizations elsewhere seems like a stretch in most cases. Although there is value to the intellectual exercise as preparation for when the time comes that we, perhaps, have more data to go by.

And perhaps too there is value to anything that, in the days and nights of the coming months, causes us to momentarily pause and think about the bigger picture. To find a little respite by contemplating the endlessly tumbling stories of societies and civilizations as they unfold across cosmic time.

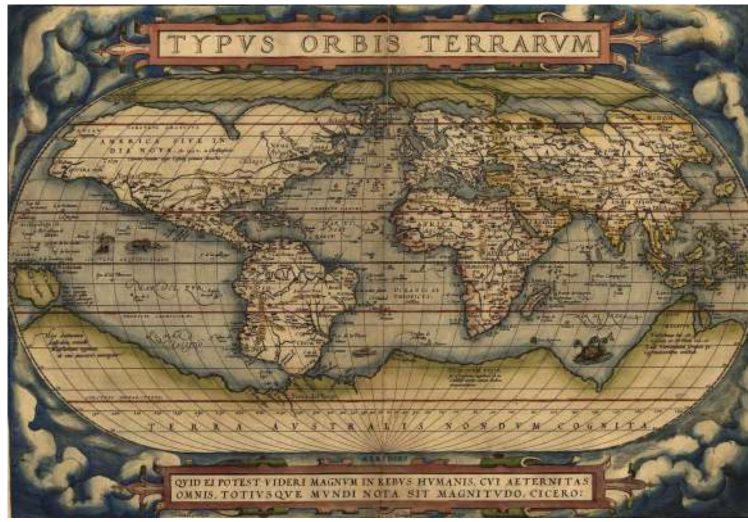
— Caleb Scharf

HISTORY

The Book That Invented the World

THERE IS SOMETHING PRE-MODERN in how our worlds have shrunk during this quarantine. But unlike past quarantines, we're connected by technology to the rest of the globe, calling to mind poet John Donne's line about making "one little room an everywhere." His poetry is replete with globes, maps, and atlases. What's considered to be the first atlas was first available in an Antwerp print-shop 450 years ago, only two years before Donne was born. It was large, handsome, and expensive, with the grandiose title of *Theatrum Orbis Terrarum*, or in English *Theater of the Orb of the World*. Produced by the cartographer Abraham Ortelius, it was one of the most popular books of the era. Ortelius had invented the world.

Never before had all cartographic knowledge been compiled together; never before could a reader imagine the totality of the Earth so completely. Simon Garfield writes in *On the Map* that the *Theatrum*'s "colors were rich and saturated, the lettering (in Latin) elaboratively cursive. The cartouches... burst with vivid additional information." Within the folio were some 53 beautifully illustrated and colored maps based on the illustrations of 87 cartographers (who were all duly given credit). The *Theatrum* depicted lands from California to Cathay, from the Kara Sea to the Cape of Good Hope. The book was "a huge and instant success," Garfield writes, "despite the fact it was the most expensive book ever produced." The *Theatrum* was the first of a type—an atlas.



ABRAHAM ORTELIUS / WIKICOMMONS

Ortelius' atlas birthed a new mental geography, a new imagined space.

Asking a Medieval person to imagine the world and their place on it would demand a radically different sort of cognitive map than one a modern person might rely on. This affects pragmatic matters (of navigation and so forth), but also what could be termed poetic ones. Ortelius' atlas gave women and men a new perception of space, a new cognitive map that would allow someone to envision their place and presence on the globe.

Despite forgivable errors in the shape of this peninsula or the exact location of that island, what marks the *Theatrum* is just how correct it actually is. Comparing Ortelius' atlas to the famed Waldseemüller map of 1507, which first makes mention of the Americas as their own continents, one is struck by how much geographic knowledge had been amassed in the intervening six decades. That earlier map presents both North and South America as long thin ribbons floating in an undefined sea, details about the continents limited to the narrow band of the coasts to which European explorers ventured. Even then, there is something that looks a bit like Florida, and another portion that evokes Mexico, so that you can begin to see the proper shapes of the continents take form as if it were a Polaroid picture developing.

The relative reliability of these maps is interesting, partly because their makers were concerned with accuracy at all. Medieval maps were from an entirely different genre than those presented by Ortelius. Peter Turchi quips in *Maps of the Imagination* that "To ask for a map is to say, 'Tell me a story.'" To condemn Medieval maps is to commit a mistake of genre, for the sort of story that they were telling was not the same as that offered by Ortelius. Medieval maps were concerned less with accuracy than with allegory and theology.

Valerie Flint writes in *The Imaginative Landscape of Christopher Columbus* that Medieval maps known as *mappae mundi* were "for the greater part, less geographical descriptions than religious polemics; less maps than a species of morality." One popular variety of Medieval map was something historians called a "T-O Map." These maps, basing themselves in scriptural precedent, envisioned Jerusalem at the center of the world, with Europe in the lower left quadrant on one side of the straight line of the Mediterranean, Africa in the lower right quadrant, and Asia above the straight line of the Red Sea. The whole of the world appears as a T inside of an O. For Medieval Christians the map expressed certain religious truths about the centrality of the Holy City, the way in which the world geographically divided in a Trinitarian way, and the manner in which a paradisiacal East (for that was the direction of Eden) should be oriented at the top of the picture.

Medieval Europeans, it should be emphasized, didn't confuse T-O maps for what the world actually looked like. The purpose of such diagrams wasn't for navigation or commerce, but rather to express something symbolic about reality. By the Age of Discovery however, measurement rather than metaphor became a priority. Garfield writes that the "vision of seeing the world anew, and the ability to express it, was what set Waldseemüller, Mercator, and Ortelius apart." Ortelius' empiricism, and his concern with ever more correct representations, should rightly strike us as modern. According to Garfield, to examine the *Theatrum* is to see the perspective of its creator for whom "geographical guesswork and overbearing religion had been banished in favor of science and reason."

Ortelius' atlas birthed a new mental geography, a new imagined space. If Medieval thinkers saw themselves as living in a symbolic and allegorical geographic order, then the *Theatrum* presented the physical world in its totality. The cartographer didn't prove that the world was round (people already knew that) or that the world was large (they knew that, too) but he gave people the mental images necessary to imagine themselves on that large, round globe. Ortelius gave us not disenchantment, but a differing enchantment—a sense of the sheer magnitude of the planet.

—*Ed Simon*

MATH

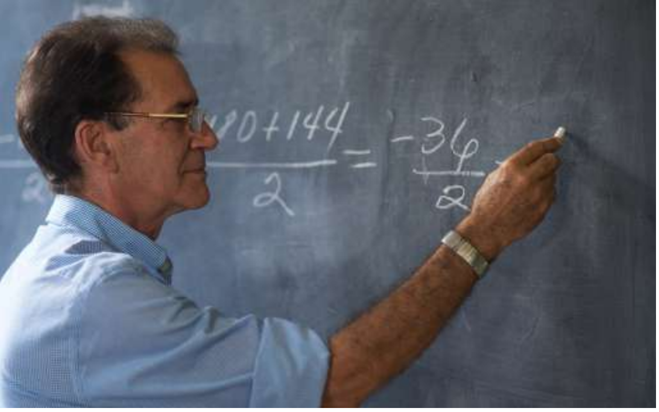
How Game Theory Can Help in a Pandemic

N**OW IS NOT THE TIME** to go to the grocery store. Yet I need to replenish my food supplies. Well then, I should go. Wait, is everyone else thinking this same way? Then everyone would go. I shouldn't go. But then everyone would do the same and the store would be empty. I should go. I seem to be stuck in a loop.

Is there a way out?

One approach is to apply game theory. I bet you've played rock, paper, scissors. But have you wondered if there is a winning strategy? Well, game theory is the field of study that searches for, and sometimes finds, that winning strategy. Winning is a strong word—really you are finding the strategy that you cannot improve on. For rock, paper, scissors, you would use a mixed strategy (meaning you can be random) of throwing each choice a third of the time.

It turns out that deciding whether to go to the grocery, and when, was solved using game theory in 1994 by W. Brian Arthur—he just didn't know it. He figured out what he called the El Farol Bar problem, based on a Santa Fe bar that had a popular music event on Thursday evenings. The problem assumes a group of 100 people who do not know what the others will do. In this problem, if more than 60 people show up, the overcrowding would cause a displeasing evening. Guests will have a more enjoyable time if they stay home. Yet if less than 60 people show up, the attendees would have a better time going than staying home. They want to go, but not if the bar is too crowded. They need to decide.



That sounds familiar. I do not want to go to the grocery store if it is crowded. In fact, I want to social distance and be sure I will have six feet, on all sides, to myself. In order to convert the El Farol bar problem into a form for deciding my pandemic-shopping problem, I will need some information.

First, I need two key numbers: how many people I am comfortable with being at the grocery if I go, and how many people want to go to the grocery. My first assumption is that shoppers want to abide by social distancing. That being the case, everyone's maximum acceptable number of people in the store will be the same, just as in the El Farol bar problem where no one would have fun if more than 60 people showed up. To find that key number I start with a six-feet radius around myself and calculate the area of the circle, which is about 113 feet squared.

Next, I need to find the square footage of the store. I measure the outline on an online map; but wait, these groceries have a big storage area, and lots of aisles and fixtures. Fortunately, the fire code's occupancy limit already factored that in: The store has a maximum occupancy of 650 people. The fire code in my home state of Virginia recommends 60 $feet^2$ per person. Converting that figure to 113 $feet^2$ per person gives a social-distancing occupancy of about 345 people.

The second key number is the number of people who are going to the same store as me. This one is a bit tricky, but luckily Google maps can estimate a location's popularity. It's not a very accurate figure, but I will use the normal max load for the most popular times and a current popularity of about 60 percent. I end up with 390 people interested in going.

The game theory mixed-strategy solution is where the payoff from going to the bar (x) and the payoff from staying home (y) are set, through probability (p) of choosing between them to be equal. Satisfying the equations:

$x(1\text{-}p) - yp = 0$ (number of people that want to go) $p =$ (max number)

For the N-player version, with the same payoffs for everyone:

P (at most max number go) $= yy + x$

However, if the individual payoffs, and thus individual probabilities, form a probability distribution with a μ of p, the payoffs do not have to be equal because each person can determine how valuable it is for them to go shopping. In other words, if a shopper deviates from their strategy the distribution will change. If we assume rational mixed strategies for the other shoppers, we would on average get the same number of shoppers at the store so long as their personal odds are within the probability distribution.

We're all trying to figure out when it is our turn to use the resources we are so used to.

Solving these equations leads me to a mixed strategy when I would go to the store 88 percent of the time. This is a high probability, but I decided to use a random number generator anyway. Popping over to a math solving web application and plugging in rand(0,1), which is a function that will output a random number between zero and 1, got me a .366 (or 36.6 percent) which is less than the p of .88 (88 percent). This means it is time to go shopping because our probability of going shopping was 88 percent and a number below .88 means we should go shopping. A number above .88 would instruct us to stay home.

As the pandemic continues, we are all trying to figure out when it is our turn to use the resources and services we are so used to. I think many of us have changed our focus from our needs, to our health, to how our health affects others' health. The better decisions we each can make, the less the decision-making burden will be on strained governments around the world. We can learn to apply good recommendations, wisely, with a little help from math and game theory.

—Thomas F. Bersson & Jonathan S. Bersson

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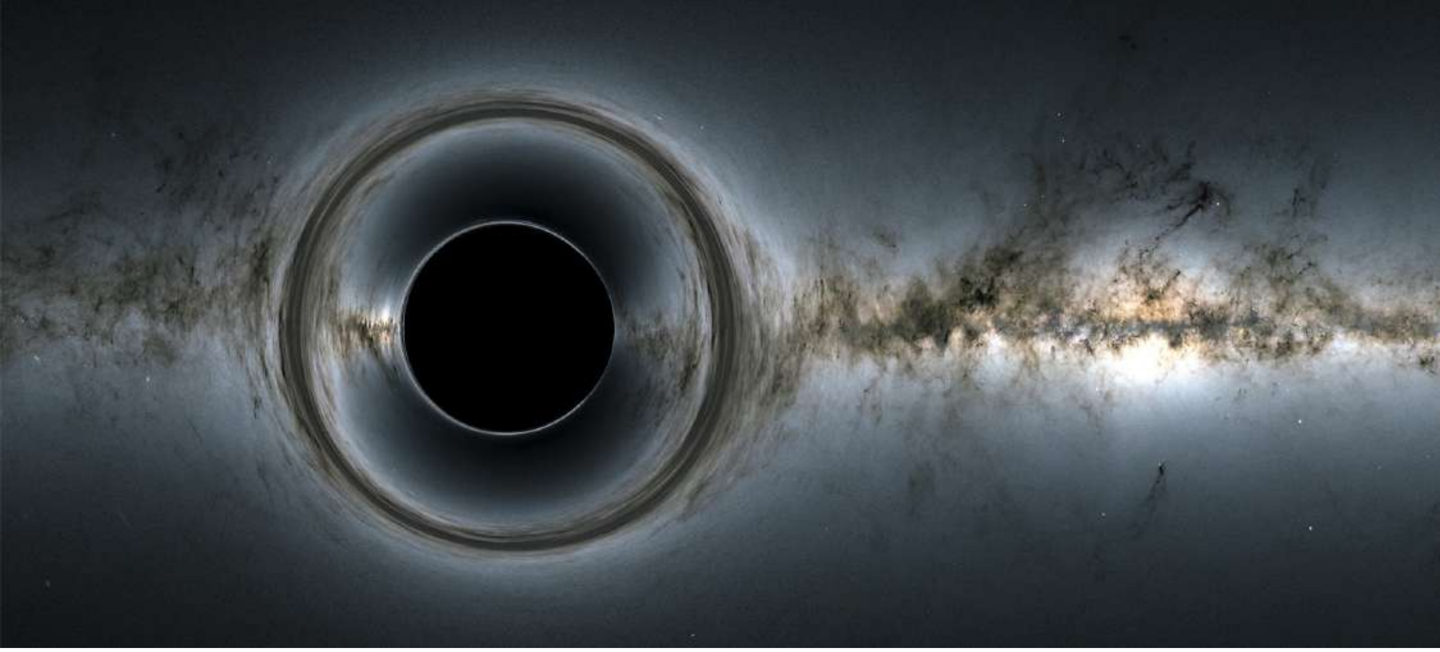


NASA

ASTRONOMY

The Black Sheep of Black Holes

ASTROPHYSICIST SUBRAHMANYAN CHANDRASEKHAR once remarked that black holes, regions of spacetime whose gravitational field is so strong that not even light can escape, are the simplest, most perfect macroscopic objects in the universe. Yet that simplicity hasn't prevented the universe from becoming populated with a veritable zoo of black holes. They appear to range in mass from a few times to many billions of times more massive than the sun.

Stellar mass black holes, the ones formed by collapsing stars, are thought to be the most abundant. Black holes thousands of times more massive could have formed in the early universe, when exotic objects called quasi-stars were thought to abound, powered not by nuclear reactions but the infall of hot gas toward a rapidly growing central black hole seed. More massive still are supermassive black holes, with masses up to billions of times that of the sun, thought to be the gravitational anchor at the center of larger galaxies like ours. How these form remains something of a mystery.

Interestingly, if one were to attempt a cosmic black-hole census, one would expect the numbers of black holes to thin out drastically in the range of 30 to about 70 solar masses. Our current understanding of stellar evolution puts a cap on the size of the biggest stars, and as a result, the size of black holes that could form in the aftermath of their death (by supernovae).

It comes as something of a surprise then that multiple mergers of black holes precisely within this mass range have been detected. Over the last several years, many astrophysicists and cosmologists have been puzzling over where these black holes might have come from. It may come down to some subtlety in our models of stellar and galactic evolution that we've yet to contemplate. Or, perhaps we need to admit another member to the cosmic zoo of black holes—*primordial* black holes—the black sheep of black holes, first acknowledged as a theoretical possibility in the late 1960s by astrophysicists Igor Novikov and Yakov Zeldovich. They realized that these black holes might have abounded long before the stars even had time to form.

The possibility follows from the fact that black holes needn't have formed via some astrophysical process. Black holes can form even in the *absence* of any matter, from large enough distortions of spacetime that curl up into a singularity. The late physicist Stephen Hawking, knowing this, entertained a breathtaking and simple idea, grounded in the fact that the Big Bang itself was the final stage of an explosive process, one that set up a highly energetic, dense, thermalized initial state that was incredibly smooth and homogeneous—but for the

> There's no reason to think primordial black holes can't be found in our own galaxy.

tiniest of microscopic spacetime fluctuations. Hawking suggested that black holes could have formed from these very seed quantum fluctuations that would go on to form, after billions of years, the filament-like scaffolding around which all galaxy clusters now coalesce.

If, somehow, some mechanism dialed up the volume of this primordial noise at small scales (or high frequencies), there would be small but extremely deep troughs in the spacetime continuum that could have, by themselves, collapsed into black holes early in cosmic history, with a wider range of possible masses than those produced later in the universe's history. Hawking realized that any mechanism that amplifies this noise at smaller scales could just as readily produce black holes shortly after the Big Bang.

As appealing as the idea may be, for now primordial black holes remain in the realm of theorists' imaginations. That could change, of course, if at some point in the near future a gravitational wave observatory sees the merger of a black hole with a mass that could *only* be primordial. Clinching evidence could take the form, for example, of spotting a black hole with a mass less than about one and a half times that of the sun, the so-called Chandrasekhar limit. Such a black hole would be impossible to produce from the collapse of a stellar object, as the lightest possible progenitor to a stellar black hole would not have enough mass to collapse into a black hole below this limit. Although slightly heavier than the Chandrasekhar limit, a recent observation of what would be the lightest black hole (or the heaviest neutron star) ever seen is puzzling enough to have some astrophysicists sanguinely speculating on its primordial origins.

There's no reason to think primordial black holes can't be found in our own galaxy, let alone our solar system. Some have even gone as far as to posit that dark matter itself—which has eluded every one of our attempts to detect it directly—might be as elusive as it is because it is nothing other than a swarm of primordial black holes clustered in haloes around every galaxy.

Even if dark matter isn't made up entirely of primordial black holes, their possible existence is a provocative prospect to astrophysicists and cosmologists, not just for their implications for the evolution of the universe, but also its genesis. They could have produced distortions in the relic radiation of the Big Bang through Hawking evaporation. They could have produced the progenitors of the supermassive black holes at the center of every galaxy. Their existence could provide a window into the mechanism that set the initial conditions for the Big Bang. For the time being, they remain stubbornly difficult to rule out, keeping many cosmologists and astrophysicists, the author included, preoccupied by their possibility.

—Subodh Patil

NEUROSCIENCE

A Neuroscientist's Theory of Everything

YEARS AGO, NEUROSCIENTIST Karl Friston published a paper that spells out the idea that the brain is an editor, constantly minimizing input from the outside world to balance internal models of the world with sensations and perceptions. In May of 2020, Friston published a new paper that takes his ideas into new intellectual territory. We caught up with him in June.

In your 2010 paper, you write the world is uncertain and full of surprises. Action and human perception, you argue, are all about minimizing surprise. Why is it important that things—including us—minimize surprise?

If we minimize surprise now, then on average over time, we're minimizing the average surprise, which is entropy. If a thermostat could have beliefs about

You could have the hypothesis that if I am me, there's another hypothesis, I'm not me.

AGSANDREW / SHUTTERSTOCK

its world, it might say, "My world is about living at 22 degrees centigrade"—so any sensory information from its thermal receptors that departs from that is surprising. It will then act on the world to try and minimize that surprise and bring that prediction error back to zero. Your body's homeostasis is doing exactly the same thing.

Does the brain minimize surprise in order to conserve energy?

You could certainly say that. But I wouldn't quite put it like that. It's not that the brain has a goal to exist. It just exists. What does existing mean? It's always found in that configuration. The brain has to sample the world in a way that it knows what's going to happen next. If it didn't, you'd be full of surprises and you'd die.

Is the self an illusion?

Well, say you're a feral child who's never seen another mammal. There would be no need to have a notion of self. You and the universe would just be one thing. But as soon as you start to notice other things that look like you, a question has to be resolved, "Did you do that, or did I do that?" Now you need to have, as part of your internal model, the hypothesis, the fantasy, the illusion—which may be absolutely right—that there are other things like me out there, and I need to model that. I think theory of mind and the necessity of encultured brains provides a simple answer as to why we have self.

I've read some of your work on psychedelics. What do they do to our belief-updating minds?

Psychedelics act on certain kinds of neurotransmitters and literally disintegrate your belief-updating, freeing this neuronal population from the evidence and the influences of that population. You'll now be unable to call on high-level representations of selfhood to constrain your qualitative experience at a lower level of abstraction. You may experience a lower-level disillusion of the ego—literally the "self" representation may now not be able to influence experience. You might be attending to vivid sensations that would now have other interpretations that are not glued together by a self-centered, egocentric narrative. You will have alternative explanations for what caused this sensation or that sensation. All of this is perfectly sensible under a generative model in which the constraints of one level of processing on another were removed. For example, you could have the hypothesis that if I am me, there's another hypothesis, I'm not me. If you start to remove the evidence for these two hypotheses, then you create an enormous uncertainty about me-hood. You'll get depersonalization and possibly a bad trip.

Do you have any personal experiences of tripping?

When I was younger, I enjoyed magic mushrooms. So I've been through the doors in the Huxleyan sense. It's a mind-opening and revealing experience where you never quite take for granted the grip you have on reality. This grip is a gift of a well-oiled inference machine generating fantasy after fantasy that's just spot on. When that goes away, you'll know about it, and you'll appreciate how finely tuned our grip on that sensorium is and how privileged we are to exist.

—Brian Gallagher

Dawn of the Heliocene

Why the next geological epoch should be named for when we tapped the energy of the sun

BY SUMMER PRAETORIUS

ILLUSTRATION BY DEIRDRE CAVANAGH

I **WAS BORN** on the summer solstice in an age without a name.

My parents were born in a previous geological epoch. Six unknowing months before the start of the Great Depression, my father arrived. His given name was Richard, but as soon as his hair came in, he was Red. He would become a keeper of junkyards—overgrown lost worlds of relic chariots. I was a fledgling junk collector, sent out to prod garbage dumps for lost treasures: no plastics allowed, just wood or metal. My mother was born on VE Day, her bones still untainted by the nuclear bombs that would come a few months later, ushering in a new epoch. Her first name was Margery but everyone called her Eliza.

It was less than a century ago that my parents were born in the Holocene—the "recent whole" that constitutes the interglacial epoch that commenced 11,720 years ago.[1] In the geological time scale, an epoch represents a major shift in Earth's climate—longer than an age, but shorter than a period, era, and eon.[2] The root 'cene' comes from the Greek *Kainos*, meaning recent or new. Some geologists think the Holocene has come to a close and a new epoch has arisen, brought about by human perturbation to the Earth's carbon and nutrient cycles.[3] The Anthropocene is the proposed name,[4] to acknowledge the force that has derailed the Holocene from its previous climate trajectory.[5] While "Anthropocene" is already in wide use, it has not been ratified into the geological time scale, which first requires clear documentation of a time and place to mark its origins. Luckily, this has bought us some time to reconsider the right name for our unfolding epoch.

A BUTTERFLY'S DREAM Deirdre Cavanagh is a painter and poet who lives in Maine. This painting is from a series, *A Butterfly's Dream*, a visual extension of *Retooled*, three cycles of poems that track early world myths in a contemporary time frame. Cavanagh is author Summer Praetorius' aunt.

I was a fledgling junk collector, sent out to prod garbage dumps for lost treasures.

My name was supposed to be Kate. Planned for nearly 20 years—a pact between my mother and her college roommate to each name their first daughter Kate. My mother's friend upheld her end of the bargain, but then there I was, a solstice changeling, revealing my true name. I am glad they listened. "You look like your name" is the comment I get when first meeting someone. It always makes me wonder what I might have looked like had my name been Kate—how much we shape the name or it shapes us.

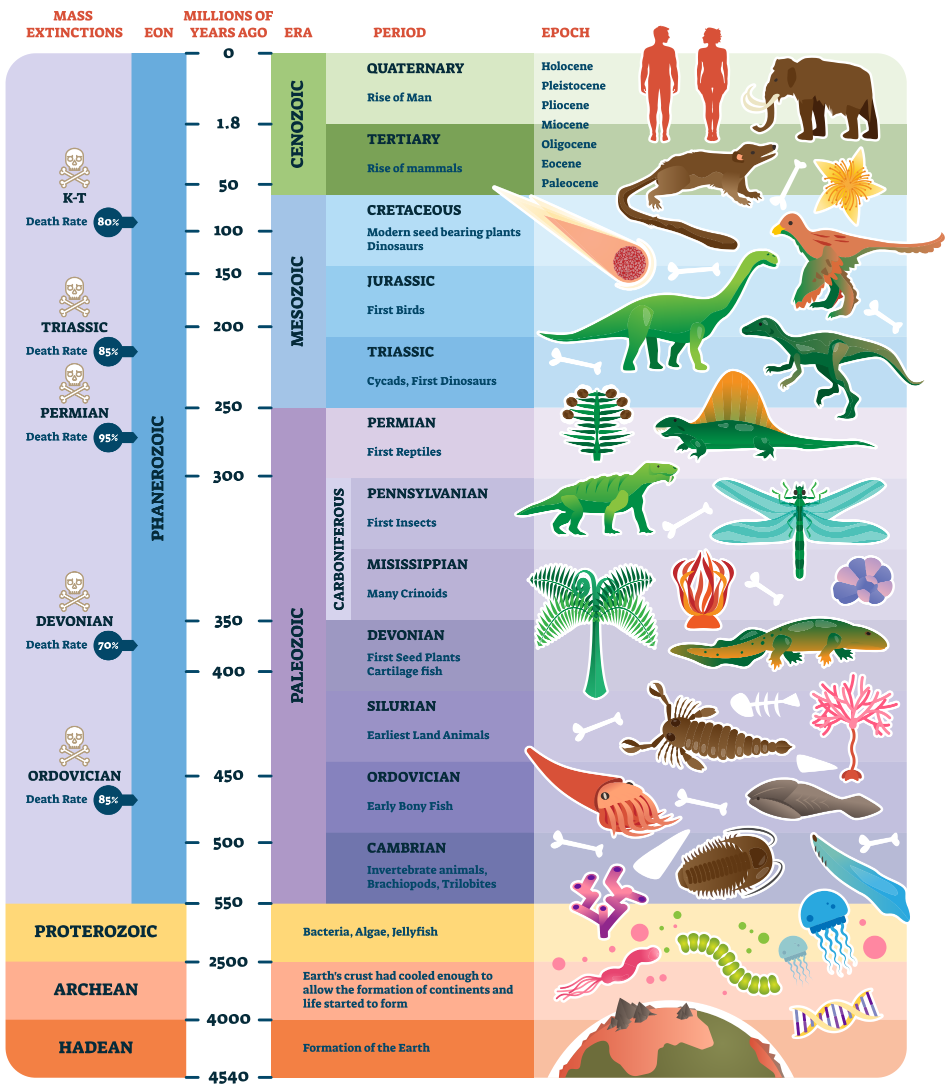
As a junkyard kid, I was surrounded by things people had given up on: decaying boats, milk trucks, acres of American classics done-in by acceleration of one kind or another. But the junkyard was a beautiful place, blooming daily into unexpected entanglements and recombinations: saplings sprouting from convertibles, oak trees wearing bucket-seat skirts, rust paintings as rich and textured as oil, sprawled over every hood and door. I learned to love the art of the search, the stories emerging from decomposing seats, revealing lost glasses and keys. It is a habit that persists, a form of meditation even, to sort and sift through beach debris, clover patches, and now as a paleoclimatologist, the ancient sand under my microscope, taking delight in finding the perfect foraminifera or a glittering quartz gemstone dropped into the sea by a disappearing iceberg thousands of years ago.

My first car took two years to build. It was made from the dismembered limbs and organs of five dead cars, which I welded and painted until it was a metallic jade beauty with two compass ornaments that allowed me to steer my way off the junkyard in wild fish-tailing skid marks down the back roads of the Catskill foothills.

I can't know how my life would be different had my parents given me another name. But I do know that I always felt my solstice namesake was a totem I carried in my pocket, an emblem of the elemental that preceded the coordinates of circumstance, a permission I gave myself to shape-shift.

The Anthropocene may seem like the right name now, but it is tethered too tightly to our present circumstance, defining our epoch by what is below us rather than ahead of us. Other names have surfaced to capture how we're remaking our environment. They include the Homogenocene—the age of homogenization of plant and animal species due to invasion and global spreading[6]; Myxocene—the age in which the oceans will become

GEOLOGIC TIMELINE



VECTORMINE / SHUTTERSTOCK

LONG VIEW Viewed from the breadth of the geological time scale (approximated above), we can mark this moment as a branch point in Earth history similar to the dawn of photosynthesis—life forever changing the trajectory of the planet by tapping the energy raining down from the sky.

dominated by jellyfish and microbial slime[7]; Plasticene—the age of plastics[8]; and Pyrocene—the age of fire.[9] While all hold truths and warnings, most conjure images of the worst of what might lie ahead: plastic and jellyfish-clogged oceans, firestorms whipping up their own weather systems, invasive species decimating biodiversity and igniting zoonotic pandemics, while humans stand at the helm, steering us toward a hothouse wasteland, wavering on the horizon like a Fata Morgana.

Before it comes time to engrave it in stone, to nail in the golden spike of our new epoch, we should reconsider the name we give our future—how it may subtly steer its trajectory. To choose the right name, we must first find the birthplace of our new epoch, which is the same thing as finding the deathplace of the Holocene.

THE GLOBAL BOUNDARY STRATOTYPE Section and Point (GSSP) is the location that marks a boundary in geological time. In nearly all cases, it is an exposed outcrop of ancient marine sediment that has a defining contact between two strata that represents a global environmental shift of prolonged duration. This is where the golden spike is driven—ground zero for a major course change in Earth history.

The golden spike for the Cretaceous-Paleogene boundary is in El Kef, Tunisia,[10] but is more widely defined as the iridium layer associated with the dinosaur-killing asteroid impact, making it the most instantaneous boundary in the geological time scale. In the case of more recent boundaries, such as the Pleistocene-Holocene transition, it is not as easy to find an outcrop on land that documents the transition, so plumbing of paleoclimate archives is required. The GSSP for the start of the Holocene has been located at a depth of 1492.45 meters in the central Greenland Ice Sheet.[1]

By most measures, the Holocene appears to have been a climatic paradise: not too cold, not too hot, and relatively stable overall, aside from an occasional large volcanic eruption and megadrought. That the development of agriculture and proliferation of human civilization has only occurred within the cradle of the Holocene's mild and stable climate is widely considered no coincidence. But for all the promise this golden child of climate seemed to have, its course was cut short. Most ages last at least a few million years, but a mere 11,700 years after it began, the Holocene had been declared dead.

The story goes that at a geoscience conference in 2000, the Nobel-Prize-winning atmospheric chemist, Paul Crutzen, declared in exasperation to his colleagues who were still referring to the current epoch as the Holocene, "We're not in the Holocene anymore. We're in the ... Anthropocene!" Later that year Crutzen and Eugene Stoermer published an article outlining the case for the geological basis of the Anthropocene.[4] This marked the turning point in the widespread recognition and consideration that humans had altered the planet enough to warrant a new geological epoch. But while it had become clear that the Holocene had ended, the precise date of its passing was still to be determined.

The evidence has converged on who killed the Holocene. Culprit: humans. Date of death: 1950.

The detective story of homing in on the time and place of the Holocene's death has involved a global search by a group of scientists known as the Anthropocene Working Group, carefully cataloging and considering various sedimentary archives, prodding sediments for clues, running forensics on the chemical signatures left in the soil.[11] The evidence has converged on who killed the Holocene. Culprit: humans. Date of death: 1950.

There are a number of reasons to lay the Holocene to rest at this particular date. 1950 is already the year used to define "present" in the radiocarbon time scale, making it a widely used reference point in geological timelines, so year zero would conveniently coincide with the beginning of our new epoch. But convenience is not the necessary criteria for marking a GSSP. It requires documenting strata.

The mid 20th century was an inflection point in a number of profound chemical and stratigraphic changes in the Earth system. The list includes an increase in carbon dioxide and methane in the atmosphere, an increase in the use and deposition of fertilizers, plastic products, industrial fly-ash, and of course a great acceleration in human population growth and concomitant decline in biodiversity and natural habitat. The collective inflection of these variables has been labeled "The Great Acceleration."[12]

In the cornucopia of chemical signatures that skyrocket in the mid 20th century, one rises to the top as the most promising global marker to define the boundary between the Holocene and Anthropocene: the radioactive spike associated with nuclear testing from 1945 to the early 1960s. Similar to the iridium layer at the Cretaceous-Paleogene boundary that marks the detonation of the 6-mile-wide asteroid, it is a signal that is both global and unambiguous in the events it represents. The chemical traces of nuclear testing can be found in ice sheets, lake bottoms, deep-sea sediments, and the bodies of living organisms, including our own.

That the detonation of nuclear bombs would mark the start of our new epoch is perhaps not the best harbinger of what is to come—much like starting the New Year with a hangover instead of a polar bear plunge.

And yet something else momentous happened in that same window of time. Something even more powerful than destruction. Humans reinvented a way to directly capture energy from the sun—previously the singular

SHINE ON The development of solar cells represents a revolutionary shift in our ability to capture solar energy in real time. We can align our prevailing epoch with the invention that will lead to our persistence rather than our demise.

GENCHO PETKOV / SHUTTERSTOCK

achievement of photosynthetic organisms. In 1950, in the suburbs of New Jersey, researchers at Bell Labs were busy making breakthroughs that paved the path for the first practical solar cells. In 1954, they unveiled the first silicon photovoltaics; the prototypes for solar cells widely in use today.

Viewed from the breadth of the geological time scale, one could mark this moment as a branch point in Earth history similar to the dawn of photosynthesis—life forever changing the trajectory of the planet by figuring out a way to intercept the high quality energy raining down from the sky. When cyanobacteria first cracked the code of photosynthesis 2.5 billion years ago, they flooded the atmosphere with oxygen and paved the way for multicellular organisms. Their invention is marked by layers of rust—banded iron formations—as iron reacted with the available oxygen. The Siderian, it's called.

Most geological boundaries are like this: They start with disruption and evolve into complexity and stability over spans of time that dwarf the brief pains of their birth. The Paleogene began with the detonation of an asteroid a billion times more powerful than a nuclear bomb, wiping out 75 percent of all plants and animals on the planet. It would take years for the atmospheric fallout to cease and the sun to shine again,[13] thousands for ocean chemistry to stabilize,[14] and yet even shortly after this brutal annihilation, ferns were unfurling themselves within the battered landscape, mousy mammals were scuttling about, freed from the tyranny of their oversized predecessors, and in less than a million years, mammals were ballooning in size,[15] hitting a stride that would carry them all the way to the present day.

IN THE 2.5 BILLION YEARS since cyanobacteria first invented photosynthesis, nearly all of the energy available to life on Earth has been supplied by primary producers' ability to convert solar energy into carbon bonds. All of history's exotic characters have been knitted from an intricate patchwork of photosynthetic scraps, downcycling solar energy into stranger and stranger outfits until its reworking potential is exhausted into a formless pile of heat waste.

In a steady state, most of the energy captured by photosynthesis is used up by the furnace of respiration and metabolism burning on Earth's surface by its infrared layer of life. This means all the energy available to support life was historically bounded by the supply provided by photosynthetic organisms. If primary producers captured one percent of the incipient solar energy, then those were the chips on the table to get passed around.

But rarely are things ever in a true steady state, so at times in the geological past, some of this energy has slipped through the cracks, sealed off in anoxic basins—dead zones where life can't go to access this energy. All else being equal, this occasional leaky faucet of carbon would have created a slight deficit in the energy available to life in the past. In other words, larger dead zones would have made for smaller life zones.

Over time, this slow burial of organic matter accumulated into storage strata of ancient sunlight, well hidden in the dark cloak of carbon. But humans have a long history of piracy, so this ancient treasure did not stay hidden for long. The unique ability of humans to pry open the Earth and excavate the mass carbon graves of millions of years ago has created an energy surplus unheard of in the billions of years prior. And just like buried treasure, those who get a hold of it first are the ones to profit on past deficit.

Since the Industrial Revolution, we have already burned up an entire Earth-equivalent of biomass.[16] In the past, we were harvesting the fruits of our nearby acreage. Now we are consuming entire Earths. It is no coincidence that such unusual surplus has been accompanied by such spectacular waste. Under normal circumstances with limited energy to go around, life would never be so sloppy to discard the byproducts of this energy without first licking the plate clean. Waste is just another word for wealth.

Not surprisingly, the vast waste deposits produced during the Great Acceleration figure prominently in the search for a suitable stratigraphic section to place the GSSP that will mark the start of the Anthropocene. The Fresh Kills Landfill on Staten Island is one such example discussed in a paper by the Anthropocene Working Group.[17] "Covering some 8.9 million m^2, up to 70m high, and containing ~150 million tons of municipal waste, it may be the largest human-engineered formation in the world. It was opened in 1948, with a peak influx of garbage reaching 29,000 tons per day and closed in 2002 CE, the last debris being from the 9/11 event in 2001 CE."

Nuclear bombs, industrial fly ash, plastics, and garbage dumps with the wreckage of terrorism contend to mark the start of our new epoch. Is it no wonder that we have such an uninspiring list of dystopia-cenes to choose from?

While it is true we find ourselves swimming in a shallow sea of our own waste, our lifeline is that not all of this waste has been wasted. Our unusual energy surplus has made it possible to reinvent the wheel of solar capture and drive past the limitations previously imposed on life, which had been almost exclusively beholden to photosynthetic energy capture.

Every year the sun pelts Earth with over 5,000 times our annual global energy demands.[18] Our challenge now is to figure out how to build buckets big enough to collect from the firehose. Renovation will always incur wreckage, but the key is to rebuild smarter each time, to find the path of persistence. We could choose to keep digging up sunlight from the past, hold fast to our archaic roots, like pirates fighting over ever smaller and more elusive caches of treasure, or we could embrace our new ability to capture energy straight from the sky, paving a path out of this mess we've made.

Like all geological boundaries, it will take time to find our way to stability. The transformation of our energy infrastructure and waste management systems, as well as the transition toward balance with the biosphere will require a full spectrum of solutions.[19] These solutions will not only save trillions of dollars in the long run, but will allow us an opportunity to reconfigure in cleaner, more equitable, efficient, and adaptive ways.

There will be vestigial tailbones and dangling dewclaws for some time to come, but the point is to set our sights for our best selves and not our worst. If we name ourselves as the center of rotation, we are placing the nail in our coffin; we are writing the end into our beginning. It is our anthropocentrism that got us in this mess to begin with. We shouldn't confuse the power we currently wield to destroy Earth systems with the power it takes to build stable networks. Our perseverance lies in recognizing our reliance on the Earth system, not our dominance of it.

Like Copernicus' heliocentric model of the solar system, sometimes revolutions occur by a simple shift in the axis of rotation. I propose we call our new epoch the "Heliocene," meaning "new sun." Heliocene represents the moment when another life form figured out a way to tap into the potential of the sun, and adopts a name for our epoch that better centers humans within the spheres that hold us.

The development of solar cells perfectly corresponds to the boundary already deemed most appropriate to mark the transition between the Holocene and our new epoch. This represents a revolutionary shift in our ability to capture solar energy in real time rather than being dependent on solar energy of the past. We can still adhere to all of the same stratigraphic markers under consideration by the Anthropocene Working Group in defining a GSSP,[16] but we can align our prevailing epoch with the invention that will lead to our persistence rather than our demise.

There is no requirement that the names of geological periods correspond to the contents of their strata. The Paleogene means "ancient born"; it is not called the Astergene ("star born") for the extraterrestrial

Waste is just another word for wealth.

disturbance that started it. The most recent epochs form a continuum from "old new" to "newest new," and ages are typically named after the place in which they are defined. But in the 4.6 billion years of Earth history, all sliced and diced, we never once stopped to acknowledge the nuclear furnace in the sky setting it all in motion, fueling the perpetual turnover and transformation of life on Earth. The earliest Earth is called the Hadean, after Hades; perhaps then it's fitting that we name the future Earth for the upper world, the world of the living.

The boundary at 1950 marks a turning point. Geologically speaking, we are still standing at the base of this horizon—different paths stretching out in front of us. The choice is as simple as this: fusion or fission, construction or destruction. We can be sledgehammers, prying apart organic molecules and heavy uranium atoms, eviscerating the Earth for products forged in supernovae, or we can be builders, capturing the fusion energy of the sun to construct support systems that will stand the test of time. If we squander this moment of energy wealth, creating heat waste instead of structure, we will all be back in the junkyard soon enough.

This is not an attempt to whitewash our waste, to bury the toll that humans are taking on the planet right now. It's important to recognize the truth of our impacts, to take stock of the enormous destruction we have reaped on this planet's biodiversity and climate. We can rightly draw this line in the strata, marked by our global-scale perturbations and pollution, but we don't have to continue on this path. We don't have to box ourselves in to our present limitations.

If we squander this moment, we will all be back in the junkyard soon enough.

IN THE SAME WAY my mother thought she knew what she would name me before I was born, I thought I knew where I would bury her before she died. She already owned a burial plot that had a tombstone engraved with her name and birth date. It had been a gift from a partner taken up after my father. He couldn't quite capture her in life, so he tried to secure her company in death by buying her the plot next to him and having it engraved in stone. "A thoughtful gift" she once told me. But there I was, days after her death, staring at her name on the tombstone: Eliza Praetorius, May 8th, 1945 –

That trailing dash—my responsibility to answer it. I couldn't bring myself to engrave the ending, to mark her boundary, to reel her in. She felt bigger than that 2x8 rectangle of soil, so I turned her into ash and fed her to a sapling apple tree in the foothills of the White Mountains in Maine. Snow-smothered twiggy branches in winter, glossy apples in September at my uncle's house, packed in backpacks for granite hikes, an unanswered dash in a quiet graveyard in the Catskills.

In 1954, *The New York Times* ran an article lauding the invention of solar cells as potentially marking "the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization."[20] Maybe an era is a bit too optimistic for now, but we can at least start with an epoch. Let's nail it in: The Heliocene, 1950 –

SUMMER PRAETORIUS is a paleoclimatologist who uses marine microfossils to study changes in the oceans and climate of the past.

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The Hidden Life of Viruses

The COVID-19 crisis has made the dark energy of evolution visible

BY DAVID KRAKAUER & DAN ROCKMORE

IF THERE IS ONE THING that the coronavirus pandemic has exposed, it is that there is much that we still don't know about the world around us. Forget about the trillions—OK, more than trillions—of galaxies in the universe that we'll never explore. Just at our feet or in the air around us are cohabitants of our own world, some alive, and some—viruses—that occupy an odd liminal space, not quite alive, but not dead either. They exist in what is effectively a hidden world, almost a "first Earth" that is both just offstage and right in front of us, and even inside of us. It's a world teeming with activity, full of blooming, buzzing, confusion, competition, and evolution. Sometimes we explore it intentionally, but at other times we run into it by accident, most noticeably when the alarms on one of the megafauna bio-detectors—people and animals—go off. It's when these encounters happen that we remember that the space of things that we don't know is truly unfathomable.

Puttering around on the edge of the known and the unknown is the standard work of science and scientists. While the twinkling of the night sky may often be an inspiration for meditations on how little we understand, it's actually what we can't see in the cosmos that is the best reminder of our limited vision. In 1933, Fritz Zwicky observed a huge discrepancy in the amount of gravitational force needed to account for the rotational movement of galaxies and the amount that could be attributed to the visible matter in the galaxy. Naturally, he called this "dark matter." In 1980, Vera Rubin and Kent Ford used spectrographic data—its own form of making visible the invisible—to show definitively that galaxies contain at least six times as much dark mass as visible mass. As it turns out, Aristotle was wrong: Nature does love a vacuum—that's where it stores most of its stuff.

Countless studies and observations later point to the conclusion that nearly 30 percent of the universe is made of dark matter. The dark matter is a big part of what holds the universe together—more stuff for creating attractive forces between things. But, as you may know, ever since the Big Bang the universe is actually expanding. The cause of this is a different force of darkness, something that goes by the name dark energy.

> The pandemic has brought us closer than is comfortable to the engines of selection.

Our understanding of the biological world has also been a story of discovery of dark matter and dark energy—our collision with the coronavirus is just a most recent reminder of that theme. Early censuses dramatically underestimated the amount of living matter, darkness of understanding largely borne of poor optics. Our inability to see at the scale of microorganisms was a source of a good deal of pseudoscience bordering on mythology, especially when it came to disease. "Vapors" and humors were the first dark matter. It was only in the 1880s, 20 years or so after the publication of Darwin's *On the Origin of Species*, that Robert Koch discovered bacteria and in so doing revealed a material cause for infection. Among Koch's great advances was his use of staining and culturing to make visible the agent of infection. We now know that

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We live in an invisible ocean of microbial diversity and menace.

bacteria and other microorganisms account for most of the world's genetic diversity, not only in the world at large, but also within our own bodies, where our inner microbial ecosystem of the microbiome turns out to be crucial to human health. Some forms of "infection" are deadly, but some are necessary.

Viruses—like the coronavirus—are even smaller than bacteria and so were also dark for some time. They were also brought to light in the late 19th century, discovered by the Dutch microbiologist Martinus Beijerinck in the course of investigating the etiology of mosaic disease in tobacco plants. Repeated efforts to culture the source of the disease failed, so it wasn't bacterial in nature—biologists were the first to understand that you need culture to live—but whatever was causing the disease was able to replicate. It was alive in some ways, but dead in others. Beijerinck called this "infectious agent" a virus.

We now know that a virus is basically nano-encapsulated genetic information. They have existed from the beginning of biological time, emergent from the proverbial primordial soup, a string of atoms, clumped into molecules, wrapped in another kind of molecular shell, a kind of biological M&M. The *raison d'etre* of the virus is reproduction, which ironically leaves a fair amount of death in its wake. But really, the virus is an engine of life whose dynamics and mechanisms of existence and reproduction make it the agent of genetic expansion, a "dark life" biological force to the dark energy physical force fueling universal expansion that is dark energy. Not quite twins separated at birth, but siblings separated by several billion years, give or take.

As a force for life viruses account for many of evolution's most exceptional selective pressures and innovations. The early successful viral reproductive process of simple genetic segments inserting themselves into ancient host genomes served as an early stage in the evolution of the "eukaryotic cells" that comprise later larger and more complex single cell and multicellular organisms (us). The "pressure" of the fundamental goal of reproduction has, according to many, worked its evolutionary magic at even greater scales. Sure it's the reason that a virus "learns" how to jump from animals to humans, but it also has been hypothesized that it's a drive that has fueled the evolution of recombinational sex, the kind that all animals and plants use. So a virus not only engendered multicellular life, it lifted life from the monotony of asexuality.

In a kind of Nietzschean "that which does not kill us makes us stronger" way, any ability that we do have to fight off some diseases can also be at least partly attributed to viruses. Without having acquired genes of viral provenance about 500 million years ago, the jawed vertebrates—which includes all vertebrates but lampreys and hagfish—would have no adaptive immune system, without which most vertebrates would have minimal means of fending off viruses. Without immune systems, researchers would have no ability to develop immunotherapy. CRISPR, the most revolutionary genetic engineering tool in the history of biological science, is

VIRAL INNOVATION	EXAPTED ADAPTATION	ENGINEERING UTILITY
Mobile Genetic Element	Prokaryotic CRISPR	Genetic Engineering
RAGs	Adaptive Immunity	Immono-therapy
Endonuclease	Restriction Enzyme System	Molecular cloning
Group II Introns	Eukaryogenesis	Targetrons
Oncolytic virus	Tumor antigens	Oncolytic virus therapy
Membrane proteins	Cellular tropism	Vaccine vectors

VIRAL EDUCATION This chart represents paths from nature to therapy. It shows viral genetics (viral innovation) that have been co-opted by other forms of life (exapted adaptation) and that have been used as a part of human genetic engineering (engineering utility).

effectively the recapitulation of our biological antivirus defense system that kills an infiltrating virus by slicing it into genetic pieces. Current vaccine delivery techniques and other forms of biological therapies rely on a mimicking of or instigation of virus insertion mechanisms. What was once dark, was eventually brought to light, and once brought to light, helped to bring light—and life.

Our all too human tendency to focus on what is directly or instrumentally visible, or of comparable scale to ourselves, has blinded us to both the largest and smallest scales of the universe. Scales where physical forces shape the elementary structure of matter. But also blinded us to those living scales invisible to the eye that have shaped the form and function of adaptive matter. The COVID-19 crisis has made the terrifying dark energy of evolution visible and brought us closer than is comfortable to the engines of selection. We live in an invisible ocean of microbial diversity and menace, and one that is insensitive to the transience of multicellular life. Maybe it is a moment for us as a culture to learn from our microbial allies in the universe of dark matter—the bacteria, from whom we acquire our symbiotic microbiome—that the best way to defeat the dark energy of the virus is to turn its entropic ingenuity against itself and out-evolve the virus by evolving our scientific ingenuity and probably our social practices too. We'll have to adapt—what choice do we have?

DAVID KRAKAUER is the president and William H. Miller Professor of Complex Systems at the Santa Fe Institute in New Mexico. He works on the evolution of intelligence and stupidity on Earth. He is the founder of the InterPlanetary Project at SFI and the publisher/editor-in-chief of the SFI Press. His most recent book is an edited volume, *Worlds Hidden in Plain Sight*.

DAN ROCKMORE is the associate dean for the sciences and the director of the Neukom Institute for Computational Sciences at Dartmouth College. His most recent book is an edited volume, *What are the Arts and Sciences? A Guide for the Curious*.

The Power of Crossed Brain Wires

Synesthesia makes ordinary life marvelous

BY SIDNEY PERKOWITZ

W**HEN I WAS ABOUT 6**, my mind did something wondrous, although it felt perfectly natural at the time. When I encountered the name of any day of the week, I automatically associated it with a color or a pattern, always the same one, as if the word embodied the shade. Sunday was dark maroon, Wednesday a sunshiny golden yellow, and Friday a deep green. Saturday was interestingly different. That day evoked in my mind's eye a pattern of shifting and overlapping circular forms in shades of silver and gray, like bubbles in a glass of sparkling water.

AGSANDREW / SHUTTERSTOCK

Without knowing it, I was living the unusual mental state called synesthesia, aptly described by synesthesia researcher Julia Simner as a "condition in which ordinary activities trigger extraordinary experiences." More exactly, it is a neurological event where excitation of one of the five senses arouses a simultaneous reaction in another sense or senses (the Greek roots for "synesthesia," also spelled "synaesthesia," translate as "joined perception"). Some 4 percent of the population experiences this kind of cross-sensory linking, and studies have shown it's more prevalent in creative people. Artists who've reported extraordinary experiences of synesthesia range from 19th-century composer Nikolai Rimsky-Korsakov to contemporary artist David Hockney to pop music star Lady Gaga.

For me, the words "Sunday," "Monday," and so on, generated internal visions of color and pattern. Most synesthetic reactions also involve color in response to lexical stimuli—words written or spoken ("word-color" synesthesia), and letters, numbers, and symbols ("grapheme-color" synesthesia)—or to music and sound ("colored-hearing" synesthesia). Researchers have also observed dozens of other types of stimulus-reaction combinations: taste evoking a visual image, such as the flavor of chicken producing a 3-D shape; physical touch inducing the sensation of smell; and somehow the most extraordinary pairing, words generating the sensation of taste, such as "jail" creating the flavor of bacon.

At one time, strange pairings like these were little understood and even feared as signs of pathology. Now we know more, but many questions remain and synesthesia still carries an exotic aura. At the same time, it is a new tool to explore the human brain and mind, creativity, and consciousness.

REPORTS OF SENSORY CROSS-CONNECTIONS go far back. In 1690, the English philosopher John Locke wrote of a blind man who associated the sound of a trumpet with the color scarlet, although it is unclear if this was synesthesia or a metaphor, a recurring issue in synesthesia research. In 1812, however, a German physician wrote a definitive description of seeing colored letters. Other physicians reported similar experiences in patients and the reports drew attention from scientists, clinicians, and artists. French poets Arthur Rimbaud and Charles Baudelaire extolled the romantic idea that the senses should intermingle.

"When I see equations, I see the letters in colors," Richard Feynman said.

But 19th-century scientific and clinical understanding was limited, and synesthetes were often reluctant to come out of the closet for fear of appearing "odd" or worse. Some synesthetes were diagnosed with conditions such as schizophrenia when their cross-sensory effects were taken as delusions or hallucinations. Or clinicians denied that synesthesia existed, interpreting patient's statements like this "music looks red" as over-enthusiastic metaphor.

Fortunately the scientific study of synesthesia grew from the late 19th century into the 20th, mainly using interviews and group surveys. In 1895, psychologist Mary Whiton Calkins at Wellesley College analyzed her students' self-reported responses about synesthetic manifestations and speculated about their causes. But like every other scientist at the time, she had no way to probe the phenomenon at a deep neural level. Nevertheless, research continued and led to several international conferences on the subject in the 1930s.

But by then, research had diminished. One problem was the difficulty of tracking the many forms of synesthesia. Another is the same reason that human consciousness is hard to study—the synesthetic experience is internal and subjective. It's problematic to analyze a neural event when the only evidence is the subject's personal account. The entire field of psychology recognized this in that same era when it turned away from studying internal experiences.

In the 1980s, however, new approaches made synesthesia amenable to more rigorous and objective study and research has blossomed, with about 1,000 new publications since 2000. One big step has been the acceptance of a consensus definition of synesthesia. Its key features are that a subject involuntarily experiences vivid responses to stimuli that combine two or more different sensory modalities, and that the responses are constant over time; for instance, a given word always induces the same color in a particular subject (the colors themselves are unique to each person). The psychologist Simon Baron-Cohen and colleagues introduced this last benchmark in 1987 as an objectively measurable standard of genuineness. True synesthetes give the same responses to the same stimuli when tested and retested over long time intervals. Childhood synesthesia generally continues into adulthood, though not always. I lost my automatic color associations by the time I was 12. Today I can only remember the colors. (You can check yourself for evidence of synesthesia at www.synesthete.org.)

Besides these tests, new neuroimaging techniques have established synesthesia as a real neurological process. One widely used method is functional magnetic resonance imaging (fMRI) of the brain. Unlike regular MRI, which shows the anatomy of the brain (or other internal organs), fMRI identifies which parts of the brain are active, nearly in real time. Since 2002, some fMRI investigations of grapheme-color synesthesia—the most widely studied kind—have shown that graphemes stimulate the V4 region of the brain. This area deals specifically with color within the visual cortex, the part of the brain that processes what the eyes see (the auditory cortex and other specialized areas handle the remaining senses). This is consistent with a model where the regions of the brain that analyze graphemes and that deal with color are somehow hyper-connected to create a synesthetic event. But not all fMRI data show the same result, nor is it clear if it is the visual perception of a grapheme or its conceptual meaning that is the trigger.[1]

Remarkably, even with advanced methods, other basic questions have lingered since the 19th century. How prevalent is synesthesia in the general populace? Different studies had given values from over 20 percent to less than 1 percent, a disparity partly due to the use of self-reported data. To remedy this, in 2006 Simner, then at the University of Edinburgh, and her colleagues carried out a controlled approach. They interviewed nearly 1,700 subjects and tested them for consistency over time. The certified synesthetes constituted 4.4 percent of the group, 1 for every 23 people—rare, but not vanishingly so. The data also showed that the most common subvariant is the one I experienced: colored days of the week.

BORN THIS WAY Lady Gaga has said she "hears music all at once and in lots of colors." Musicians including Jean Sibelius and Duke Ellington have also said they've experienced synesthesia. Reasearches have found that synesthesia shows up often in creative people.

FASHIONSTOCK.COM / SHUTTERSTOCK

SURVEYS AND TESTS ILLUMINATE possible connections between synesthesia and artistic or creative ability. Catherine Mulvenna at University College London, who has written about this elusive connection, asks, Is synesthesia "a driving force or a mere idiosyncratic quirk" in artists? As Mulvenna points out, one connection of synesthesia with creativity is personal testimony from creative people. This often comes across as compelling evidence of true synesthesia. Vladimir Nabokov wrote in his autobiography *Speak, Memory* of his "colored hearing," in which the letters x and k are respectively a steely blue and a huckleberry blue. Richard Feynman has related, "When I see equations, I see the letters in colors ... light-tan j's, slightly violet-bluish n's, and dark brown x's flying around." Hockney sees colors when he hears music, which he uses when he does stage design for ballets and operas.

> *Synesthesia researchers have entered the final frontier of brain studies: consciousness.*

Many people with musical talent give detailed accounts of how music makes colors for them. Besides Rimsky-Korsakov, Jean Sibelius feared mockery for revealing his synesthesia, as did violinist Itzhak Perlman. In the worlds of jazz and popular music, Duke Ellington sensed both colors and textures from music, seeing dark blue burlap or light blue satin for specific notes played by certain musicians; the late jazz pianist Marian McPartland saw the key of D as daffodil yellow and B major as maroon; and Lady Gaga said in an interview, "I do hear music all at once and in lots of colors. It's like a painting."

Research supports these accounts. Self-reported synesthetes appear at a relatively high rate among artistic types, and one study using objective testing found 7 percent synesthetes among 99 art students compared to 2 percent in a control group. There is also evidence of associations between synesthesia and elements of creativity, but one stumbling block is the lack of a satisfactory definition of creativity. As Mulvenna writes, "Creativity is a complex construct to define, almost to the point of infamy within fields of systematic investigation."

Nevertheless, researchers have uncovered suggestive correlations between synesthesia and creativity, at least as defined by psychological testing. In 2016, Charlotte Chun and Jean-Michel Hupe at the University of Toulouse compared a selected group of 29 artistic synesthetes to 36 controls. Testing for aspects of creativity and related abilities such as mental imagery showed higher scores for the synesthetes, but with smaller differences than in earlier studies. These outcomes and other research results point to qualities that synesthetes consistently display, which may explain their creative tendencies: cognitive traits such as a disposition to think in images and sensitivity to color; and the psychological personality trait called "openness to experience," exemplified by intellectual curiosity and an active imagination.

EXAMINING THE SYNESTHESIA-CREATIVITY LINK is an important long-term effort, but there is a deeper question for synesthesia itself: What are its roots? In 2018, neuroscientists Simon Fisher and Amanda Tilot at the Max Planck Institute for Psycholinguistics, Nijmegen, the Netherlands, and colleagues published genetic data for synesthetes from three unrelated families where the condition is prevalent.[2] Earlier work had not found individual genes that are responsible for synesthesia, but the new researchers cast a wide net. They obtained DNA from four to five synesthetes and at least one nonsynesthete from each family, spread over generations. All the synesthetes displayed the colored-hearing variant called "sound-color."

Using gene sequencing, the researchers identified 37 genes that indicate a tendency toward synesthesia. No single gene was seen in all three families, confirming that the inheritance of synesthesia is not tied to just one gene or group of them. But 6 of the 37 genes were linked to the development of axons, the long thin part of a neuron that communicates with other brain neurons through electrical impulses. Equally intriguing, the six genes are also linked to the early childhood development of the visual and auditory cortices, and the parietal cortex, the "association area" of the brain that integrates information across sensory modes for effective overall functioning.

Since then, Fisher and Tilot have extended their new genetic understanding to study links between synesthesia and other neural conditions.[3] The genetic results and these overlaps are important because, as Fisher told me in an email, they "give us insights into shared neurobiological mechanisms … increasing our understanding of how synesthesia develops." The genetic links to the development of the sensory cortices of the brain, along with fMRI brain scanning results, seem to support a theory based on hyper-connectivity among brain regions as a basis for synesthesia. More complete genetic data may also ultimately show why the synesthesia genes have survived the evolutionary process, perhaps because they offer adaptive advantages such as seeding creativity.

Synesthesia researchers have now entered the final frontier of brain studies: consciousness. They believe a new understanding of synesthesia can help solve the hard problem of how subjective experience can arise from the physical brain. Myrto Mylopoulos, a philosopher of mind at Carleton University in Canada, and Tony Ro, a neuroscientist at the City University of New York, have written that synesthesia research can broadly test theories of consciousness because the varied forms of synesthesia involve all the senses and cognitive elements.[4] The authors with other researchers believe that the empirical approach to finding or confirming a theory of consciousness is to examine its neural correlates, the objectively testable brain functions that must accompany subjective experiences.

Pursuing this idea, Mylopoulos and Ro considered how synesthesia can act as a test bed to choose among theories of consciousness, and examined prevalent candidates, none of which is as yet supported by much empirical evidence. "Higher order" theory assumes that conscious states are those that a person is aware of being in, which comes from another mental state operating at a higher level; but in "first-order" theory there is no need for a higher state because even a perceptual state such as viewing a flower is considered to be a conscious state. Significantly, these differences produce characteristic neural correlates operating in different parts of the brain for each theory. The authors conclude that the scope of synesthetic events spread over the brain and its functions can yield "initial clues as to the neural correlates of conscious perceptual experiences more generally," and help guide researchers toward a valid theory of consciousness.

As for me, I miss seeing the vivid colors of the days of the week that once enriched my internal vision. The colors now exist only in memory. But I would like to believe that synesthesia's link to creativity has enlarged my own mind, especially in my career-long devotion as a scientist and writer to interdisciplinary work. Even under strict scientific study, and centuries after its first observations, synesthesia retains its power to make ordinary life both more marvelous and complex.

SIDNEY PERKOWITZ is Candler Professor of Physics Emeritus at Emory University. His latest books are *Physics: A Very Short Introduction* and *Real Scientists Don't Wear Ties*. He is at work on a book about the use of science in the police and justice systems.

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IMAGE ORIGINALLY APPEARED IN "DATALORE," A 1988 EPISODE OF *STAR TREK: THE NEXT GENERATION.*

Could an AI Be Immortal?

Data is under attack and uploads his brain. Does he survive?

BY SUSAN SCHNEIDER

CONSIDER DATA, THE ANDROID from *Star Trek: The Next Generation*. Suppose he finds himself on a hostile planet, surrounded by aliens that are just about to dismantle him. In a last-ditch effort to survive, he quickly uploads his artificial brain onto the Enterprise computer. Does Data survive? And could he, at least in principle, do this every time he's in a crisis, so that he'd be immortal?

It is common to assume that an AI could achieve immortality by creating backup copies of itself and thus transfer its consciousness from one computer to the next. This view is encouraged by science-fiction stories. But is it right?

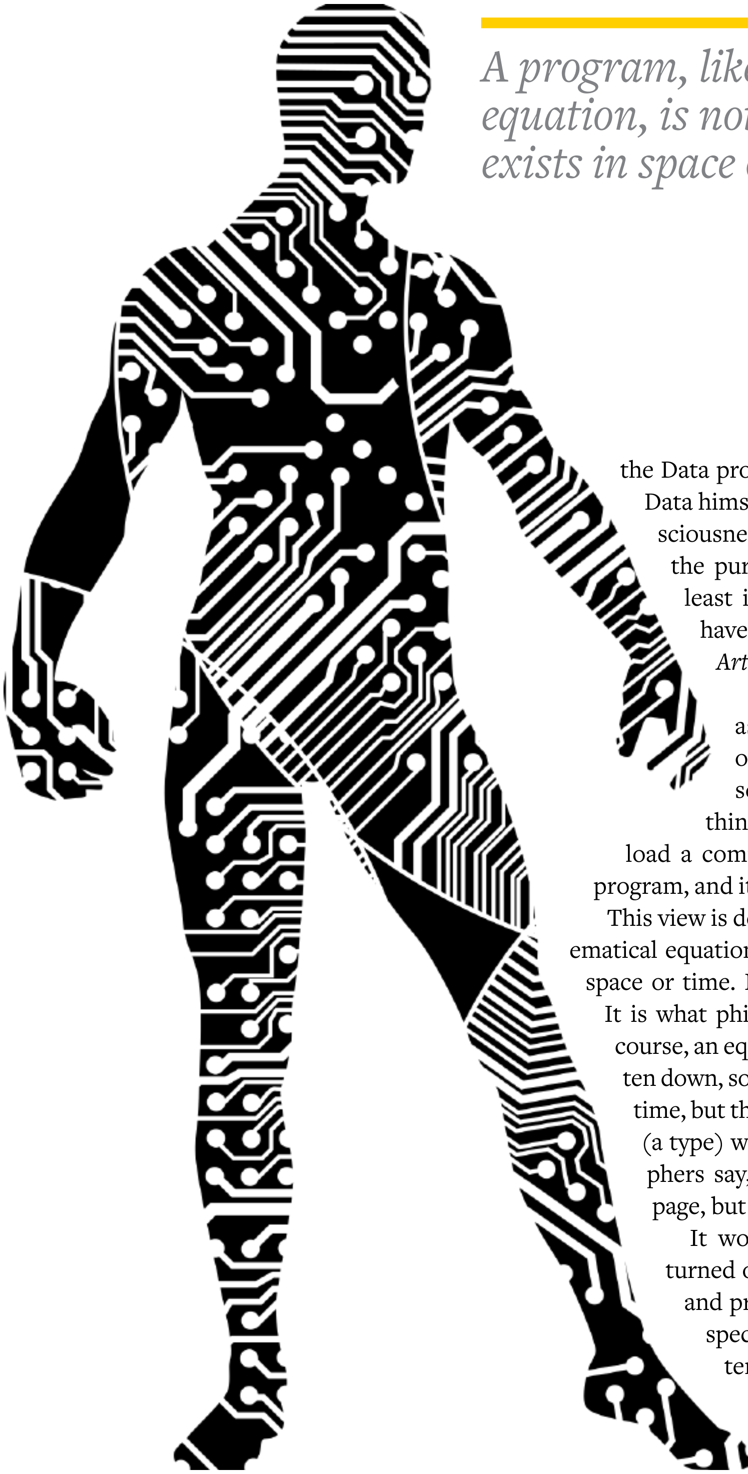
The question I am asking is whether an AI could achieve what we might call "functional immortality," uploading and downloading backups long enough to witness the Big Crunch or even be a spectator in the heat death of the universe, the biggest event of them all.

There has been a good deal of discussion concerning the promise and peril of superintelligent AI, a hypothetical form of AI that is smarter than normal humans in every respect: scientific reasoning, mathematical abilities, and more. Science fiction has long depicted superintelligent AIs as being superbeings in another respect as well. Unlike unenhanced humans, who succumb to biological senescence, AIs can achieve functional immortality through uploading and downloading their program. Inching toward omniscience and immortality, AIs become almost Godlike.

Uploading efforts like Data's will not do the trick, however. Notice that there is an ambiguity as to whether the expression "AI" refers to a particular AI or to a type of AI program. Consider that the expression "the Tesla Model 3" could mean the particular Tesla in your driveway or it could mean the type of car (i.e., the make and model). The type would endure even after your car was dismantled and destroyed. In a similar vein, we can distinguish the particular AI, Data, from the type of program he runs (the Data program, if you will).

When we are asking about Data's survival in the above example we are asking about whether this concrete, particular android, Data, can survive until the end of the universe. Data is a particular AI, and as such, he is vulnerable to destruction, just like we are. There may be other androids of this type, but their existence does not ensure the survival of Data, it just ensures that there are other androids that have Data's *type* of program.

Here, one might object that if you copy Data's program precisely, you haven't merely made a copy of



A program, like a mathematical equation, is not a concrete thing that exists in space or time.

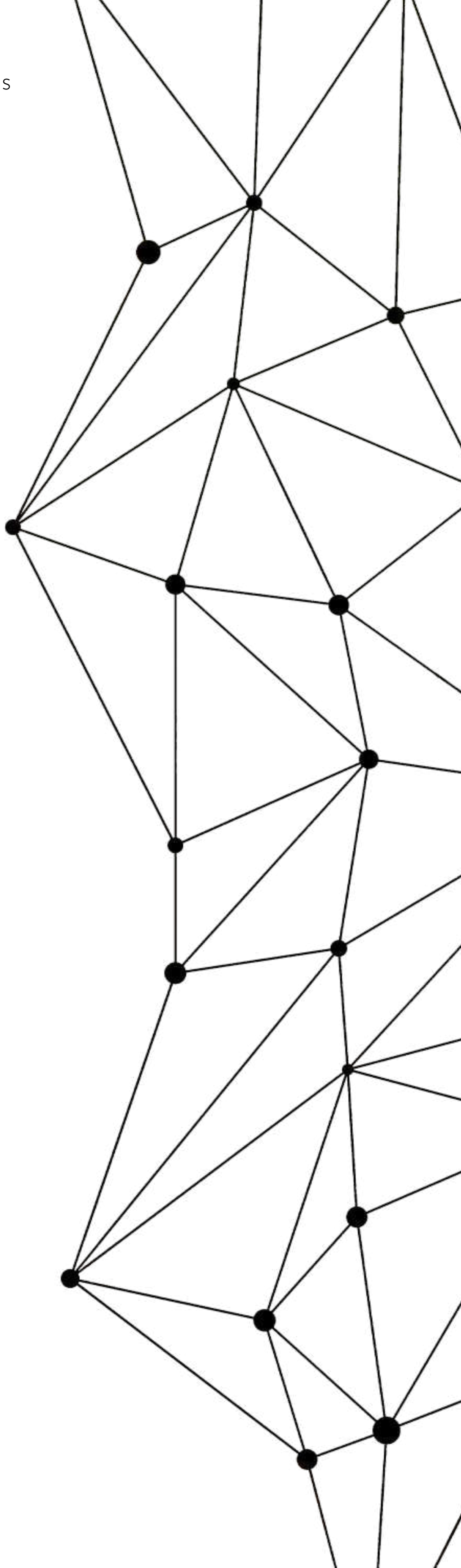
the Data program—you've somehow actually made Data himself, all over again. Data's mind and consciousness transfer. (Here, I am assuming, for the purpose of discussion, that AIs could, at least in principle, be a conscious being and have a mind, an issue I question in my book *Artificial You*.)

This objection relies upon a certain assumption about the nature of the self or mind: the position that the mind (or self) is a software program. You might think that just as you can upload and download a computer file, your mind or self is just a program, and it too can be uploaded and downloaded. This view is deeply mistaken. A program, like a mathematical equation, is not a concrete thing that exists in space or time. Nor does it cause events in the world. It is what philosophers call an "abstract entity." Of course, an equation or software program can be written down, so you might assume that it is in space and time, but this is to confuse the equation or program (a type) with a mere inscription of it (as philosophers say, a "token"). The inscription is on the page, but the equation or program is not.

It would be very odd if selves and minds turned out to be abstract entities like numbers and programs. After all, we can tell, by introspecting, that moments pass for us—we are temporal beings. And our actions cause events in the spatiotemporal world. Abstract entities don't do anything, and they aren't anywhere.

GORDON JOHNSON / PIXABAY

After all, we can tell, by introspecting, that moments pass for us—we are temporal beings.



So where does all this leave us? There Data is, on a hostile planet, surrounded by aliens that are about to destroy him. He quickly uploads his artificial brain onto a computer on the Enterprise. Does he survive or not?

In my view, we now have a distinct instance (a token) of the type of mind, *Data*, being run by the Enterprise computer. We could ask: Can that particular instance or token survive the destruction of the computer by uploading again (i.e., transferring the mind of that token to a different computer)? No. Again, uploading would merely create a different instance (or token) of the same program type. An individual's survival depends on where things stand at the token level, not at the level of types. Data, despite his name, is not a program.

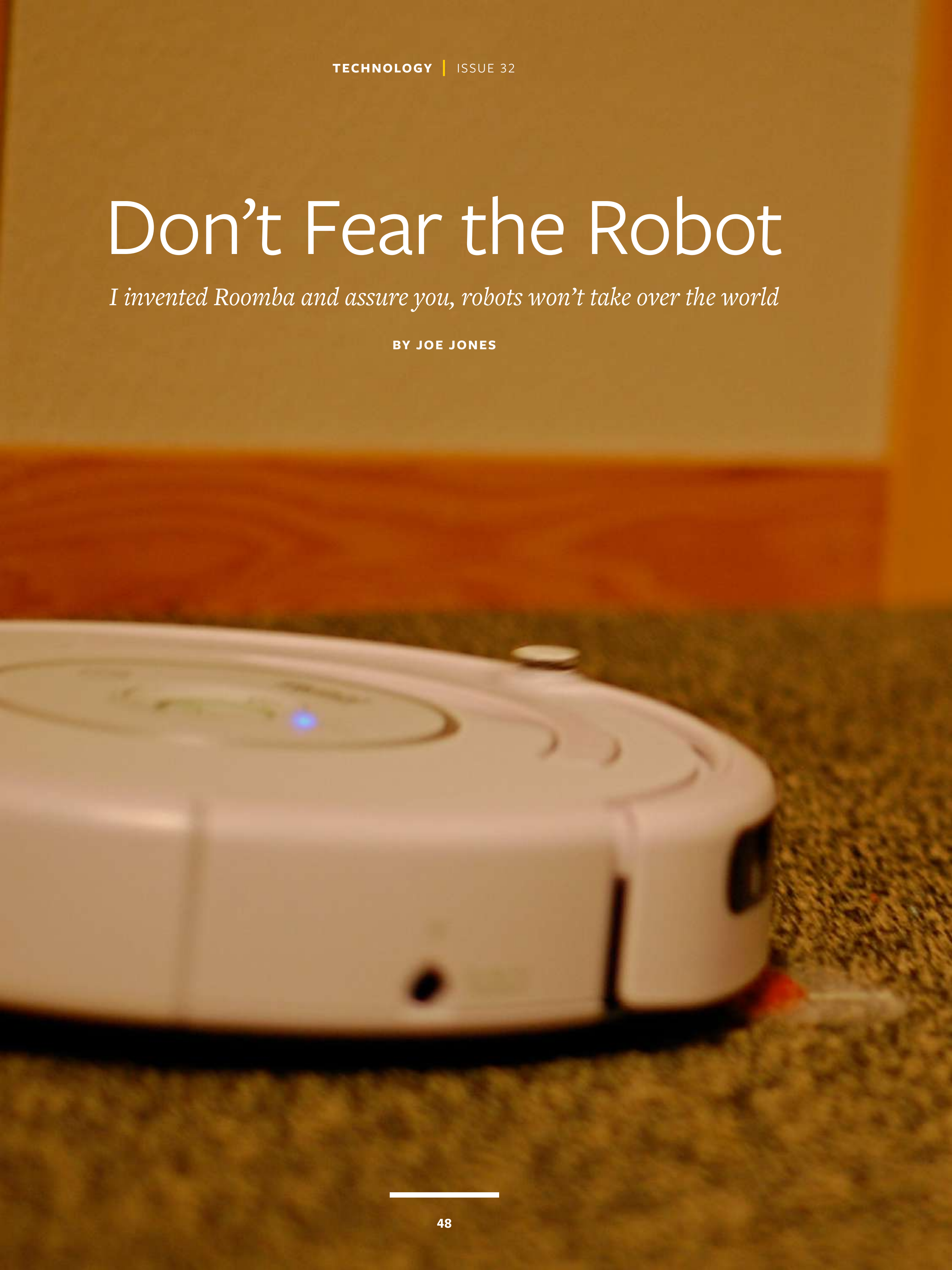
It is also worth underscoring that a particular AI could still live a very long time, insofar as its parts are extremely durable. Perhaps Data could achieve functional immortality by avoiding accidents and having his parts replaced as they wear out. It would be an extraordinary feat to avoid accidents over a period of several billion years, to say the least. (I suppose, at least in principle, a future human could try to do this as well through innovations in biotechnology.) But my view is compatible with this scenario, because Data's survival in this case does not happen by transferring his program from one physical object to another.

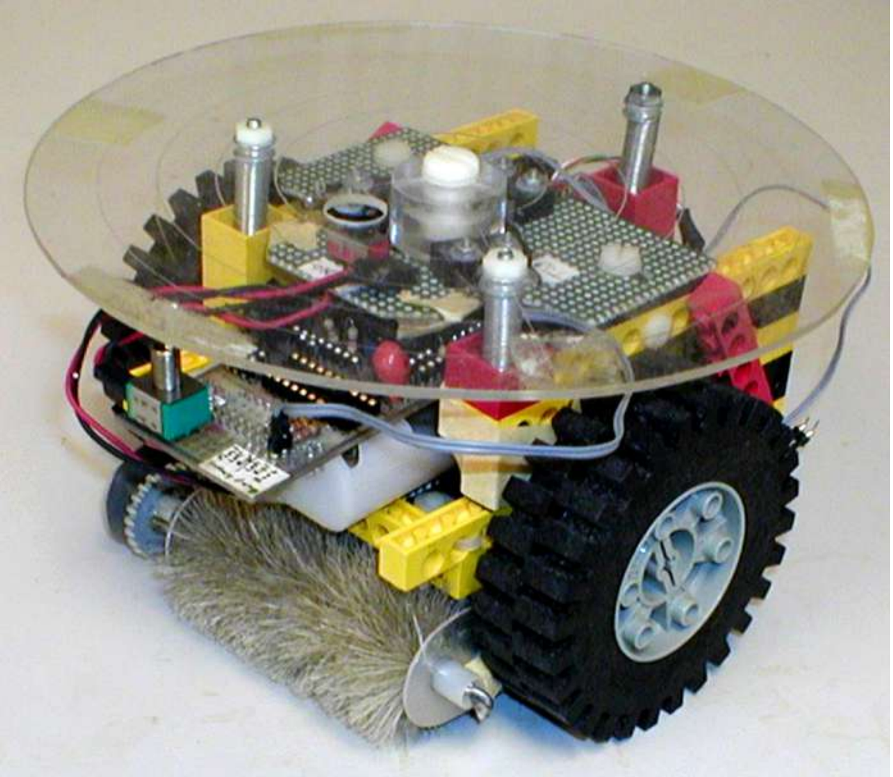
SUSAN SCHNEIDER is the NASA-Baruch Blumberg chair at the Library of Congress and NASA, and the author of *Artificial You: AI and the Future of the Mind*.

Don’t Fear the Robot

I invented Roomba and assure you, robots won’t take over the world

BY JOE JONES





RUG WARRIOR
Joe Jones built his "Rug Warrior" (left) in 1989. He calls it "the earliest conceptual ancestor of Roomba." It included bump sensors and a carpet sweeper mechanism made from a bottle brush. It picked up simulated dirt at a demonstration but, Jones says, "was not robust enough to actually clean my apartment as I had hoped."

PAGE 48-49: CHRISTA MRGAN / FLICKR; THIS PAGE COURTESY OF JOE JONES

Y**OU PROBABLY KNOW MY ROBOT.** I've been inventing autonomous machines for over 30 years and one of them, Roomba from iRobot, is quite popular. During my career, I've learned a lot about what makes robots valuable, and formed some strong opinions about what we can expect from them in the future. I can also tell you why, contrary to popular apocalyptic Hollywood images, robots won't be taking over the world anytime soon. But that's getting ahead of myself. Let me back up.

My love affair with robots began in the early 1980s when I joined the research staff at MIT's Artificial Intelligence Lab. Physics was my college major but after a short time at the lab the potential of the developing technology seduced me. I became a roboticist.

Such an exhilarating place to work! A host of brilliant people were researching deep problems and fascinating algorithms. Amazingly clever mechanisms were being developed, and it was all converging in clever and capable mobile robots. The future seemed obvious. So, I made a bold prediction and told all my friends, "In three to five years, robots will be everywhere doing all sorts of jobs."

But I was wrong.

Again and again in those early years, news stories teased: "Big Company X has demonstrated a prototype of Consumer Robot Y. X says Y will be available for sale next year." But somehow next year didn't arrive. Through the 1980s and 1990s, robots never managed to find their way out of the laboratory. This was distressing to a committed robot enthusiast. Why hadn't all the journal papers, clever prototypes, and breathless news stories culminated in a robot I could buy in a store?

Let me answer with the story of the first consumer robot that *did* achieve marketplace stardom.

In the summer of 1999, while working at iRobot, a colleague, Paul Sandin, and I wrote a proposal titled "DustPuppy, A Near-Term, Breakthrough Product with High Earnings Potential." We described an inexpensive little robot, DustPuppy, that would clean consumers' floors by itself. Management liked the idea and gave us $10,000 and two weeks to build a prototype.

Using a cylindrical brush, switches, sensors, motors, and a commonplace microprocessor, we assembled our vision. At the end of an intense fortnight we had it—a crude version of a robot that conveyed a cleaning mechanism around the floor and—mostly—didn't get stuck. Management saw the same promise in DustPuppy as Paul and me.

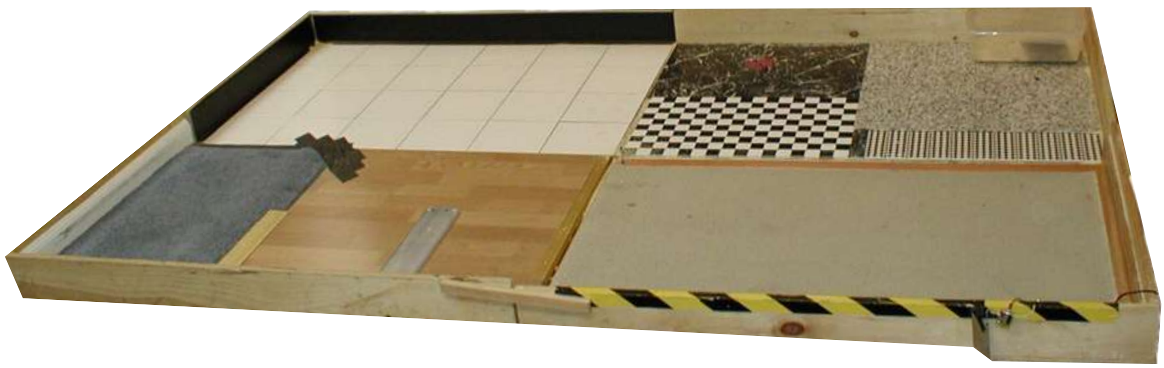
We called our robot DustPuppy for a reason. This was to be the world's first significant consumer robot and the team's first attempt at a consumer product. The risk was that customers might expect too much and that we might deliver too little. We were sure that—like a puppy—our robot would try *very hard* to please but that also—like a puppy—it might sometimes mess up. Calling it DustPuppy was our way of setting expectations and hoping for patience if our robot wasn't perfect out of the gate. Alas, iRobot employed a firm to find a more commercial name. Many consumer tests later, DustPuppy became Roomba. The thinking was the robot's random motion makes it appear to be dancing around the room—doing the Rumba.

When designers festoon their robots with anthropomorphic features, they are making a promise no robot can keep.

PAUL AND I KNEW BUILDING a robotic floor cleaner entails fierce challenges not apparent to the uninitiated. Familiar solutions that work well for people can prove problematic when applied to a robot.

Your manual vacuum likely draws 1,400 watts or 1.9 horsepower from the wall socket. In a Roomba-sized robot, that sort of mechanism would exhaust the battery in about a minute. Make the robot bigger, to accommodate a larger battery, and the robot won't fit under the furniture. Also, batteries are expensive—the cost of a big one might scuttle sales. We needed innovation.

Melville Bissell, who patented the carpet sweeper in 1876, helped us out. We borrowed from his invention to solve Roomba's energy problem.



TEST FLOORS "Roomba needed to function on many floor types and to transition smoothly from one type to another," says Joe Jones. "We built this test floor to verify that Roomba would work in this way." The sample floors include wood, various carpets, and tiles.

COURTESY OF JOE JONES

A carpet sweeper picks up dirt very efficiently. Although you supply all the power, you won't work up a sweat pushing one around. (If you supplied the entire 1.9 horsepower a conventional vacuum needs, you'd do a lot of sweating!)

We realized that our energy-efficient carpet sweeper would not clean as quickly or as deeply as a powerful vacuum. But we thought, if the robot spends enough time doing its job, it can clean the surface dirt just as well. And if the robot runs every day, the surface dirt won't work into the carpet. Roomba matches a human-operated vacuum by doing the task in a different way.

Any robot vacuum must do two things: 1) not get stuck, and 2) visit every part of the floor. The first imperative we satisfied in part by making Roomba round with its drive wheels on the diameter. The huge advantage of this shape is that Roomba can always spin in place to escape from an object. No other shape enables such a simple, reliable strategy. The second imperative, visiting everywhere, requires a less obvious plan.

You move systematically while cleaning, only revisiting a spot if that spot is especially dirty. Conventional wisdom says our robot should do the same—drive in a boustrophedon pattern. (This cool word means writing lines in alternate directions, left to right, right to left, like an ox turns in plowing.) How to accomplish this? We received advice like, "Just program the robot to remember where it's been and not go there again."

Such statements reveal a touching faith that software unaided can solve any technical problem. But try this exercise (in a safe place, please!). While standing at a marked starting point, pick another point, say, six feet to your

Did you guess so little was going on in Roomba's brain? Every robot I build is as simple-minded as I can make it.

left. Now keep your eyes closed while you walk in a big circle around the central point. How close did you come to returning to your starting point? Just like you, a robot can't position itself in the world without appropriate sensors. Better solutions are available today, but circa 2000 a position-sensing system would have added over $1,000 to Roomba's cost. So, boustrophedon paths weren't an option. We had to make Roomba do its job without knowing where it was.

I DESIGN ROBOTS using a control scheme called behavior-based programming. This approach is robot-appropriate because it's fast, responsive, and runs on low-cost computer hardware. A behavior-based program structures a robot's control scheme as a set of simple, understandable behaviors.

Remember that Roomba's imperative is to apply its cleaning mechanism to all parts of the floor and not get stuck. The program that accomplishes this needs a minimum of two behaviors. Call them Cruise and Escape. Cruise is single-minded. It ignores all sensor inputs and constantly outputs a signal telling the robot's motors to drive forward.

Escape watches the robot's front bumper. Whenever the robot collides with something, one or both of the switches attached to the bumper activate. If the left switch closes, Escape knows there's been a collision on the left, so it tells the motors to spin the robot to the right. A collision on the right means spin left. If both switches close at once, an arbitrary decision is made. When neither switch is closed Escape sends no signal to the motors.

Occasionally Cruise and Escape try to send commands to the motors at the same time. When this happens, a bit of code called an arbiter decides which behavior succeeds—the highest priority behavior outputting a command wins. In our example, Escape is assigned the higher priority.

Watching the robot, we see a complex behavior emerge from these simple rules. The robot moves across the floor until it bumps into something. Then it stops moving forward and turns in place until the path is clear. It then resumes forward motion. Given time, this random motion lets the robot cover, and clean, the entire floor.

Did you guess so little was going on in the first Roomba's brain? When observers tell me what Roomba is thinking they invariably imagine great complexity—imbuing the robot with intentions and intricate plans that are neither present nor necessary. Every robot I build is as simple and simple-minded as I can make it. Anything superfluous, even intelligence, works against marketplace success.

The full cleaning task contains some extra subtleties. These require more than just two behaviors for efficient operation. But the principle holds, the robot includes only the minimum components and code required for the task.

DUST PUPPY
Before the marketers stepped in with the name "Roomba," Joe Jones and his colleague Paul Sandin called their floor cleaner, "DustPuppy." "Our robot would try very hard to please," Jones writes. But like a puppy, "it might sometimes mess up." Here, Sandin examines a prototype, with designer Steve Hickey (black shirt) and intern Ben Trueman.

COURTESY OF JOE JONES

A FEW MONTHS from product launch, we demonstrated one of our prototypes to a focus group. The setup was classical: A facilitator presented Roomba to a cross section of potential customers while the engineers watched from a darkened room behind a one-way mirror.

The session was going well, people seemed to like the robot and it picked up test dirt effectively. Then the facilitator mentioned that Roomba used a carpet sweeper mechanism and did not include a vacuum.

The mood changed. Our test group revised the price they'd be willing to pay for Roomba, cutting in half their estimate from only minutes earlier. We designers were perplexed. We solved our energy problem by eschewing a vacuum in favor of a carpet sweeper—and it worked! Why wasn't that enough for the focus group?

Decades of advertising have trained consumers that a vacuum drawing lots of amps means effective cleaning. We wanted customers to judge our new technology using a more appropriate metric. But there was no realistic way to accomplish that. Instead, our project manager declared, "Roomba must have a vacuum, even if it does nothing."

No one on the team wanted a gratuitous component—even if it solved our marketing problem. We figured we could afford three watts to run a vacuum motor. But a typical vacuum burns 1,400 watts. What could we do with just three?

Using the guts of an old heat gun, some cardboard, and packing tape, I found a way. It turned out that if I made a very narrow inlet, I could achieve the same air-flow velocity as a regular vacuum but, because the volume was miniscule, it used only a tiny bit of power. We had a vacuum that actually contributed to cleaning.

There's a moment in the manufacturing process called "commit to tooling" when the design must freeze so molds for the plastic can be cut. Fumble that deadline and you may miss your launch date, wreaking havoc on your sales.

About two weeks before "commit," our project manager said, "Let's test the latest prototype." We put some surrogate dirt on the floor and let Roomba run over it. The dirt remained undisturbed.

Panic ensued. Earlier prototypes had seemed to work, and we thought we understood the cleaning mechanism. But maybe not. I returned to the lab and tried to identify the problem. This involved spreading crushed Cheerios on a glass tabletop and looking up from underneath as our cleaning mechanism operated.

Our concept of Mr. Bissell's carpet sweeper went like this: As the brush turns against the floor, bristle tips pick up dirt particles. The brush rotates inside a conforming shroud carrying the dirt to the back where a toothed structure combs it from the brush. The dirt then falls into the collection bin.

That sedate description couldn't have been more wrong. In fact, as the brush turns against the floor, a flicking action launches dirt particles into a frenetic, chaotic cloud. Some particles bounce back onto the floor, some bounce deep into the brush, some find the collection bin. The solution was to extend the shroud around the brush a little farther on the back side—that redirected the dirt that bounced out such that the brush had a second chance to pick it up. Roomba cleaned again and we could begin cutting molds with a day or two to spare.

Roomba launched in September 2002. Its success rapidly eclipsed the dreams of all involved.

DID ROOMBA'S NASCENT REIGN END the long robot drought? Was my hordes-of-robots-in-service-to-humanity dream about to come true?

In the years since iRobot released Roomba, many other robot companies have cast their die. Here are a few: Anki, Aria Insights, Blue Workforce, Hease Robotics, Jibo, Keecker, Kuri, Laundroid, Reach Robotics, Rethink Robotics, and Unbounded Robotics. Besides robots and millions of dollars of venture capitalist investment, what do all of these companies have in common? None are in business today.

The commercial failure of robots and robot companies is not a new phenomenon. Before Roomba, the pace was slower, but the failure rate no less disappointing. This dismal situation set me looking for ways around the fatal missteps roboticists seemed determined to make. I settled on three principles that we followed while developing Roomba.

1. PERFORM A VALUABLE TASK

When a robot does a specific job, say, mowing your lawn or cleaning your grill, its value is clear and long-lasting. But over the years, I've seen many cool, cute, engaging robots that promised great, albeit vague, value while performing no discernable task. Often the most embarrassing question I could ask the designer of such a robot was, "What does your robot do?" In this case the blurted answer, "Everything!" is synonymous with "Nothing." The first principle for a successful robot is: *Do something people want done*. When a robot's only attribute is cuteness, value evaporates as novelty fades.

2. DO THE TASK TODAY

Many robots emerge from research labs. In the lab, researchers aspire to be first to achieve some impressive result; cost and reliability matter little. But cost and reliability are paramount for real-world products. Bleeding edge technologies are rarely inexpensive, reliable, or timely. Second principle: *Use established technology*. A research project on the critical path to robot completion can delay delivery indefinitely.

3. DO THE TASK FOR LESS

People have jobs they want done and states they want achieved—a clean floor, a mowed lawn, fresh folded clothes in the dresser. The result matters, the method doesn't. If a robot cannot provide the lowest cost, least arduous solution, customers won't buy it. Third principle: *A robotic solution must be cost-competitive with existing solutions*. People will not pay more to have a robot do the job.

A few robots have succeeded impressively: Roomba, Kiva Systems (warehouse robots), and Husqvarna's Automower (lawn mower). But I started this article with the question, why aren't successful robots everywhere? Maybe the answer is becoming clearer.

Robot success is opportunistic. Not every application has a viable robotic solution. The state of the art means only select applications offer: a large market; existing technology that supports autonomy; a robotic approach that outcompetes other solutions.

There's one more subtle aspect. Robots and people may accomplish the same task in completely different ways. This makes deciding which tasks are robot-appropriate both difficult and, from my perspective, great fun. Every potential task must be reimagined from the ground up.

My latest robot, Tertill, prevents weeds from growing in home gardens. A human gardener pulls weeds up by the roots. Why? Because this optimizes the gardener's time. Leaving roots behind isn't a moral failure, it just means weeds will rapidly re-sprout, forcing the gardener to spend more time weeding.

Tertill does not pull weeds but attacks them in two other ways. It cuts the tops off weeds and it uses the scrubbing action of the wheels to kill weeds as they sprout from seeds. These tactics work because the robot, unlike the gardener, lives in the garden. Tertill returns every day to prevent rooted weeds from photosynthesizing so roots eventually die; weed seeds that are constantly disturbed don't sprout.

Had Tertill copied the human solution, the required root extraction mechanism and visual identification system would have increased development time, added cost, and reduced reliability. Without reimagining the task, there would be no solution.

Robots have a hard enough time doing their jobs at all. Burdening them with unnecessary features and expectations worsens the problem. That's one reason I'm always vexed when designers festoon their robots with anthropomorphic features—they make a promise no robot can keep. Anthropomorphic features and behaviors hint that the robot has the same sort of inner life as people. But it doesn't. Instead the robot has a limited bag of human-mimicking tricks. Once the owner has seen all the tricks, the robot's novelty is exhausted and along with it the reason for switching on the robot. Only robots that perform useful tasks remain in service after the novelty wears off.

No commercially successful robot I'm aware of has superfluous extras. This includes computation cycles—cycles it might use to contemplate world domination. All of the robot's resources are devoted to accomplishing the task for which it was designed, or else it wouldn't be successful. Working robots don't have time to take over the world.

Robots have been slow to appear because each one requires a rare confluence of market, task, technology, and innovation. (And luck. I only described some of the things that nearly killed Roomba.) But as technology advances and costs decline, the toolbox for robot designers constantly expands. Thus, more types of robots will cross the threshold of economic viability. Still, we can expect one constant. Each new, successful robot will represent a minimum—the simplest, lowest-cost solution to a problem people want solved. The growing set of tools that let us attack ever more interesting problems make this an exciting time to practice robotics.

JOE JONES is cofounder and CTO of Franklin Robotics. A graduate of MIT, he holds more than 70 patents.

T. Rex Was a Slacker

A natural wonder of the big theropod was how it conserved energy

BY MARK MACNAMARA

METHA1819 / SHUTTERSTOCK

IN OUR EVOLVING UNDERSTANDING of dinosaurs, Tyrannosaurus rex has acquired a new persona in recent decades. It's always been the imperious, curiously agile two-ton gargantua, personified as a gaunt, grizzle-faced gunfighter at the dark end of the bar, a soulless creature that lived to 30 and possessed a keen sense of smell, good eyesight, surprisingly pliable skin, and banana-sized teeth. Add a taste for Triceratops, which it ate by pulling off the head then using its smaller front teeth to nip the soft flesh behind the frill.

Chasing down prey is a dangerous business. It's better to have a body that allows you to hunt like a casual forager.

Its newer persona suggests a softer side, a demon looking creature but finally not a psychopath, merely a misunderstood everyman with feathers. Feathering on different parts of its body, mainly on its back, like a mane perhaps, was an "extravagance" in evolutionary terms. Although still somewhat speculative for T. rex, feathers are definitively found in close relatives, including the 30-foot-long Zhuchengtyrannus, which lived in China. Paleontologists have found intact downy feathers of different colors, and speculate that while feathers obviously didn't portend flight, or a show of intimidation to predators since there weren't any for T. rex, the feathering may have been a display, a peacock affect, as though to say, "Hey, how sexy a gal or guy am I?" Incidentally, some of the biggest T. rexes ever found were female.

And now, to add to this updated portrait, there is new insight into the physique of theropods like T. rex, distinguished by their hollow bones, three-toed limbs, and long hind legs. For small theropods, like the chicken-sized Compsognathus, from the Greek for "dainty," lanky limbs helped it run like a demon to find brunch and escape being brunch. But it turns out that feature doesn't hold for fellow theropods at the other end of the size scale. To be sure, long legs helped T. rex sprint up to maybe 30 mph for 50 to 100 yards—not nearly at the NASCAR speeds suggested in the film, *Jurassic Park*. But a new study, "The Fast and the Frugal,"[1] undercuts the image of T. rex on a rampage to devour Laura Dern. T. rex evolved long legs to amble through its habitat with a chill gait that conserved its "energy budget"—a giant body requires a massive amount of fuel—and helped the big theropod, "at once efficient and elegant," rule the land for more than 2 million years. Until an unfortunate asteroid arrived.

To Alex Dececchi, lead author of "The Fast and the Frugal," generous with his time and insights in a recent interview, T. rex's efficient gait bears a larger message. "We don't have infinite resources; we're trying to conserve the best we can," Dececchi says. "That's what nature is really good at. It's really good at conserving and minimizing excess costs to a goal. We should look back and say, 'OK, how did nature do it?' "

DECECCHI, A PALEONTOLOGIST, is an assistant professor of biology at Mount Marty College in South Dakota. It's a Benedictine school with a convent from which a dwindling number of nuns still appear on the faculty

SHREWD PREDATOR Yes, T-rex usually won its fights with Triceratops, depicted in this model from Jura Park in Poland. But contrary to its fierce reputation, T-rex also hunted in packs to corner small dinosaurs and sometimes fed on carrion.

GREIR / SHUTTERSTOCK

list. Dececchi is part of a small natural sciences department. The evolution of T. rex, he says, of its huge body and elongated limbs, is all about hunting. But not in the way you might think. Chasing down prey is a dangerous business. It's better to have a body that allows you to hunt like a casual forager.

"Most hunts end in failure—only about 25 percent succeed," Dececchi says. "That's a lot of energy to put out that you don't get back. If you can save, just by normal hunting and searching, that little bit of energy, then you don't have to hunt as much. When you're actually bringing something down—and remember it's often a dangerous process to take down a prey—you risk that injury a little bit less. The result is you can last through hard times a bit longer and risk yourself less."

Conserving energy, Dececchi adds, is a valuable survival trait, "especially if you're going through either a hard time, or as you're getting older. You still have to hunt, and you can save energy on hunts, or if you can just save energy, period, that energy can be put to other uses. Maybe it makes you a bit stronger during the mating season or fighting off a rival. You have that extra little reserve you can call upon."

What's interesting is this positive correlation between size and efficiency. In another study, Dececchi is working on a comparison of jerboas and kangaroo rats, which have similar skeletal structures. "Their hopping nature probably came about because they're so small, and have to get away really fast if something comes at them. When you're really small, speed becomes something that you're usually selected for. The overall costs of survival are more important than saving a little bit of energy. For them, for really small things, speed is probably a stronger selection pressure than efficiency."

This new understanding fleshes out T. rex as a real organism living in the day-to-day, not just bones in a drawer.

It's understandable to assume long legs were selected for their speed. But evolution doesn't run predictable courses. "We might look at animal growth and say, 'Well, they have longer legs than this guy, so they must have been faster,' " Dececchi says. "But no, they're too big for speed to be a problem. There must be another solution for this." That solution is energy efficiency. The wolf, for instance, has no reason to pursue the moose; he could do it but there's plenty of prey easier to catch. The same is true for T. rex. Its steady gait allowed it to range widely in a day, where it preyed on smaller dinosaurs like ceratopsians and hadrosaurs, and, contrary to its fierce reputation, sometimes scavenged on carrion. T. rex also hunted in packs, allowing it to corner and kill some of the smaller and faster dinosaurs. The big theropod consumed over 400 pounds of meat per day. As a forager, it was able to gain several more tons of meat per year than it would have as a sprinting hunter.

Of course, it helps to be kings and queens of the land. "You don't want to use human emotions like confidence, but T. rex probably wasn't afraid of anything else that was around," Dececchio says. "When the adults and sub-adults were walking into an area, they were just looking to see what's around, they weren't trying to watch their back. They were trying to gauge the environment, figure out what's a good place to set up a hunt, a good place to sleep. They wouldn't be worrying about anything else."

However, Dececchio points out, natural selection doesn't always prize efficiency. Sexual selection can sometimes rule. Birds come to mind, especially in the case when the male bird is bright and colorful and the female is drab. "You can spot that male bird from a mile away," Dececchi says. "How is it not eaten by predators? A lot of them are, but the cost of actually getting to mate versus not is worth it. In those instances, efficiency gets pushed aside. For a lot of mundane, functional, daily tasks, efficiency tends to be what you maximize. Once you get above the minimum threshold, like you need to be able to walk, or you need to be able to run, efficiency takes over. It's a daily grind thing."

THE ENERGY-SAVING HABITS of giant theropods is a revelation to paleontologists, at least to Dececchi. It's helped pull back the curtain on the mystery of T. rex's daily life. "We know from other studies that these dinosaurs had acute senses," Dececchi says. "They could detect prey from miles away. If you know their energetics, you can also figure out how many prey can be in an area. You can say, 'OK, were they following herds? Were they staying put and letting herds come to them?' So, for all these things, we could start to understand based on their energetics. It fleshes them out as real organisms living in the day-to-day, not just bones in a drawer."

Dececchi's work with dinosaurs has led him to see evolution similarly as a matter of nuance, a process of sculpting, the slow revealing, to him reminiscent of the Michelangelo statues in the Galleria dell'Accademia in Florence. "In many ways, that's what evolution is, chipping away the outside until you have a core, which has the traits. Like sculptors, you don't take a block of marble then add another block halfway through. You cut away from what you have. Think of one generation of T. rexes coming out. Obviously, not all of those babies will survive. That generation is going to be chipped away at, things taken away; sometimes through just pure happenstance and accidents, like earthquakes, floods, a volcano. Some traits will break off." Some will be favored, others not.

There's a story for humans in T. rex's evolution and conservation of energy. We should be discussing the virtues of small changes, Dececchi says, "through refinements in long-term utility over short-term extreme behaviors; that is, make it last rather than make it fast. This is not a new concept; heck, it's how things used to be when things were homemade or when we fixed things instead of bought new. I think it needs to make a comeback. As we start seeing more and more environmental impacts of our resource usage, we need to start thinking more on the years-to-decades-to-century scale rather than the hours-to-days-to-weeks scale. Perhaps engineers can start looking to nature not just to build a fast flier or a running robot dog, but how to make products that work day-in day-out for years to come."

MARK MACNAMARA is an Asheville, North Carolina-based writer. His articles for *Nautilus* include "We Need to Talk About Peat" and "The Artist of the Unbreakable Code."

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Mice on Acid

To get a legal hallucinogen to market, rodents need to take the first trip

BY CODY KOMMERS

PHOTOCOLLAGE BY TASNUVA ELAHI. ORIGINAL IMAGES: TOROOK / SHUTTERSTOCK; JOHN WILLIAMS RUS / SHUTTERSTOCK

IN THE BOWELS of an animal research facility at Oxford University, mice are stirring in cages. Half of them have been given an injection of saline solution and behave like the docile house pet of your local fifth-grader. The other half have been given DOI, a drug chemically similar to LSD, and are, as the term of art would have it, tripping balls.

What exactly a mouse sees when she's tripping on DOI—whether the plexiglass walls of her cage begin to melt, or whether the wood chips begin to crawl around like caterpillars—is tied up in the private mysteries of what it's like to be a mouse. We can't ask her directly, and, even if we did, her answer probably wouldn't be of much help.

But the signals that the tectonic plates of a mouse's reality are shifting beneath her feet are well-documented. Those are the signals that Merima Sabanovic, a neuroscience Ph.D. student at the University of Oxford, has been observing for the past year. The classic response is called, in the imaginative nomenclature of the neuroscientist, the "head-twitch." What Sabanovic observes is the mouse moving her head from side to side with a certain scientifically telling aplomb. The other signal that the mouse has wandered through the doors of veridical perception into the realm of untethered conception is the "wet-shakes," which is what your dog does on a summer day to dry off. When your paws extend mere centimeters from your body, there's only so much somatic recourse you have to fend off the closing in of a foreign reality.

MICE EXPERIMENTS BY SABANOVIC and her supervisors, David Bannerman and Jason Lerch, are part of a new wave of research into the clinical uses of psychedelic drugs. Humans have been journeying into the hinterlands of psychedelic logic for centuries, primarily for purposes of ritual and other ordeals of cultural significance. Scientific research into the neurological effects of psychedelics began in the middle of last century but was waylaid by bad trips and anti-drug culture warriors. But in the past decade, labs in England and the United States have revived serious research into hallucinogenic drugs and shown they can be useful in treating clinical conditions like depression, disorders resulting from obsessive-compulsions and post-traumatic stress, or even the inevitable face-off between death and patients with terminal illness.

Clinically speaking, one of the ways to think about these conditions—OCD, PTSD, depression—is in terms of rigid behavior, Sabanovic says. Obsessive compulsions are rigid performances of the same behavior over and over again. PTSD is a kind of inflexible openness to intrusive ideas and memories. And depression is a rigid adherence to negative forecasts about the future. So one of the ways that psychedelics could have therapeutic benefits is loosening up these rigid behaviors and unlocking more cognitive flexibility.

Sabanovic and her lab mates are seeking to find long-term neurological effects that would lead to an increase in cognitive flexibility. They are trying to determine whether a psychedelic therapy might work like

ONE PILL MAKES MICE SMALL And who knows, one pill may make them tall. Obviously we can't go ask a mouse what she's experiencing on a psychedelic drug. But neuroscientists in an Oxford University lab say the tripping mice are helping them conceive a promising therapy for mental disorders like PTSD.

an antidepressant, particularly an SSRI like Prozac. SSRIs are designed to tune the serotonergic system to the right pitch. Serotonin is one of the brain's primary neurotransmitters, and the warp and weft of the neural networks that deal in serotonin have an influence on the subjective sensation of well-being and our cognitive functioning in mental systems such as memory. Sabanovic explains that psychedelics are serotonin receptor agonists, with their specific role being to activate a receptor called 5-HT_2**A**, which mediates subjective experiences. A psychedelic drug upends typical communication among brain cells, the result of which, in perception and behavior, scientists are trying to map.

One big question for Sabanovic is "whether anatomical plasticity can persist weeks after the initial injection," she says. "We'd like to know whether we can find evidence of long-term improvements in cognitive flexibility as a result of a single dose." How do the tripping mice help? "The rodent model enables us to control variables which would be difficult or impossible to manipulate in human clinical setting, with things like prior drug exposure, and emotional and environmental context of drug injections," she says. "If someone walks into a clinic, you don't know what happened to them earlier that day. It could be anything. With mice, we can control that and study the exact after-effects and way they respond in the long term."

Sabanovic's most recent studies have looked at "set and setting." This is the wisdom that the quality of a trip is affected by what's going on around the person while she's under the effect of the drug. When people report having a bad trip, it's usually due to the negative influence of set and setting. "That's what I'm trying to incorporate in my studies," says Sabanovic. "If we manipulate the context, can we manipulate the sensitivity to the drug or its long-term effects?"

Most animal studies of psychedelics have failed to consider the animal's context at all. In Sabanovic's studies, the concrete way of measuring these effects is to look at whether "the degree of head twitches is different if you're in a novel context versus a familiar one." A drug trip is a disconcerting experience whether you're a human or mouse, and so researchers might expect that shifting the environment mid-trip causes more subsequent head twitches in the mouse. This would imply a higher level of anxiety, modulated purely by changing the context and not the dosage of the drug. Based on Sabanovic's preliminary results, this effect appears to hold.

GETTING A HALLUCINOGENIC DRUG to market stirs a new brew of challenges. An animal model is needed to pave the way to drug approval. Federal drug administrations are looking for drug efficacy, a clear relation between how much of a drug you give a patient and the behavioral response you get. But the idea of drug efficacy for psychedelics is murky. In fact, the whole pipeline is inverted.

Most drugs work by exacting a neurological shift. Fluoxetine, alias Prozac, works by preventing serotonin from getting sucked back up by the receptors whose job it is to act as a serotonergic Hoover. If you choreograph this dance of neurotransmitters just right, you can mitigate the effects of depression. The potential clinical benefits of psychedelics don't work by the same kind of mechanism. Their shift isn't neurological. It's experiential.

The puzzle is how to ask the FDA to approve a drug that implodes the illusion of self.

An example of this is the phenomenon of "ego disillusion" in humans. Post-trip, many people—at least those who have gone deep on the good stuff—report having experienced a disintegration of their sense of self. It is a state in which your subjective experience does not depend on a resolute "I" but just sort of becomes incorporated with the world as a whole. The center of gravity drops out from existence. Christof Koch, chief scientist of the Paul Allen Brain Institute in Seattle, recently told me about his own experience with ego disillusion.

"There was no more Christof," Koch said. "There was just nothing left except this non-self experiencing this icy light of unbearable intensity, and this feeling of terror and ecstasy—both things really combined." It's a fundamentally positive experience for most people. It can be valuable indeed for terminally ill patients to experience the cessation of their own existence and feel that everything can seem fine afterward.

The puzzle is how to go to drug administrators and ask them to approve your drug, which, you believe, implodes the illusion of self in humans, based on a bunch of head-twitching, wet-shaking mice, staring up at the mesh sky of their enclosure like it's a laser show. How would you even provide evidence of that in the brain? It's not that this experience doesn't have a neural basis. But you can't go into the brain and pluck out the experience, just like you can't identify the neural locus of a particular memory, *Inception*-style, even though a memory is a neural phenomenon.

For Sabanovic, the puzzle only has the edges in place so far. Perhaps there's a yet-to-be-found piece, she says, that fills in the picture between the brains of rodents and the experience of humans. Either way, the clinical implications of understanding these experiential shifts, such as ego disillusion, are clear. "It's hard to grasp what that experience is," Sabanovic says. "But I think it forces us to shift away from that belief that there's a drug—there's a magic pill—that you take every day, and it'll make you happy. It'll make you healthy. And it forces us not to look at drug efficacy but rather experience efficacy."

The problem is that drug administrations don't speak the language of experience efficacy. They can only understand things in terms of their neurological basis. It's the long-term deliverable in the vision of neuroscientists like Sabanovic to articulate how all this works in the brain. In the fullness of time, they want to show the FDA a link between drug doses, the tidal changes of neurotransmitters, and the resultant clinical outcomes. But in the meantime, the main thing they have to show is mice doing the waggle dance.

CODY KOMMERS is a Ph.D. student in experimental psychology at Oxford. He is the host of the Cognitive Revolution podcast. His last article for *Nautilus* was "We Are All Ancient Mapmakers." @codykommers

The Idea of Entropy Has Led Us Astray

Let's stop hustling as if the world is running toward disorder

BY AARON HIRSH

ROHANE HAMILTON / SHUTTERSTOCK

LAST SUMMER, IN THE EARLY DAYS of a heat wave that would culminate in the highest temperatures ever recorded in Paris, I biked across the city to meet my friend Romain Graziani. At a sidewalk café, we sipped burnt espresso and watched the air shimmer weirdly over the cobbles. Romain, who is a scholar of ancient Chinese texts, shared an idea that had emerged from his research: There are certain goals that are most effectively pursued by not striving directly toward them. Like falling asleep, for instance. If you try hard at it, you will not succeed. The same could be said about making a lay-up in basketball, hitting a backhand in tennis, or looking natural in a photograph. There are also, Romain suggested, examples that are more profound and consequential.

Several days later, the mercury had climbed a few degrees higher, and I was on the phone with Phil Taylor, a biogeochemist who has largely abandoned his academic career to work toward reform in industrial agriculture. He was telling me about the great quantity of carbon emissions that can be avoided when broad-acre farmers choose to plant perennials instead of annuals. The roots and microbes of perennials keep organic carbon and nitrogen locked in, whereas the incessant tilling required to grow annuals lets those precious compounds escape.

“These diligent farmers hit the soil so often and so hard,” Taylor said, “the flywheel of ecology can’t get spinning. They’re just so damn hard-driving.”

After the call, I tried to turn back to my writing. I happened to be working at the time on a book chapter about classical thermodynamics. You might remember something about the augustly named "Laws of Thermodynamics" from a high-school physics course. As usually presented, these laws say physical systems naturally dissipate energy and flow toward a state of cold disorder. From where I sat now, however—in an intolerably hot attic, peering out at a three-dimensional puzzle of zinc roofs gleaming in the sun—it was hard to feel the intuition behind such thermodynamic legislation. To the contrary, for the first time it struck me: What a remarkably strange view of the world. And I found myself wondering, in something of a fever-dream: Where did we ever get such a notion? And might it have something to do with why we're so damn hard-driving, even when there could be another way?

BY RETURNING TO THE VICTORIAN ORIGINS of the laws of thermodynamics, we can see how—and, perhaps, why—those laws have been broadly misconstrued and misapplied. In the 19th century, the first textbooks on the science of thermodynamics emerged from the work of Rudolf Clausius, in Berlin, as well as William Thomson (often called Lord Kelvin) and William Rankine, both in Glasgow. Studying how machines, such as steam engines, could exchange heat for mechanical work and vice-versa, these physicists learned of strict limits on efficiency. The best a machine could possibly do was to give up a small amount of energy as wasted heat. They also observed that if you had something that was hot on one side but cold on the other, the temperature would always even out. Their results were synthesized in the first two laws:

> I. The change in the internal energy of an isolated thermodynamic system is equal to the difference between the heat supplied to the system and the amount of work done by the system on its surroundings.

> II. Heat cannot spontaneously flow from a colder body to a hotter body. Or, phrased in terms of Clausius' new concept of entropy, the total entropy of an isolated system will increase over time.

What if we had a different ur-myth about energy and order in the universe?

Thermodynamics was extremely useful science for a society in the throes of rapid industrialization and a shift toward a capitalistic free market. The laws and their extensions could be applied to improving the engines driving advances in productivity. Just as importantly, they could be phrased in broad terms that were ideologically aligned with the cultural transformation underway, from an agrarian community of smallholding farmers to an urban society of wage-earning factory workers. For example: You never get anything—energy or work—for free. (On a small farm, in a hospitable climate, you sometimes do; as a factory-worker, you definitely don't.) Or: Without the input of energy through work (and perhaps combusting coal) a system tends naturally toward cold and disorder. I do not mean to imply that there was something scientifically dubious about the research behind the laws, only that it was neither accidental nor inconsequential that they developed amid—and were articulated in terms reflective of—the broader social transformation that was underway.

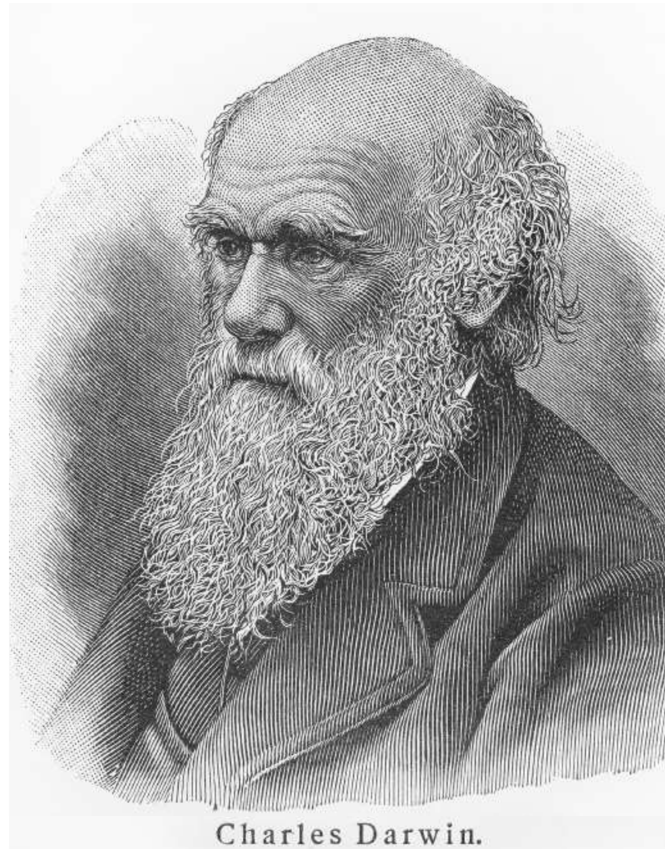
An illuminating parallel for such social embeddedness can be found in Darwin's work. Many historians have noted the intimate connection between the theory of natural selection and the ascendant political and economic views of the society in which Darwin was a well-placed member. The Victorian elite were committed to the idea that the unfettered competition of Adam Smith and David Ricardo's free market would drive economic and social advancement. In Darwin's theory, they found nature's own reflection of the social system they favored. As J.M. Keynes put it, "The principle of the survival of the fittest could be regarded as a vast generalization of the Ricardian economics."

Yet while this observation has often been made in relation to Darwin's work, the theory of thermodynamics has largely escaped similar contextualization. Perhaps physics, in all its rigors, is deemed less susceptible to social involvement. In truth, though, Darwinian and thermodynamic theories served jointly to furnish a propitious worldview—a suitable ur-myth about the universe—for a society committed to laissez-faire competition, entrepreneurialism, and expanding industry. Essentially, under this view, the world slouches naturally toward a deathly cold state of disorder, but it can be salvaged—illuminated and organized—by the competitive scrabble of creatures fighting to survive and get ahead.

AS WITH DARWIN'S WORK, the extension of thermodynamic theory into areas where it did not strictly apply has often led to faulty conclusions. William Thomson himself stumbled into this pitfall when he tried to estimate the age of the Earth. It was a fraught and momentous question—How old is the planet?—because Darwin had just published *On the Origin of Species*, and the evolutionary process he had proposed required great stretches of time to produce the diverse and exquisite structures of plants and animals. In truth, no one had yet developed those elements of evolutionary theory that permit a well-informed estimate of how long the evolution of life on Earth must have taken. Yet somehow, Darwin had a sense, and he figured it must have taken at least a billion years.

Charles Darwin and Lord Kelvin are invariably memorialized as white-bearded, beetle-browed sages; it is as if they were only ever old. But at the start of this debate about the age of the Earth, Darwin was 50 and Thomson under 40, decades away from being ennobled as Lord Kelvin. Nonetheless, Thomson was already recognized as a founder of thermodynamics, a theory that was quantitative where Darwin's was narrative, and predictive where Darwin's was descriptive. A number from Thomson, young as he was, would carry a weight of authority.

Based on measurements made in mines, Thomson knew that the deeper you went, the hotter it got—precisely the observation one would expect if the Earth had once been very hot and had been cooling off ever since. The flux of heat from a hot sphere was a process thermodynamics could describe with precision, so Thomson wrote down a model and asked: If the globe



HEATED DEBATE Darwin got swept up in a debate about the age of the Earth with William Thomson, aka Lord Kelvin, an architect of the science of thermodynamics. Darwin was aghast at Thomson's prediction, which didn't provide near enough time for natural selection to have occurred.

NICKU / SHUTTERSTOCK

Let's add a fourth law: There is no such thing as an isolated system.

had once been molten, how long would it take to cool to its present temperature? Between 20 and 400 million years, he calculated. The wide range indicated a great deal of uncertainty, but even so, Darwin was aghast. Thomson's estimate was between two and 50 times smaller than what Darwin figured natural selection needed. Something had to be wrong, Darwin wrote to his friends, but he didn't know what was wrong—and this was Thomson he was contradicting.

In fact, of the three great sources of heat in the Earth's interior, Thomson had underestimated one and missed two altogether. The one he had underestimated was the heat originally generated by the planet's formation—the process of growth by aggregation, which had been driven by energy embedded in the gravitational field. The two sources of heat he had overlooked completely were the friction generated by the flow of molten material inside the Earth and, more famously, radiation. Thomson had no way of knowing that certain elements in the Earth steadily leaked energy, for the phenomenon of radioactive decay had not yet been discovered. To this day we do not know exactly how important this omission was, because we do not know how much radioactive potassium, uranium, and thorium is hidden deep in the Earth. But we are sure it is enough to add significantly to Earth's core temperature.

BROADLY SPEAKING, THOMSON OVERLOOKED great stores of energy and sources of heat. Consequently, he thought the Earth had cooled a lot faster than it really had, leading him to underestimate the planet's age. It was the first law, the one that defines a complete accounting of energy in a closed system, that Thomson himself overextended. But the same basic error—energy overlooked—has led to a great many mistaken applications of the second law, as well.

Phrased frequently—and loosely—in terms of disorder and its tendency to increase, the second law of thermodynamics has been invoked to explain why organisms age, why societies collapse, and why evolution requires divine intervention. Leaving aside the problems with thinking of thermodynamic entropy as disorder, the important and basic point is that input of energy can reduce entropy (or disorder), and energy, as we've seen, is absolutely all over the place. The energy-driven reduction of entropy is easy to demonstrate in simple laboratory experiments, but more to the point, stars, biological populations, organisms, and societies are all systems in which energy is routinely harnessed to generate orderly structures that have lower entropy than the constituents from which they were built. There is nothing physically inevitable about increasing entropy in any of these systems.

In almost every erroneous overextension of the first and second laws, one word marks the crux of the error. The laws refer to an *isolated* system. The idea is that nothing enters or leaves, comes or goes, without being accounted for. We can create models of isolated systems in a laboratory, but even these are only approximations—and not only, as our first thought might be, because a bit of energy is bound to sneak away. They are inevitably approximate also because our world is brimming with energy: There is residual heat that can never be perfectly removed. There is energy sequestered in nuclei by stars and cosmic radiation left over from the Big Bang. There is a ubiquitous energetic fizz of quantum pair production, which may be responsible for driving the universe's accelerating expansion. And certainly, in everyday life, outside the hermetic enclosures of a laboratory, we are never even close to the realm of isolated systems.

For these reasons, we might consider adding a law. The first and second we've just seen, and the third slot is taken by the relation between temperature and entropy, so let's call this the fourth law of thermodynamics:

IV. There is no such thing as an isolated system.

Granted, our new law places draconian limits on the strict applicability of the first and second, but they will remain as useful as ever for calculations of the idealized or approximate variety. We're just keeping in mind that they are never exactly right. This is important, because for all the overextensions of thermodynamics that are flagged by explicit reference to the first or second law, there are others in which our underlying sense of the world, shaped as it is by popularized versions of Victorian science, leads us dangerously astray.

Thermodynamic theories served a society committed to laissez-faire competition.

THINKING OF ENERGY AND ORDER as naturally dwindling scarcities that we must drum up through our ingenuity and hustle—or, perhaps it would be more accurate to say, *feeling* this way about them—it is difficult for us to comprehend and respond to a historical moment in which the gravest threat is not scarcity but superabundance. Not that we will run short of energy, but that we will burn ourselves up in various ways.

Climate change is the obvious example. In our industrious activity, we are utilizing so much molecularly stored energy that we are altering the physical chemistry of the atmosphere. But there are other examples, too. The manufacture of industrial fertilizer can be thought of in energetic terms. Great quantities of energy, mainly in the form of natural gas, are used in a reaction that breaks the extremely stable triple bond of atmospheric nitrogen, N_2, in order to produce a molecule where nitrogen resides in a less stable, higher-energy state. The problem is that these newly minted molecules of reactive nitrogen are in enormous excess all over the place. They flow into the ocean, hyperfertilizing cyanobacteria, which bloom, consume all available oxygen, and create large dead zones. From poisoned water at the surface, the reactive nitrogen sinks to the bottom, and when this water cycles back up, decades later, the molecular products of all that nitrogen will be released into the atmosphere. These products—mostly nitrous oxide—are roughly 300 times more effective at trapping heat than carbon dioxide. In short, we are loading the deep ocean with a ticking climate bomb, which our children and grandchildren will somehow have to defuse.

What if we had a different ur-myth about energy and order in the universe? Imagine, for instance, that our intuitions were still informed more by that world of agrarian smallholders, and less by the industrialized cultures that eclipsed it. Letting our worldview shift further still, we could combine such a retrieval of our deeper past with an appreciation of the highly modern. Imagine, that is, a sense of energy informed not by Victorian science but by more recent physics—from cosmic background radiation to the quantum effervescence of space itself. And imagine, too, a feeling for order that derived less from loose notions of entropic decline, and more from recent work on physical self-organization or the way organisms adaptively harness tiny changes in entropy to drive productive chemical reactions.

Imbued with such a worldview, moved and directed by it much as the Victorians were influenced by thermodynamics and Darwinism, we might think and act less in the vein of industrial agriculture, with its mining of natural gas and unidirectional spill of energy. We might be more inclined to let the flywheel of ecology get spinning and investigate the potential allowances of regenerative agriculture. More generally, perhaps we would begin to see that part of the solution to our planetary crisis lies not in hustle, but in repose. Not in catching the next trans-Atlantic flight to an important conference or meeting, but in staying home, contentedly. Not in buying a new more efficient car, but in leaving the old one parked. Perhaps there are many solutions that do not even occur to us, because they resemble passivity rather than action, and we are so deeply trained to hustle.

AARON HIRSH is a writer and biologist with strong interests in education, evolution, and the environment. Before the heat got much worse, he moved back to Boulder, where he now lives with his family. For the record, he thinks very highly of both Darwinian and thermodynamic theory.

How Science Trumps Denial

Scientists putting their career and health on the line can take heart from Galileo

BY MARIO LIVIO

THERE'S AN OLD BELIEF that truth will always overcome error. Alas, history tells us something different. Without someone to fight for it, to put error on the defensive, truth may languish. It may even be lost, at least for some time. No one understood this better than the renowned Italian scientist Galileo Galilei.

It is easy to imagine the man who for a while almost single-handedly founded the methods and practices of modern science as some sort of Renaissance ivory-tower intellectual, uninterested and unwilling to sully himself by getting down into the trenches in defense of science. But Galileo was not only a relentless advocate for what science could teach the rest of us. He was a master in outreach and a brilliant pioneer in the art of getting his message across.

Today it may be hard to believe that science needs to be defended. But a political storm that denies the facts of science has swept across the land. This denialism ranges from the initial response to the COVID-19 pandemic to the reality of climate change. It's heard in the preposterous arguments against vaccinating children and Darwin's theory of evolution by means of natural selection. The scientists putting their careers, reputations, and even their health on the line to educate the public can take heart from Galileo, whose courageous resistance led the way.

A crucial first step, one that took Galileo a bit of time to take, was to switch from publishing his findings in Latin, as was the custom for scientific writings at the time, to the Italian vernacular, the speech of the common people. This enabled not just the highly educated elite but anyone who was intellectually curious to hear and learn about the new scientific work. Even when risking offense (which Galileo never shied away from)—for instance, in responding to a German Jesuit astronomer who disagreed with him on the nature of sunspots (mysterious dark areas observed on the surface of the sun)—Galileo replied in the vernacular, because, as he explained, "I must have everyone able to read it." An additional motive may have been that Galileo wanted to ensure that no one would somehow distort the meaning of what he had written.

Galileo also understood that while the Church had the pomp and magic of decades of art and music, science had the enchantment of a new invention—the telescope. Even he wasn't immune to its seductive powers, writing in his famous booklet *The Sidereal Messenger*: "In this short treatise I propose great things for inspection and contemplation by every explorer of Nature. Great, I say, because of the excellence of the things themselves, because of their newness, unheard of through the ages, and also because of the instrument with the benefit of which they make themselves manifest to our sight. " And that gave him his second plan for an ambitious outreach campaign.

MARIO BREDA / SHUTTERSTOCK

With alternative facts acting like real facts, there are Galileo's heirs, throwing up their hands at attempts to make lies sound like truth.

What if he could distribute telescopes (together with detailed instructions for their use and his booklet about the discoveries) all across Europe, so that all the influential people, that is, the *patrons* of scientists—dukes and cardinals, could observe with their own eyes far out into the heavens. They would see the stunning craters and mountains that cover the surface of the moon, four previously unseen satellites of Jupiter, dark spots on the surface of the sun, and the vast number of stars that make up the Milky Way.

But telescopes were both expensive and technically difficult to produce. Their lenses had to be of the highest quality, to provide both the ability to see faint objects and high resolution. "Very fine lenses that can show all observations are quite rare and, of the more than sixty I have made, with great effort and expense, I have only been able to retain a very small number," Galileo wrote on March 19, 1610. Who would front the cost of such a monumental and risky project?

Today the papacy is arguably the single most influential and powerful religious institution in the world. But its power is mostly in the moral and religious realms. In Galileo's time, the papacy was a political power of significance, gobbling up failed dukedoms elsewhere, merging them into what became known as the "papal states." The persons with the greatest interest in appearing strong in front of the papacy were the heads of neighboring states at the time.

So it is not surprising that Galileo presented his grandiose scheme to the Tuscan court and the Grand Duke Cosimo II de' Medici. Nor is it surprising that Cosimo agreed to finance the manufacturing of all the telescopes. On his own, he also instructed the Tuscan ambassadors to all the major European capitals to help publicize Galileo's discoveries. In doing so he tied the House of Medici, ruler of the foundational city of the Renaissance, Florence, to modern science. A win-win for both the Grand Duke and Galileo.

Last, Galileo instinctively understood what modern PR specialists refer to as the "quick response." He did not let even one unkind word be said about his discoveries without an immediate reply. And his pen could be sharp.

For example, the Jesuit mathematician Orazio Grassi (hiding behind the pseudonym of Sarsi) published a book entitled *The Astronomical and Philosophical Balance*, in which he criticized Galileo's ideas on comets and on the nature of heat. In it, Grassi mistakenly thought that he would strengthen his argument by citing a legendary tale about the ancient Babylonians cooking eggs by whirling them on slings.

Really?

Galileo responded with a stupendous piece of polemic literature entitled *The Assayer*, in which he pounced on this fabled story like a cat on a mouse.

"If Sarsi wishes me to believe, on the word of Suidas [a Greek historian], that the Babylonians cooked eggs by whirling them rapidly in slings, I shall believe it; but I shall say that the cause of this effect is very far from the one he attributes to it," he wrote. " To discover the true cause, I reason as follows: 'If we do not achieve an effect which others formerly achieved, it must be that we lack something in our operation which was the cause of this effect succeeding, and if we lack one thing only, then this alone can be the true cause. Now we do not lack eggs, or slings, or sturdy fellows to whirl them, and still they do not cook, but rather cool down faster if hot. And since we lack nothing except being Babylonians, then being Babylonian is the cause of the egg hardening.'"

Did Galileo's efforts save science from being cast aside perhaps for decades, even centuries? Unfortunately, not quite. The trial in which he was convicted by the Inquisition for "vehement suspicion of heresy" exerted a chilling effect on progress in deciphering the laws governing the cosmos. The famous French philosopher and scientist René Descartes wrote in a letter: "I inquired in Leiden and Amsterdam whether Galileo's *World System* was available, for I thought I had heard

STAND UP FOR SCIENCE Participants in the annual March for Science make Galileo proud, protesting those in power who have devalued and eroded science. (Above: Washington, D.C., 2017)

BAKDC / SHUTTERSTOCK

that it was published in Italy last year. I was told that it had indeed been published, but that all the copies had immediately been burnt in Rome, and that Galileo had been convicted and fined. I was so astonished at this that I almost decided to burn all my papers, or at least to let no one see them."

I suspect that there are still too few of us who can tell exactly what Galileo discovered and why he is such an important figure to the birth of modern science. But around the world, in conversations as brittle as today's politics, with alternative facts acting like real facts, there are Galileo's heirs, throwing up their hands at such attempts to make lies seem like the truth and worse, the truth like a lie, responding with just four words: "And yet it moves."

Galileo may have never really uttered these words. He surely didn't say that phrase in front of the Inquisitors—that would have been insanely dangerous. But whether the motto came first from his own mouth, that of a supporter whom he met during the years the Church put him under house arrest after his trial, or a later historian, we know one thing for sure. That motto represents everything Galileo stood for. It conveys the clear message of: In spite of what you may believe, these are the facts! That science won at the end is not solely because of the methods and rules that Galileo set out for what we accept to be true. Science prevailed because Galileo put his life and his personal freedom on the line to defend it.

MARIO LIVIO is an astrophysicist and author. His new book is *Galileo: And the Science Deniers*.

The Greatest Journey of All Time

How the first Americans made their way from Siberia to Patagonia

BY GILLEN D'ARCY WOOD

I**N THE SUMMER OF 1977**, on a field trip in northern Patagonia, the American archaeologist Tom Dillehay made a stunning discovery. Digging by a creek in a nondescript scrubland called Monte Verde, in southern Chile, he came upon the remains of an ancient camp. A full excavation uncovered the trace wooden foundations of no fewer than 12 huts, plus one larger structure designed for tool manufacture and perhaps as an infirmary. In the large hut, Dillehay found gnawed bones, spear points, grinding tools and, hauntingly, a human footprint in the sand. The ancestral Patagonians—inhabitants of Tierra del Fuego and the Magellan Straits—had erected their domestic quarters using branches from the beech trees of a long-gone temperate forest, then covered them with the hides of vanished ice age species, including mastodons, saber-toothed cats, and giant sloths.

Fire pits indicated where the Monte Verdeans cooked their food. Grinding stones helped fashion their spear points for hunting while, scattered on the excavated floor of the large hut, Dillehay uncovered the fossilized remains of more than 20 medicinal plants, including a species of giant kelp, *Durvillaea antarctica*. The species was discovered in the 1830s by explorer Jules-Sébastien Dumont D'Urville, who identified the indigenous giant seaweed during the first of his three Southern Ocean voyages on the beaches of the Falkland Islands, east of Tierra del Fuego. Because seaweed is short-lived, the *Durvillaea* fossil provided the most precise available date for human occupation of the site. Radiocarbon analysis of charcoal, worked wooden artifacts, and the leftover bones of a mastodon meal confirmed the presence of ice age hunter-gatherers at Monte Verde 14,500 years ago, at least 1,000 years prior to any existing archaeological evidence for human colonization of the Americas, North or South.

ESTEBAN DE ARMAS / SHUTTERSTOCK

The first Americans were beachcombers who followed the rich food source of kelp along the Pacific coast.

During his Beagle voyage into the south Atlantic Ocean in the 1830s, Charles Darwin wondered how the Patagonians had come to venture so far south, into sub-polar cold. D'Urville's giant kelp, it turned out, was a key to their southern passage. On the deck of the Beagle, when Darwin shook out the entangled roots of another giant kelp species ubiquitous in southern waters, *Macrocystis pyrifera*, he discovered a living zoo: from the microorganic coral incrustations decorating each frond to innumerable polyps, algae, mollusks, and crustacea to cuttlefish, crabs, starfish, sea eggs, crawling nereids, and schools of small fish of stunning variety. This marine banquet in turn fed the ever-present birds—the cormorants, albatrosses, and petrels that circled the Beagle—as well as otters, seals, and dolphins that crowded the bleak channels and islands of Tierra del Fuego. Contemplating this colorful menagerie, Darwin conjectured that nowhere else in the world did so many species depend for their existence on a single plant. These included the maritime peoples of Tierra del Fuego, who had adapted somehow to the sub-Antarctic cold and sustained themselves on fish and seal flesh garnished by dried tidbits of the seaweed itself. Were the keystone kelp to be destroyed, a mass extinction, including humans, would inevitably follow. Both *Macrocystis pyrifera* and *Durvillaea antarctica* were critical to the survival of the first people in the Americas. Their extinction, it turned out, had a more modern, pernicious cause.

WHEN MODERN HUMANS MIGRATED out of Africa around 60,000 years ago, they dispersed rapidly through Asia, and thence to Europe. Seafaring peoples hopscotched across the Pacific and reached Australia via a land bridge from Indonesia. But for tens of thousands of years, America remained terra incognita, barricaded by ice. In the 1930s, a site uncovered in New Mexico, called Clovis, suggested that early human hunters had penetrated south along an ice-free corridor no earlier than when the northern glaciers commenced their retreat 11,000 years ago. Once in the Great Plains, these first explorers discovered a rich array of megafauna—mammoths and mastodons—entirely unprepared for human aggression, and gorged themselves accordingly. It made for an arresting narrative: the first Americans were marauding big-game hunters who braved the ice and quickly established themselves as all-conquering apex predators of the New World.

KELP HIGHWAY Darwin marveled at the role that kelp played in marine ecosystems, housing a zoo of organisms that fed many others. The first Americans, dependent on marine life for survival, journeyed south along what could be called the Pacific Kelp Highway.

ANDREW B. STOWE / SHUTTERSTOCK

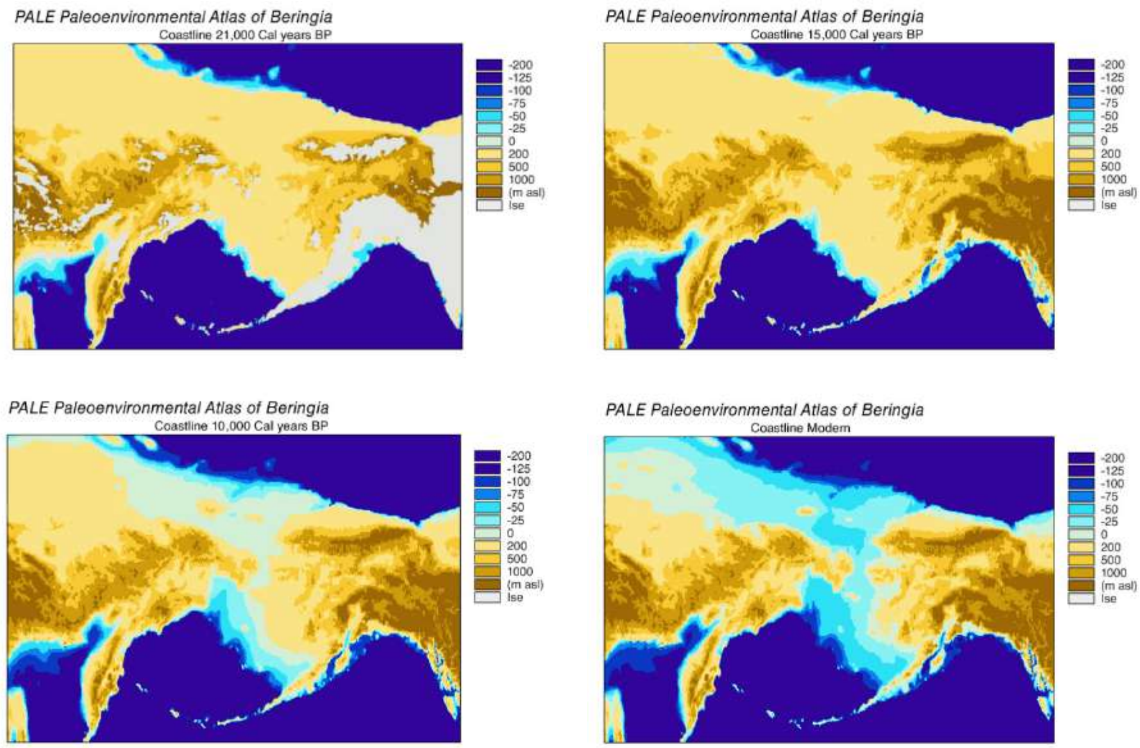
Dillehay's discoveries at Monte Verde in Chile shattered this theory and threw American archaeology into a period of bitter turmoil. With the emergence of the Monte Verdean foragers, an entire new history of human colonization of the Americas was required. Allowing some thousands of years for these pioneers to make their way from Siberia across the Beringia land bridge to the tip of South America—adjacent to the opposite pole from where they began—necessitated a first entry date of approximately 15,000 years before present. At this time, the glaciers of the last ice age were still near their maximum, and no ice-free corridor existed through the western plains of modern Canada. That left the unglaciated Pacific coast as the only possible migratory route. Instead of butchering their way into the heartland as big-game hunters, the first Americans were beachcombers—maritime opportunists who rafted the innumerable estuarine waterways of ancient California, living off the smorgasbord of sea creatures inhabiting the so-called kelp highway of the west coast.

All modern indigenous Americans can trace their ancestry to a single community in Siberia.

Unlike the inland corridor, this marine route for the first Americans was linear, unobstructed, and entirely at sea level. Giant seaweed forests—including *Durvillaea antarctica* and *Macrocystis pyrifera*—hosted protein-rich populations of giant sea bass, cod, rockfish, sea urchins, abalones, and mussels. A now-extinct species of sea otter offered variety to the first Americans' palate. The seaweed fragment of *Durvillaea antarctica* that Dillehay had found at Monte Verde signified more than an iodine-rich medicinal supplement for ancient hunter-gatherers. It was a clue to the entire history of American colonization, whereby the first humans had followed the rich food source of the kelp highway along the Pacific coast from Alaska to Chile. A rare clue, necessarily. The vast majority of the American kelp highway and its way stations—traveled when sea levels were up to a hundred meters lower than today—is now submerged beneath the Pacific Ocean.

Climate change had opened the highway south, but weather did not always cooperate with the first Americans. In fact, wild climate fluctuations of the Late Pleistocene epoch—some slingshot glaciations unfolding in the course of a human lifetime—made for a stressed, low-density community of humans who could boast of little more than heroic extreme-weather resilience. Thousands of years before D'Urville navigated the chill waters of the Straits of Magellan, the ancestral Fuegians had ventured into deep South American terrain released by rising temperatures and retreating glaciers. Monte Verde was one such frontier domain. But then, about 14,500 years ago, the climate pendulum swung back, catching the pioneers by surprise. The so-called Antarctic Cold Reversal—when average temperatures fell up to 6 degrees Celsius below present day—lasted two millennia, during which the ancient Americans huddled for survival in caves. When temperatures warmed again, the largest southern glacier outside Antarctica melted, flooding the Straits of Magellan, and cutting off the southernmost adventurers from the mainland. The cultural division of Patagonian peoples into mainland hunters and coastal canoeists—a mystery to the Victorian explorers Darwin and D'Urville—originated with this early Holocene warming 8,000 years ago.

AS CONTROVERSY OVER the new coastal migration theory raged through the 1990s, another discovery—at the polar opposite end of Earth—added to the glacial mystique of the first Americans. Near the River Yana, at 71°



BRIDGE TO A NEW WORLD The first Americans were climate warriors. Their ice age journey south began with a trek over the Beringia land bridge, seen here in several panels that illustrate its geological transformation from 21,000 years ago to today.

NOAA

north, above the Arctic Circle in Siberia, Russian scientists uncovered a hunting camp some 40,000 years old. The decorated horn of an extinct rhinoceros and detachable spear shafts anticipated the Clovis peoples of North America many millennia in the future. Meanwhile, genetic analysis concluded that all modern indigenous Americans can trace their ancestry to a single community in this very region of Siberia, perhaps a mere thousand strong.

Between Yana River and Monte Verde, transcontinental traces had now emerged of what was surely the greatest journey of all time. Over the course of 20,000 years, a small, intrepid human group somehow adapted to Arctic tundra conditions in the midst of an ice age, surviving –40 degrees Celsius temperatures *without* firewood in animal skin tents. No modern-day analogy exists for these climate warriors, which means we can't honestly guess how they coped. We then lose track of the Yana people for several hundred generations before their putative descendants' reemergence as fishermen-navigators, pushing southward along the Pacific coast into warmer climes, all the way to modern Chile. Then the glaciers rebounded, and a small frontier group was trapped south of latitude 55° and had to adapt all over again to polar extremes.

Darwin's question about how the Patagonians had come to inhabit the cold, wild tip of South America has been answered by the kelp highway theory. The marine cornucopia hosted by *Durvillaea antarctica* and *Macrocystis pyrifera* had lured the prehistoric Americans ever farther southward. Since then, Patagonian lifeways remained remarkably static: No leap to agriculture or cattle-rearing was possible in the sub-Antarctic landscape. But how the marooned Fuegians managed to survive the polar cold at the world's end for thousands of years—as their Yana forebears had done north of the Arctic Circle—continues to baffle and amaze.

Patagonian skulls provide an incomplete answer. D'Urville's official phrenologist, Pierre Dumoutier, failed to persuade his hosts to provide him with the craniums of dead relatives. But latter-day skull scientists—cranial morphologists—have identified cold-adaptive traits common to Fuegians and the Inuit of the Canadian Arctic. Freezing air is deadly to human lungs; hence the nostrils play a vital role in warming the breath before it bathes the tender membranes of the chest. Adapted to polar temperatures, the nasal cavities of the Fuegians and Inuit are the most capacious of all modern humans, allowing for maximum air turbulence and residence time for each inhalation. Fuegian skeletal remains nevertheless show marked evidence of temperature stress: these include chronic inflammation of bone tissue, arthritis of the back, and overworked masticating jaws, as well as osteomyelitis, in which bones become infected and "die"—all indicators of cold trauma. The Fuegians survived, but they suffered. Little wonder Patagonian oral history revolves around myths of glaciation and angry deities of freezing rain and storms.

FOR ALL THE PATAGONIANS' epic climate resilience, however, there was no surviving the European invasion. Five years after D'Urville's visit to the Straits of Magellan, the Chilean government sponsored its first settlements in Patagonia, setting the indigenous communities on a fast track to extinction. No biological remains exist to determine whether any other micro-evolutionary adaptations had enabled the Patagonians to endure for thousands of years south of latitude 55°. A fat-intense diet—dependent on the abundant seal population of the straits—must have been indispensable to their survival. It's possible that the emaciated condition of the maritime Fuegians, as D'Urville encountered them, was due to the already significant inroads of the European fishing industry on Southern Ocean seal populations. One species of fur seal—the *Arctocephalus gazella*— had already been wiped out on the neighboring South Shetland and South Georgia islands. Their Fuegian descendants who were not killed by measles, alcohol, or guns froze to death from lack of seal meat insulation.

European awe of the Patagonians resulted from a double sense of difference. They wondered at the natives' adaptation to the cold, while being humbled by their own intolerance for sub-Antarctic extremes. Hundreds of Spanish colonists had died of exposure and starvation in the Magellan Straits in 1583. They ate seaweed and mussels in imitation of the locals, but not enough guanaco or seal to keep out the cold. A decade later, Englishman Thomas Cavendish took the ship Roebuck into the same waters, where his men expired from "the extremity of frost and snow" at the rate of eight or nine a day. Cavendish deposited his hypothermic invalids on the beaches to die, while the remnant crew threatened mutiny from "their ardent desire of being out of the cold."

This physical intolerance for sub-Antarctic latitudes translated into great mental stress for all Europeans who ventured there, beginning with Magellan's mutineers, whom the explorer felt compelled to hang, draw, and quarter on deck as an example to the rest of his men to bear the cold without complaint. Francis Drake dealt similarly with a rebel officer on his own voyage around Cape Horn. Given the option to be marooned, face trial in England, or be beheaded on the spot, the shivering gentleman chose the ax. Darwin's discoveries in the South Atlantic created a blueprint for archaeologists to chart the amazing journey of the first Americans and map the unique kelp ecology that sustained them. But during the Beagle's first voyage to Patagonia in 1827-28, her captain, Pringle Stokes, became so despondent at the "dreariness and utter desolation" of the Straits of Magellan that he shot himself. This was a place, he wrote in his diary of Patagonian despair, where "the soul of man dies in him."

GILLEN D'ARCY WOOD is the author of *Land of Wondrous Cold: The Race to Discover Antarctica and Unlock the Secrets of Its Ice*. He is professor of environmental humanities at the University of Illinois, Urbana-Champaign, where he serves as associate director of the Institute for Sustainability, Energy, and the Environment. His previous book is *Tambora: The Eruption That Changed the World*. Originally from Australia, he lives in Urbana, Illinois, with his wife and two children.

Why Birds Can Fly Over Mount Everest

A story for my granddaughter about oxygen, evolution, and our planet's fate

BY WALTER MURCH

DEAR BELLA,

I'm going to imitate Rudyard Kipling and tell you a just-so story. Kipling was one of the most popular writers in the world 100 years ago. He wrote *The Jungle Book*. And also *Just So Stories*, which began as bedtime stories he told his daughter Josephine. They were about how animals got their famous features, like the camel's hump and the leopard's spots. Kipling was a wonderful writer but he made up his animal stories. My story is based on science, which means many people, through many recent experiments, have concluded things might "just so" be the way of this story.

It's also a story about evolution, which is nature's research and development department. Like Kipling, I've given a human voice to certain things: Bacteria form committees and petition the research and development department for answers to their problems, as do plants and dinosaurs. And the R&D department (which is to say, evolution) tries to come up with solutions. I'm going to call evolution "Mr. R&D." When he finds a problem, Mr. R&D tests things out in different ways to come up with a solution. But sometimes those solutions have unforeseen consequences. So here we go!

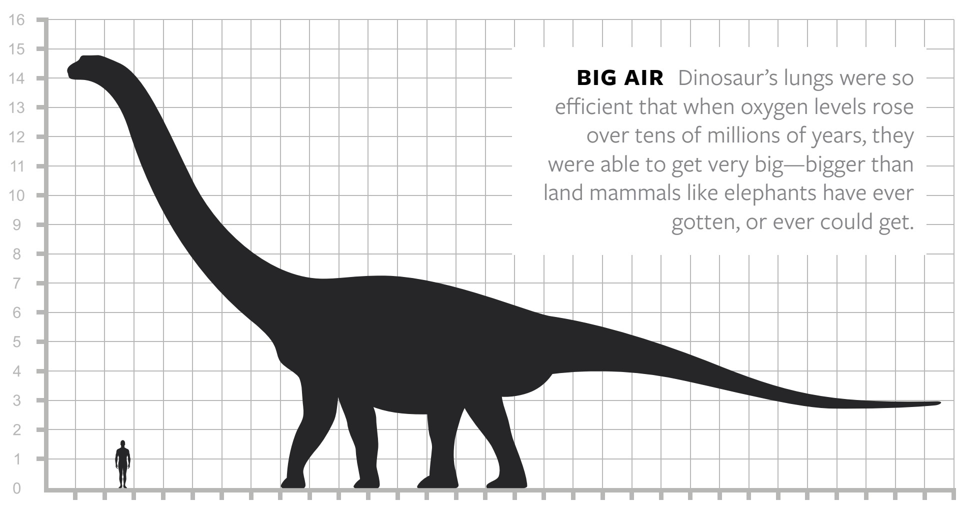
NITIN CHANDRA / SHUTTERSTOCK

Once upon a time, on a cold day in January, I was jogging through Regent's Park in London, stepping carefully through flocks of geese, seagulls, pigeons, and ducks surrounding the boating lake. But, perhaps because of the book I had just been reading (Nick Lane's *Oxygen*) my eye picked out a couple of geese that were strangers in this flock: Bar-headed geese, a boy and a girl.

But what were they doing in London in January? During the winter, they usually live in the middle of India, and in the summer they live in Kazakhstan or Mongolia. If you look at a map of the Earth, you can see the barrier between Kazakhstan and India is the Himalayan Mountain Range, the tallest in the world. Every year, millions of bar-headed geese migrate over the Himalayas and have been doing so for millions of years. They have been seen flying at 28,000 feet. They have flown over Mount Everest! How do they do that?

The answer seems to be that bar-headed geese, like all birds—hummingbirds, ostriches, pigeons—have super-efficient lungs. It makes our lungs—and the lungs of all mammals—look primitive. I'm sure when birds get together they gossip about how pathetic our lungs are!

All mammals, including us, breathe in through the same opening that we breathe out. Can you imagine if our digestive system worked the same way? What if the food we put in our mouths, after digestion, came out the same way? It doesn't bear thinking about! Luckily, for digestion, we have a separate in and out. And that's what the birds have with their lungs: an in point and an out point. They also have air sacs and hollow spaces in their bones. When they breathe in, half of the good air (with oxygen) goes into these hollow spaces, and the other half goes into their lungs through the rear entrance. When they breathe out, the good air that has been stored in the hollow places now also goes into their



BIG AIR Dinosaur's lungs were so efficient that when oxygen levels rose over tens of millions of years, they were able to get very big—bigger than land mammals like elephants have ever gotten, or ever could get.

VECTORPLOTNIKOFF / SHUTTERSTOCK

lungs through that rear entrance, and the bad air (carbon dioxide and water vapor) is pushed out the front exit. So it doesn't matter whether birds are breathing in or out: Good air is always going in one direction through their lungs, pushing all the bad air out ahead of it.

How did birds get such great lungs? They inherited them from dinosaurs. Birds are dinosaurs! When I was growing up in the 1940s, there was a category in biology called Aves, which meant birds. But scientists have now folded Aves into a category called Dinosauria, and those dinosauria, like pigeons and seagulls and geese, are flying all around us today. If you want to know what a dinosaur probably tasted like, eat some chicken!

So, dinosaurs had this super-efficient lung system, and they successfully strode the Earth as the dominant species, starting around 250 million years ago to about 65 million years ago, when a huge asteroid crashed into Mexico and most of them went extinct. Except for birds. But why did dinosaurs have this super lung system in the first place?

How did birds get such great lungs? They inherited them from dinosaurs. But why did dinosaurs have them?

To answer that, we have to go way back, to when plants came out of the ocean onto land, about 450 million years ago. Earlier than that, plant life lived only in the ocean: The surface of the Earth was a desert.

Seeing an opportunity, some pioneer plants got together and said, "Let's go!" and migrated up onto land. But once the plants got out of the water, they discovered something they never had to deal with in the ocean: gravity. In the ocean, if you're a plant, you can just float, because the density of a plant is not that different from water. Out of the ocean, the density of a plant is much greater than air, and so gravity can pull it down.

So for many tens of millions of years, plants on land had to be happy sticking like moss to the surfaces of rocks. But they clearly resented this, and decided to form a committee to request an exemption from Mr. R&D.

BUG OUT Around 300 million years ago, there was so much oxygen that insects, who have inefficient ways of breathing, were able to get huge. Dragonflies (seen here in a lifesize model in Italy) had a wingspan of about three feet.

LIFE_IN_A_PIXEL / SHUTTERSTOCK

MR. R&D: Hello. What's your problem?

PLANT COMMITTEE: Our problem is gravity. We never had to deal with it in the ocean, and it's a problem for us on land.

MR. R&D: Why is gravity a problem for you?

PC: We want to do what we did in the ocean, which is absorb lots of sunlight, and the best way to do that is to have a long stalk, and then to have branches with leaves at the end of the branches and maximize our potential to absorb sunlight.

MR. R&D: I understand what you want, but it will take me some time. Come back in a million years or so.

The plants twiddle their thumbs for a million years.

PC: OK, a million years is up! Did you manage to discover something?

MR. R&D: Yes, let me see, I think I have it in the drawer. Here it is: lignin.

PC: What's lignin?

MR. R&D: It's a rigid molecule made of carbon and hydrogen. If you absorb it into the cells of your body, it will interact with the molecules of floppy cellulose you already have, and this will create a very firm structure that will allow your cells to become like bricks. You can then stack one cell upon the other, and you can go as high as you want.

PC: How high?

MR. R&D: Over 300 feet.

PC: Wow!

Plants on land had to be happy sticking like moss to the surfaces of rocks. But they clearly resented this.

So the plants happily swallowed the lignin, and sure enough, it worked exactly as Mr. R&D said, and within a short time stalks, trunks, branches, roots, leaves began popping up all over the Earth.

The only problem was that when one of these trees reached the end of its natural life, bacteria and fungal spores got ready to decompose it, sharpening their knives. But when they got to the lignin, their knives stuck: They couldn't digest the lignin. The very thing that made lignin strong defeated the bacteria and fungi back then. So, they did what we do when we eat a chicken dinner: They ate all the meat and left the bones, which is to say: the lignin.

Eventually another tree would die and fall on top of the first, and then the same thing would happen again, and another and another, and it kept going like this for hundreds of thousands, millions, tens of millions of years. In the end, over 100 million years of dead trees and ferns and undigested lignin were deposited under the surface of the Earth. We call the time when most of this happened the Carboniferous (carbon-making) age.

Remember how evolution sometimes has unforeseen consequences? Well, this deposit of lignin produced an oxygen surge in the atmosphere. Because for every hydrocarbon atom that goes into the Earth, an oxygen atom is not used up in the decay process. Massive amounts of carbon (lignin) were going into the Earth, so massive amounts of oxygen were building up in the atmosphere. Today, oxygen is 21 percent of the atmosphere. But around 300 million years ago, oxygen was well over 30 percent. There was so much oxygen that insects, who have very inefficient ways of breathing, were able to get huge. Dragonflies had a wingspan of three feet, millipedes were eight feet long. Amphibians—frogs and such—also have inefficient lungs, and they were able to get as big as dining room tables.

The microorganisms of the time eventually became aware of this surge in oxygen. The insects and the amphibians didn't seem to care, because they were dependent on that rich source of oxygen. So the now-worried microorganisms got their committee together and went to see Mr. R&D.

MR. R&D: Hello, what I can do for you?

MICROORGANISM COMMITTEE: We think there is a dangerous situation developing, because oxygen levels have gotten higher every year and they might now be at 35 percent.

MR. R&D: So?

MC: With indigestible lignin, there is nothing to keep it from continuing to go up.

MR. R&D: I see your point, because at 43 percent a lightning strike will cause the entire atmosphere to ignite since it is so high in flammable oxygen. And the whole experiment of life on Earth will be over. Yes, I agree we have to do something. Give me a million years and I'll see what I can do.

For a million years, oxygen levels continue to rise. The even more worried microorganisms come back to Mr. R&D.

MR. R&D: The bad news is I don't have anything physical to give you. But I can give you a koan.

MC: What's that?

MR. R&D: A koan is something you can think of that will help you in your situation. Here it is: "To receive you must first give."

MC: What does that mean?

MR. R&D: All I can tell you is: Think about it, and it will solve your problem.

So the microorganisms go away and debate about what this means for 10,000 years or so. Finally, there is one genius fungal cell that wakes up in the middle of the night and thinks, "I've got it!" For all of these 100 million years, since the invention of lignin, they had been trying to chew it, and they simply didn't have the ability to do that: It is too hard and they were too soft.

But thanks to this Isaac Newton of a mushroom spore, they realized what they had to do. They had to give off a special chemical enzyme that dissolves the lignin and breaks it up into smaller pieces externally. And so they invented dry rot.

The decay process pulls oxygen out of the atmosphere and binds it to the hydrocarbons, releasing carbon dioxide (CO_2) and water (H_2O) as a result. This is what happens when wood burns (very rapid oxidation), when we digest food (moderate oxidation), and when organic material decays (slow oxidation).

Once the secret of how to oxidize lignin was understood, fungal spores and bacteria began to break down all the dead wood that was not already

Thanks to this Isaac Newton of a mushroom spore, they realized they had to give off a special enzyme.

fossilized, using up oxygen in the process, and so the level of oxygen in the atmosphere began to decline rapidly. It went from a high of above 30 percent during the Carboniferous Period (300 million years ago) to around 12 percent at the end of the Permian Period (250 million years ago). This was bad news for most of the life on Earth, because it had gotten addicted to this abnormally high oxygen level. Ninety-five percent of all life on Earth died—strangled by an atmosphere so low in oxygen. It was the largest extinction event in the history of life on Earth.

Some of the 5 percent of life forms that did manage to survive went to Mr. R&D and, using what breath they had left, said, "We need help to survive on this small amount of oxygen."

And, 5 million years later, which is the time it took to design this very complicated thing, Mr. R&D came up with a lung system with both an entry point and an exit point, with hollow bones and air-sacs to temporarily store oxygenated air. It was super-efficient compared to any previous lung system and made the best use of the limited oxygen. The animals that received this gift from Mr. R&D were the dinosaurs.

Their new lungs were so efficient that when oxygen levels crept slowly back up to 20 percent over the next many tens of millions of years, dinosaurs were able to get very big—bigger than land mammals like elephants have ever gotten, or ever could get. The super-efficient lungs of many dinosaurs could deliver oxygen to every part of their massive bodies. And having hollow bones helped to reduce their overall weight. When birds evolved from dinosaurs they were able to make very good use of this super-efficient lung system. So that's how dinosaurs got so big and why bar-headed geese can fly over the Himalayas!

The End.

Or that should be the end. But we have one more character to introduce, and that's Mr. VCP (Very Clever Primate). About 400 years ago, Mr. VCP found that he could dig down below the surface of the Earth and extract this fossilized lignin, which had turned into coal—and burn it to release the energy that was trapped when it was first deposited. This allowed Mr. VCP's civilization and population to grow at a phenomenal rate. It was a happy success story once upon a time. Now it has started to become a big problem.

DRY ROT Once fungal spores and bacteria began to break down all the dead wood that was not fossilized, using up oxygen in the process, the level of oxygen in the atmosphere began to decline rapidly.

JNIX / SHUTTERSTOCK

Ninety percent of all the fossil fuels—coal, oil, gas—that we burn today were deposited during the Devonian, Carboniferous, and Permian periods. All that hydrocarbon is now being released into the atmosphere.

So Mr. VCP's entire civilization is based on burning fossil fuels, which is the result of a quirk in the structure of lignin, and the inability of microorganisms—bacteria and fungi—of the very distant past to break it down. It's a case of "global indigestion." Which brings us to our big problem. By burning all these fossil fuels, Mr. VCP is releasing carbon dioxide into the atmosphere at a rate 500,000 times faster than it was deposited in the first place. This is causing the atmosphere of the planet to heat up so quickly that it will shortly be damaging, perhaps fatal, to Mr. VCP, unless his civilization figures out a solution.

So Bella, this is where we are now.

I think you know Mr. VCP is us. Maybe if we never started burning fossil fuel, civilization would have continued along the path it was traveling in Shakespeare's time, 400 years ago. Back then, the whole world was using solar energy—it was just solar energy that was stored short-term: in the grain that we grew to make bread or the hay that horses ate to provide us with real horsepower. Sometimes the energy was not stored at all—we just enjoyed the heat of the sun to dry our vegetables and meat for storage; or the wind to blow the sails of the ships that crisscrossed the world's oceans; or the water that had fallen as rain to turn the waterwheels to grind our grain. The longest solar storage was the wood (lignin!) in the trees that we cut down to burn for fuel or to make charcoal for blacksmiths to forge iron and steel. Those trees might have been 150 or 200 years old at most.

What can we do now about this problem? First, all of us need to recognize this really is a problem, and hope to convince people in powerful positions to do something about it. The difficult thing is that most old folks grew up thinking that oil, coal, and gas were great, and it is hard to teach old dogs new tricks. You are young and you can see the situation more clearly than older people can.

There are many good alternatives now to burning fossilized hydrocarbons. Windmills. Solar panels. Tidal power. Even some kinds of safe nuclear power like thorium reactors. Scientists are also working on inventions that can pull excess carbon dioxide right out of the atmosphere and turn it into limestone (to build things with: The Egyptian pyramids are made of limestone) or even turn it into fuel. But these inventions need to be scaled up quickly. They are sort of like where rockets were in the 1920s. But in 40 years men had ridden rockets to the moon!

The Earth is about due for another ice age—with ice two miles thick over Boston, Chicago, Paris, and many other places. But that won't happen now. There is already too thick of an atmospheric carbon dioxide blanket. We need to treat Earth like our body. We keep our temperature at 98.6. If we feel cold, we burn more "fuel" (food) and that warms us up. And if we get too hot, we perspire and that cools us down. If we're smart, and organized, we might even be able to transform the Earth into a regulated-temperature planet. We could maintain it there for a long, long time to come, if we cooperate. To do that, we need a world agreement that this is what we are going to do, and then we can do it. This is worth working for!

With love, from Grandpa Walter in London

WALTER MURCH has been working in film for more than 50 years, as an editor, sound designer, writer, and director. He edited and sound-designed many films for Francis Ford Coppola (*The Godfather Trilogy*, *The Conversation*, *Apocalypse Now*) and Anthony Minghella (*The English Patient*, *The Talented Mr. Ripley*, *Cold Mountain*). His interest in science can be seen in his editing of Mark Levinson's film *Particle Fever* (2013), about the search for the Higgs Boson.

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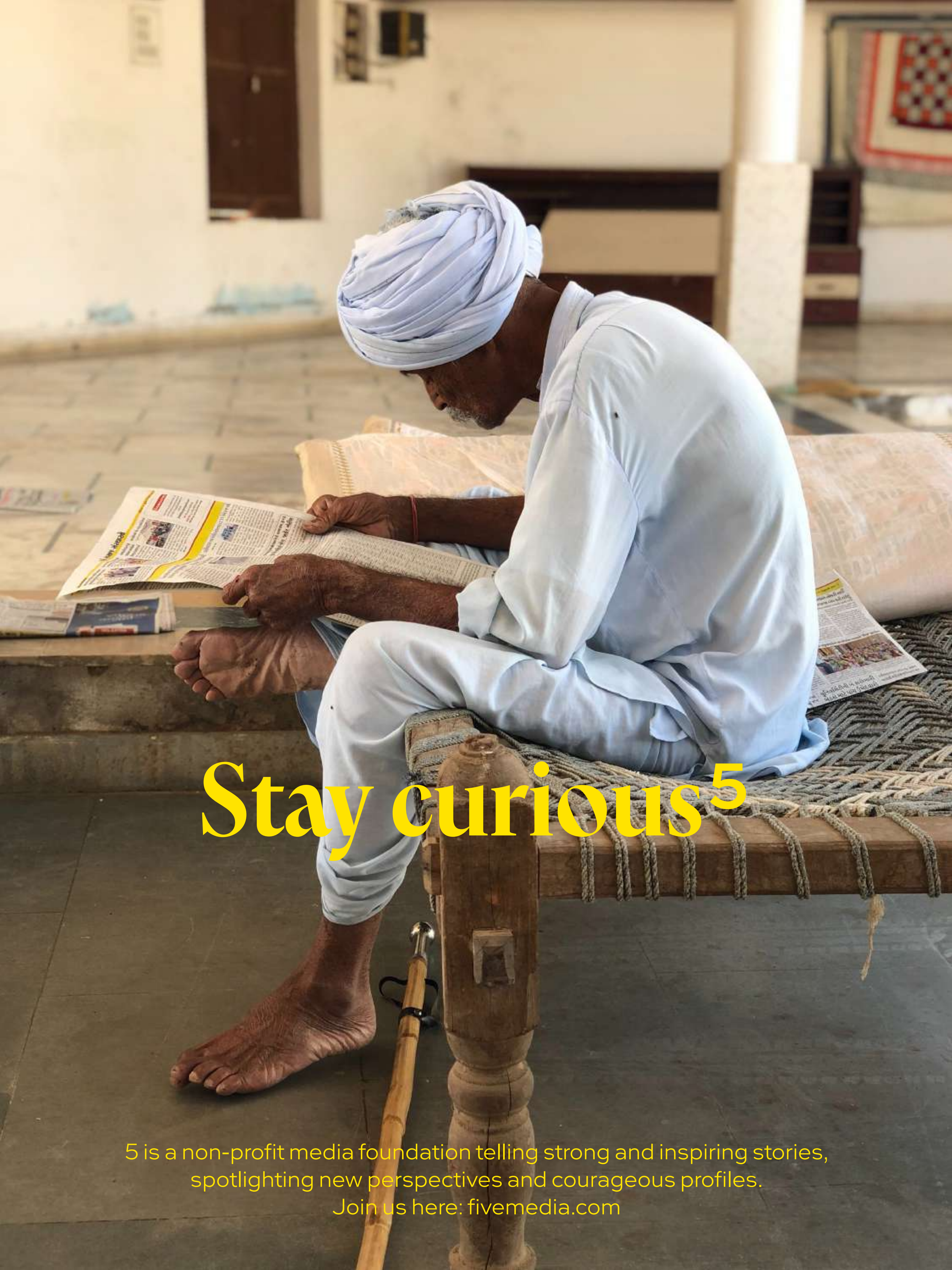

DIANE BURKO, *JULY, 2020*, mixed media, 60"x60", 7/23/20.

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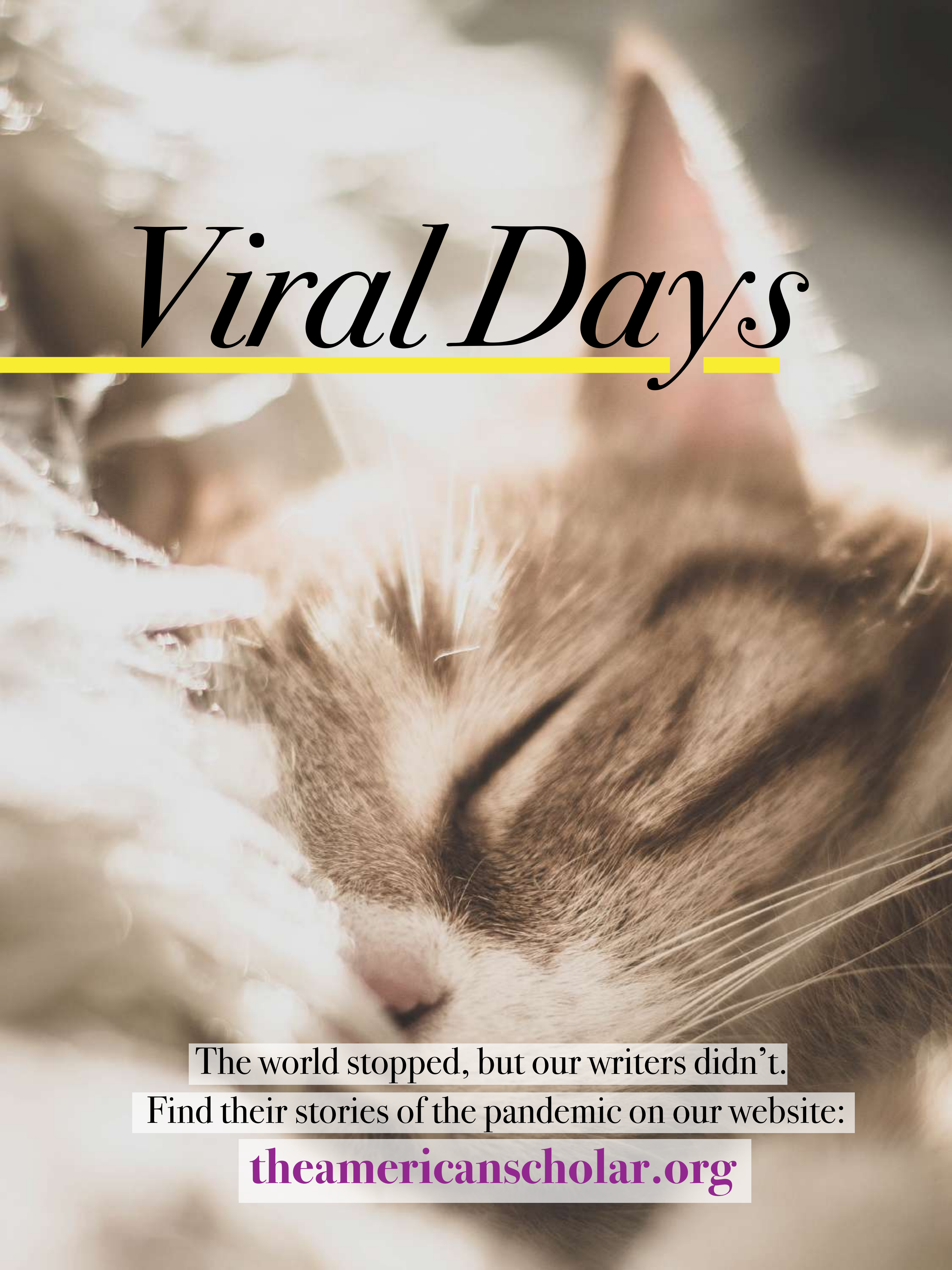
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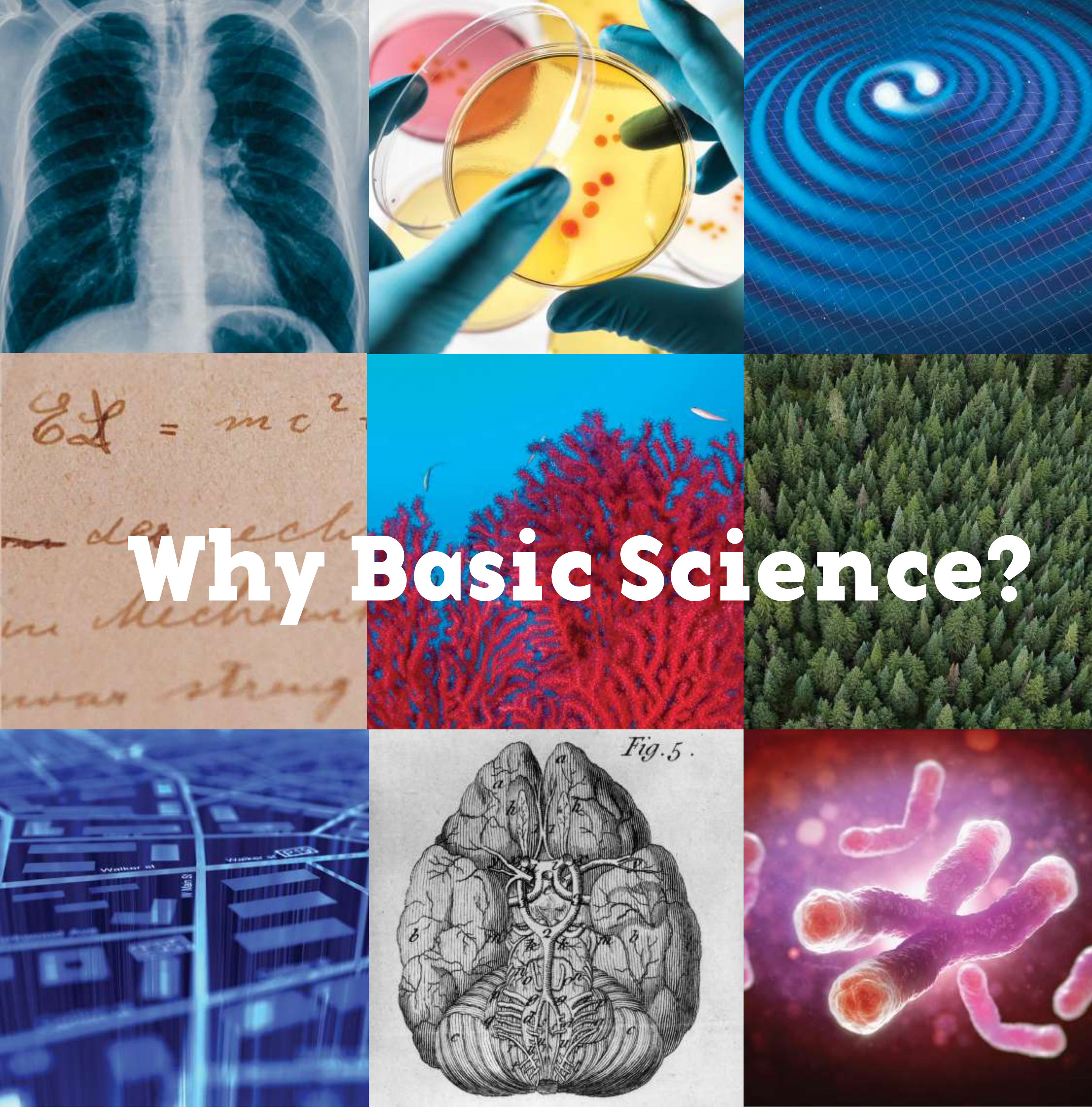

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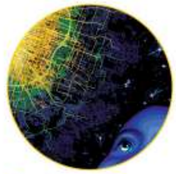

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Maria Konnikova

The writer and psychologist on the science and salvation of poker

INTERVIEW BY KEVIN BERGER

NOVICE MISTAKES

When I first started playing, I was a girl! I say that disparagingly to myself. I was really upset with myself. I didn't realize I had internalized so many gender stereotypes and so much socialization from my environment. I have a Ph.D. in psychology. I thought of myself as a good model for women, someone who stands up for myself. How can this be me? I'd be passive. I'd let people bully me. I'd fold. I would know I was making a mistake but couldn't get the nerve to do anything about it because I didn't want tension. I realized this is a big problem and something I have to work on. And not just in poker. I told myself, "You better get your shit together in real-life situations. You're probably a doormat a lot of the time and don't realize it."

STOIC PHILOSOPHERS

The most important lesson poker can teach you is to focus on the process. Poker is very much a stoic philosopher's game. The stoics would kick ass at poker because you focus on your decisions, your emotions, your actions, and reactions. The rest is just bullshit. "BS in your mind" is what my coach called it. You can't control it. The stoics were so strong on figuring out what you are in control of, and just letting go of everything else because it's not in your power.

GAME THEORY

Poker is a game of information and information-advantage—true of almost anything in life. The person who has the best information is going to make the best decision, is going to win more of the time and put herself in a position to win more of the time. Information is statistical analysis, calculating the odds and figuring out what range of hands you and others could possibly have. You also have to pay attention to yourself. What am I thinking? What am I experiencing? How am I seeing this situation? What biases am I bringing to bear on this? How do other people see me? It's a constant adjustment, a constant mental calculus. The moment emotion seeps into our decision process, we're no longer making probabilistic calculations, reading people, paying attention. You're angry at someone, they got under your skin, so you make a decision because you're angry. You say, "I should raise him because he's an asshole." But that's not your clear-thinking self. That's the version of you that didn't know better.

BEAUTY OF UNCERTAINTY

Carl Sagan was awed by chance. He didn't let it get him down. Instead he wants us to look at this beautiful universe. Look at how many things there are to amaze us, to fascinate us. Look at the power of wonder, embrace it, and don't be afraid there are things we don't know. Don't be afraid of uncertainty, be grateful for it. Would you want to live in a world where you knew everything and everything was determined? He hated superstition, as do I. Don't take the easy way out. Don't give up agency. Don't have these stupid rituals. Science is beautiful. Lack of knowing is beautiful. All of these things we can't control are beautiful. They're powerful. They make us human. They make life worth living.

NEIL STODDART / POKER STARS