NAUTILUS

The Boy Who Dreamt Steel

THE BIRTH OF STAINLESS p.22

US$12

MAY/JUNE 2016 Science Connected NAUTIL.US

human

aging

is the

climate change

of biology

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A Material History

CHRISTIAN THOMSEN, A COIN COLLECTOR largely untrained in archaeology, divided a broad swathe of human history into stone, iron, and bronze ages in the early 1800s. The objections started soon afterward. For one thing, the archaeological record doesn't divide itself as cleanly along material lines as Thomsen had imagined. For another, some argue the classifications are better suited for Europe than the rest of the world.

But they persist, both in academia and in the public imagination, in part because they carry an important insight: Materials are transformational. Cheap iron cutting tools, for example, allowed people to deforest and inhabit fertile land, dramatically expanding populations as well as the production of iron. As they age, civilizations make materials—and materials make civilizations.

Harry Brearley is that story in microcosm. As a poor boy growing up in industrial-revolution era Sheffield, the sparks and forges of the local steelworks caught his imagination, prompting him to sneak into factories and spend his days perched on coal piles watching furnaces. Soon he was a lab assistant, then a chemist, then he ran a lab. Some 30 years after he first entered a steelworks, he would become one of the fathers of stainless steel. Steel makes man, man makes steel.

Brearley's career exposed him, as well, to some of the major currents of the 20th century, including both world wars and the Russian Revolution. These intersections remind us of Thomsen's insight, that materials run through every dimension of a developing society. At the end of his career, Brearley put it this way: "The castles in the air must conform to the possibilities of material things ... [Myriad] possibilities ... become ultimately an object. A vision crumpled into a thing."

Welcome to the May/June 2016 *Nautilus* print edition.

—Michael Segal
Editor in Chief

We're pleased to have produced our Aging issue in partnership with the Glenn Foundation for Medical Research.

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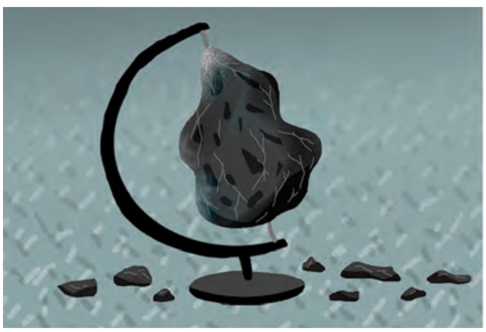
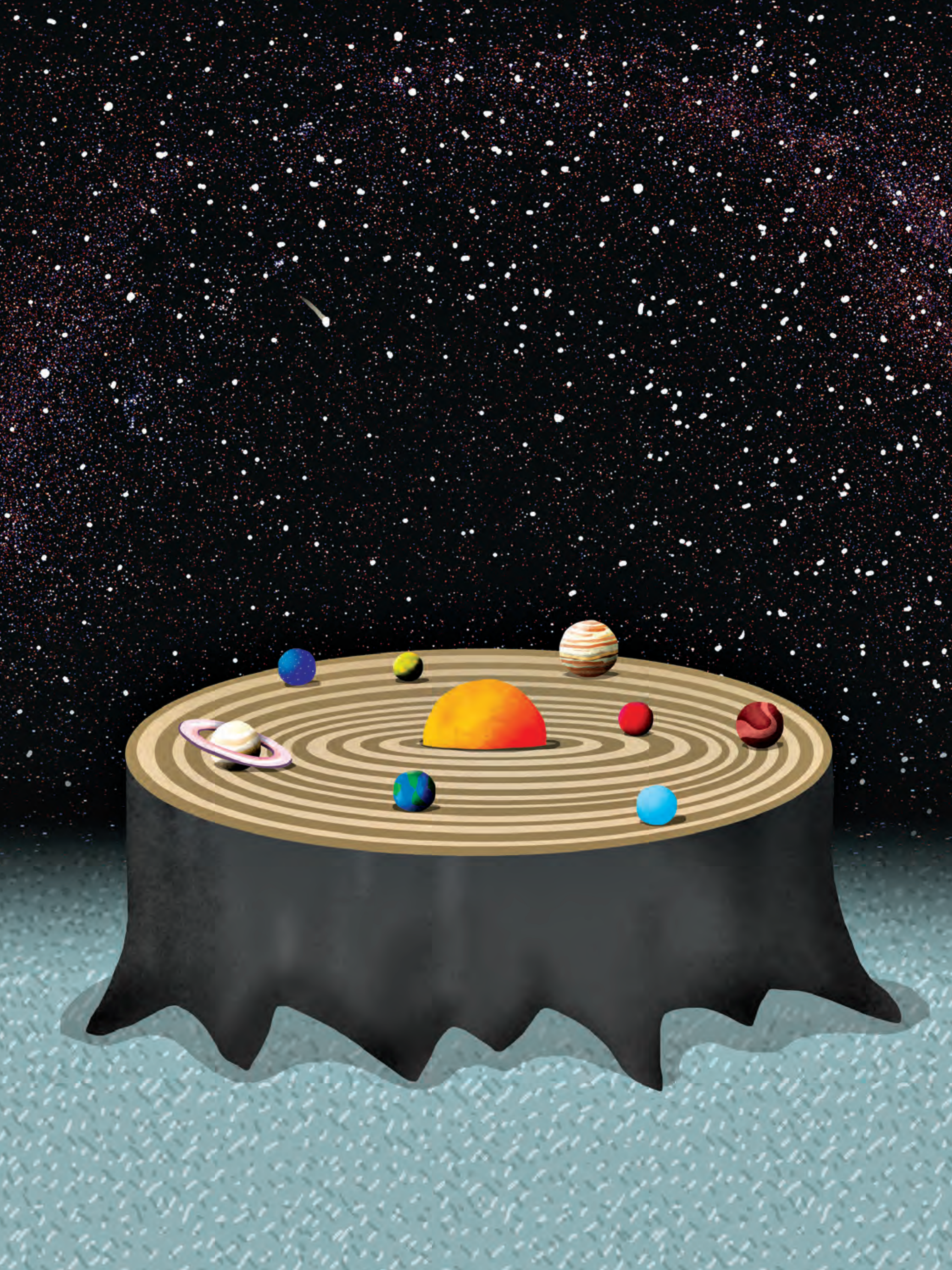


Aging

"Human beings are extraordinary in that long after we've stopped reproducing, we just keep on living."

—David P. Barash, p. 48

THEME ART Alexander Glandien



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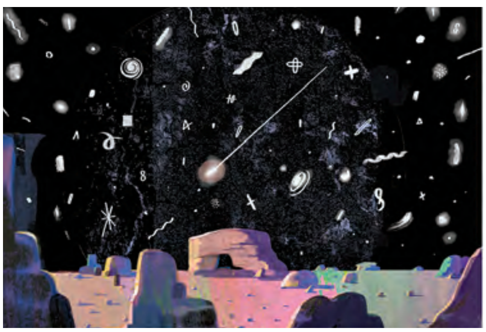

Currents

"Microbes can stay aloft in the atmosphere for days to weeks—long enough to jump a continent, or an ocean, in one go."

—Chelsea Wald p. 100

THEME ART Lisk Feng & Jun Cen

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NAUTILUS *think*

Letters

Reader responses to the March/April 2016 print edition.

“MY FAMILY, MY SCIENCE”

Absolutely fantastic. Well written, and it brought back memories of my high school chem lab, down to the smallest detail. The growing up in rural mid-America was spot on as well. Everything about it was spectacular.

—Steve Denham

“FAMILIES OF CHOICE ARE REMAKING AMERICA”

One can only pity those who are left alone toward the sunset of their days. Bringing up kids and creating a family is not for everyone, that is true. And yet, this is the most humane way toward happiness. Look at gay people, how hard they fight for the right to create families. We can learn from them about something that we have lost.

—Kirill Azhitsky

The author misses the whole point about families: children, aka the next generation. When it comes to child rearing, the only real functional alternative to nuclear families is probably extended families. When it comes to long term goals and a rewarding life, the attractions of singlehood begin to wane for most people. We certainly have a lot more choices socially available to us today. However, human nature remains very much the same.

—Archimedes

“WHEN YOU LISTEN TO MUSIC, YOU’RE NEVER ALONE”

The ability of (at least some) listeners at an art music concert to actually *hear* music and to engage with it in the isolation of their own minds, without need for constant reference to an audience of others, is an objective sign of their superiority. But of course this must be despised and ridiculed in a mob society like ours.

—Dani Eruces

“PARASITES ARE US”

Sure gives credence to the observation of Buddhists that “all is one.”

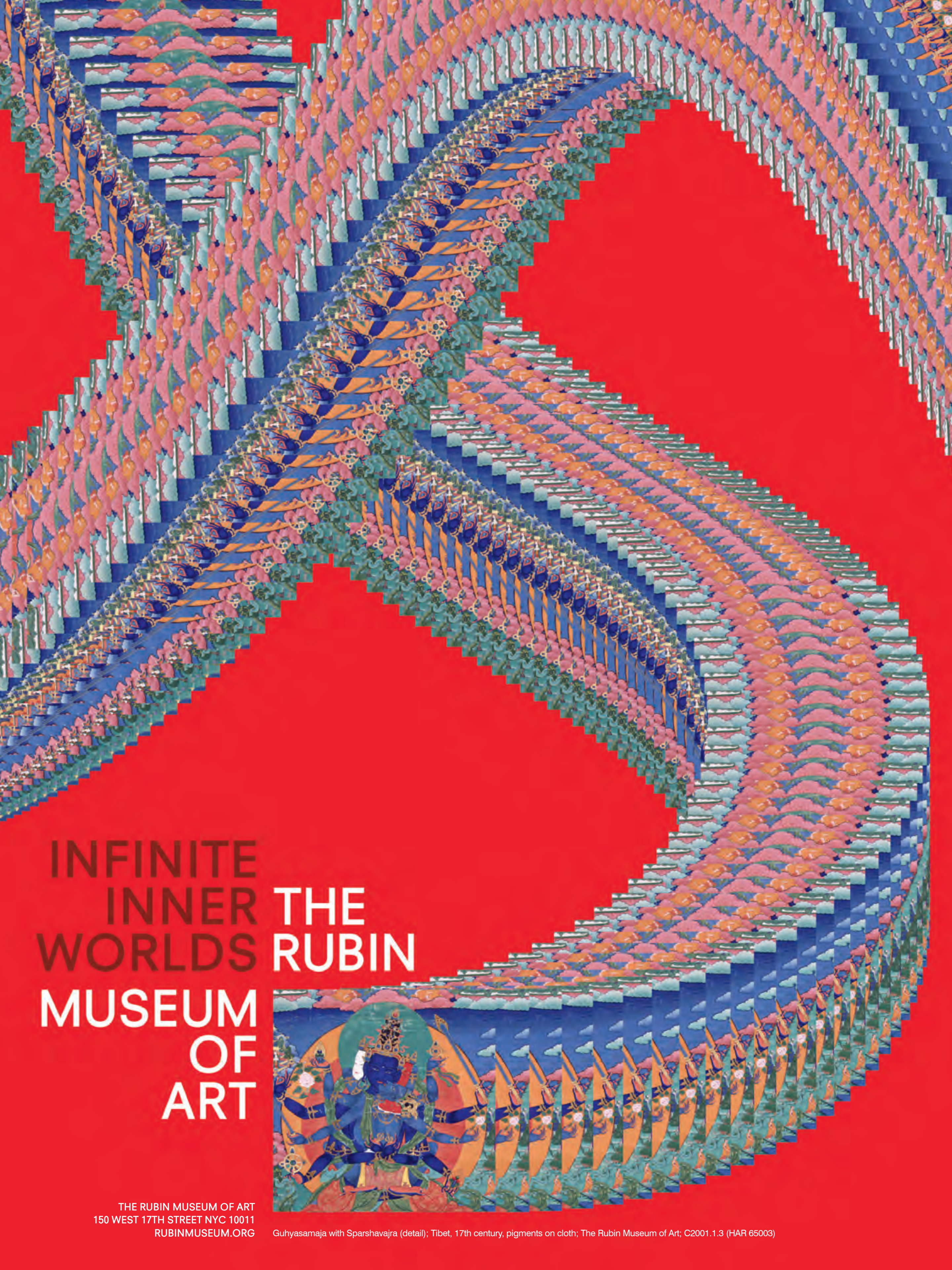
—Mike Griffin

CORRECTIONS

As originally published in the March/April 2016 print edition of *Nautilus*, the opening quotation in “How Do You Say ‘Life’ in Physics” was mistakenly attributed to Ludwig Wittgenstein’s 1921 *Tractatus Logico-Philosophicus*. It is from his 1953 *Philosophical Investigations*.

As originally published in the March/April 2016 print edition of *Nautilus*, “Parasites Are Us” was missing a series of footnotes stating attribution and sourcing. You can see the full list at http://go.nautil.us/parasites.

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



Guhyasamaja with Sparshavajra (detail); Tibet, 17th century, pigments on cloth; The Rubin Museum of Art; C2001.1.3 (HAR 65003)


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PHOTO CREDIT: Yuri Beletsky, Las Campanas Observatory, Chile, 6.5-meter Magellan Telescope (Baade)

Preludes

NEUROSCIENCE

Why Neuroscientists Need to Study the Crow

Corvids, such as crows, ravens, and magpies, are among the most intelligent birds on the planet. But neuroscientists have not scrutinized their brains yet, for one simple reason: They don't have a neocortex. Because birds lack this structure—the most recently evolved portion of the mammalian brain, crucial to human intelligence—neuroscientists have largely neglected the neural basis of corvid intelligence.

Avian brains diverged from mammals' more than 300 million years ago, giving them plenty of time to develop along remarkably different lines. Instead of a cortex with six layers of neatly arranged neurons, birds evolved groups of neurons densely packed into clusters, called nuclei. So, any computational similarities between corvid and primate brains—which are so different neurally—would indicate the development of common solutions to shared evolutionary problems, like creating and storing memories, or learning from experience.

Birds don't have a neocortex.

ILLUSTRATIONS BY ROBIN DAVEY

Andreas Nieder, a neuroscientist at the University of Tübingen, has examined the neuronal activity of crows during sophisticated behavior. In a study published in 2013, Nieder and his team had the crows play an image matching game. The crows first had to briefly look at an image on a computer screen. Then, a cue indicated whether they should subsequently select the same (matching) image, or a different one, once the screen lit up again. Importantly, the cues for which image to select could be either visual (red or blue circles) or auditory (noise or glissando sound). The blue circle or glissando sound cued the crow to select the same image as appeared initially; the red circle or noise sound cued the different one. This required the crows to interpret the cue flexibly, since a sound or a visual cue could prompt the same action.

Once the birds learned the rule (they were rewarded with treats when behaving correctly), Nieder's team began recording neuronal activity in the birds' nucleus NCL (nidopallium caudolaterale), an area of the avian brain thought to be most like the mammalian prefrontal cortex, which enables decision-making, short-term memory, and planning for the future.

Examining the activity of over 300 neurons in two birds, Nieder's team found that the crow's NCL activity matched that of a primate's prefrontal cortex: Both of the species' neurons activated the most during the presentation of the rule cue, while activating much less in response to the images themselves. Some neurons responded specifically to the match cue (blue circle or glissando) and others to the non-match (red circle or noise); importantly, the neurons from each species activated in the same fashion regardless of the cue's sensory modality (auditory or visual). Nieder's results imply that both crows and primates evolved to perform the same computation, albeit through radically different machinery, to solve the problem of representing abstract information—in this case, auditory or visual rules to a game.

Avian brains diverged from mammals' more than 300 million years ago.

The next step in corvid neuroscience would be to uncover exactly how neurons arrive at solutions to computational challenges. Finding out how common solutions come from different hardware may very well be the key to understanding how neurons, in any organism, give rise to intelligence.

—Grigori Guitchounts

COMPUTER SCIENCE

The Most Important Object in Computer Graphics History

YOU MAY NOT HAVE THOUGHT much of it if you saw it in an episode of *The Simpsons* or in *Toy Story*, but the "Utah teapot," as it's affectionately known, has had an enormous influence on the history of computing. It all started in 1974, when computer scientist Martin Newell was a Ph.D. student at the University of Utah.

The U of U was a powerhouse of computer graphics research then, and Newell had some novel ideas for algorithms that could realistically display 3-D shapes—rendering complex effects like shadows, reflective textures, or rotations that reveal obscured surfaces. But he struggled to find a digitized object worthy of his methods. Objects that were typically used, like a chess pawn, a donut,

TEA, ANYONE? The famed Utah teapot, in its original form.

and an urn, were too simple.

One day over tea, Newell told his wife Sandra that he needed more interesting models. Sandra suggested that he digitize their tea service, a simple Melitta set from a local department store. The curves, handle, lid, and spout of the teapot all conspired to make it an ideal object for graphical experiment. For instance, the teapot could cast a shadow on itself in several places. Newell grabbed some graph paper and a pencil, and sketched it.

Back in his lab, he entered the sketched coordinates—called Bézier control points—on a Tektronix storage tube, an early text and graphics computer terminal. The result was a lovely virtual teapot, more versatile (and probably cuter) than any 3-D model to date.

One day, Newell's colleague Jim Blinn was demonstrating how his software could adjust an object's height, and he flattened the teapot a bit. He decided he liked the look of that version better, and the distinctive Utah teapot was born.

Newell and Blinn also took the important step of sharing their model publicly. As it turned out, other researchers were also starved for interesting 3-D models, and the digital teapot was exactly the experimental test bed they needed. It quickly became a beloved staple of the graphics community. Teapot after teapot graced the pages and covers of computer graphics journals. "Anyone with a new idea about rendering and lighting would announce it by first trying it out on a teapot," writes animator Tom Sito in *Moving Innovation*.

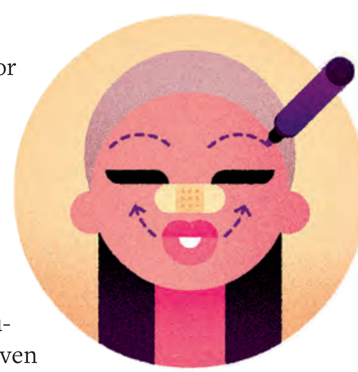
These days, the Utah teapot has achieved legendary status. It's a built-in shape in many 3-D graphics software packages used for testing, benchmarking, and demonstration. Graphics geeks like to sneak it into scenes and games as an in-joke; hence its appearances in *Toy Story* and *The Simpsons*.

Newell has jokingly lamented that, despite all his algorithmic innovations, he'll be remembered for "that damned teapot." The humble teapot serves as a reminder that, in the right hands, something simple can become an icon of creativity and hidden potential.

—*Jesse Dunietz*

PSYCHOLOGY

The Loophole in the Hedonic Treadmill



WHEN AUTHOR Fyodor Dostoyevsky wrote in *The House of the Dead* that, "Man is a creature that can get accustomed to anything," he was talking about the cruelties of life in Siberian prison camp. But the human tendency to adapt to situations is more profound than even

Dostoyevsky may have realized.

Imagine a person who, after years of drinking bland, watery beer from a mass-market brewery, finally tastes a really good craft beer. The craft beer is much more flavorful than what she has been used to drinking, and the experience is highly enjoyable. But check in after a few months when she has been drinking the craft beer regularly, and the experience is no longer as special as it was at first.

We adapt. A great pleasure, repeated often enough, becomes routine, and it takes an even greater treat to give us the same enjoyment. (Conversely, when we get used to having less, it takes less to please us.) This is known as the "hedonic treadmill."

This idea can apply to discrete pleasures—like getting accustomed to better beer—or to an overall lifestyle. There is evidence that if an individual's basic needs are met, after a certain point, increases in income do not lead to much greater happiness. As the money we have to spend goes up, so too do our expectations and desires—and with them the possibility of disappointment.

One form of pleasure that seems surprisingly resistant to hedonic treadmill-type adaptation is the feeling of satisfaction and well-being after undergoing plastic surgery. A 1986 article surveyed research between 1960 and 1982 and found that the vast majority of patients were satisfied with the results of their surgery, and that this feeling remained constant over time—in contrast with how people tend to become dissatisfied with new material possessions.

The satisfaction acquired from plastic surgery is surprisingly long-lasting.

And in 2013, the world's largest study of its type checked in with 544 first-time plastic-surgery patients three, six, and 12 months after surgery. They then compared the patients with 264 people who had considered cosmetic surgery but decided against it. The researchers found that the ones who underwent surgery were less anxious, felt healthier, had developed greater self-esteem, and reported higher rates of life satisfaction and well-being.

Why would people adapt to a larger income but not to an improved physical appearance? Perhaps this is an indication that our sense of self is more closely tied to outward appearance than it is to our bank balance. Feeling better about how you look may carry a personal meaning that a financial windfall doesn't match.

—Jeanette Bicknell

ONE QUESTION

"How did our evolutionary history shape the way we think about mass politics today?"

Michael Bang Petersen

Political psychologist and a co-director of The Politics and Evolution Lab at Aarhus University

Politics often seems to be about issues far removed from our everyday lives: the macro-economy, wars in foreign countries, judicial complexities. But at its core, it's about who gets what. So politics is both an ancient and everyday activity. Our Stone Age ancestors on the East African savanna—when dividing up meat from a hunt, when building a campsite, or when going to war—engaged in politics, too. Without a political sense, our ancestors would not have survived. In my research, I have investigated how evolution designed the human brain to deal with politics in small groups. Since humans still use the same brain to navigate modern politics, involving billions of people, many political attitudes are, as a result, infused with factors that seem irrational. For example, physically stronger men have been shown to have more self-interested attitudes and hungrier people have been shown to be more supportive of helping the needy. In our past it was necessary to use your strength to enforce your interests and to reach out to others when hungry. Our Stone Age brain presumes that this is still the case even though we don't live in small groups of foragers on the East African Savanna. You should thus be wary of your and others' political intuitions. They were designed for another world.

OPPOSITE PAGE: COMPUTER HISTORY MUSEUM
PORTRAIT ILLUSTRATION: JACKIE FERRENTINO

HISTORY

Writing Women Back Into Science History

EMILY TEMPLE-WOOD HAS WRITTEN approximately one Wikipedia article every 10 days since she was 12 years old, totaling around 330. The work of the 21-year-old undergraduate, studying molecular biology at Loyola University of Chicago, continues to unabashedly expose sexism—and in the process, is exposing her to some of it. Temple-Wood's output has made her the target of Internet trolls: Emboldened by anonymity, they deluge her inbox with cruel email s about her body, intelligence, and sexual decision-making.

Until recently, Temple-Wood simply ignored them. When their numbers jumped (she receives dozens a week), she finally responded. For every harassing email she receives, she has pledged to immortalize another female scientist on Wikipedia. It was a simple, elegant solution to a problem: Fight ignorance with enlightenment.

Nautilus caught up with Temple-Wood to chat about her passion for showcasing women's contributions to science.

How has writing these articles affected you?
Learning about all these women scientists has kept me going—they're a huge source of inspiration. Actually, once, one of my professors talked about the geneticist Barbara McClintock's page, and I was like, "Have I heard about Barbara McClintock? I wrote that page." That was surreal.

How many articles have you written since you began this latest project?
Since the start of this project, I've written about 40 or 50. But I have a backlog [laughs]. It's at like 120-something right now. I have a lot of catching up to do.

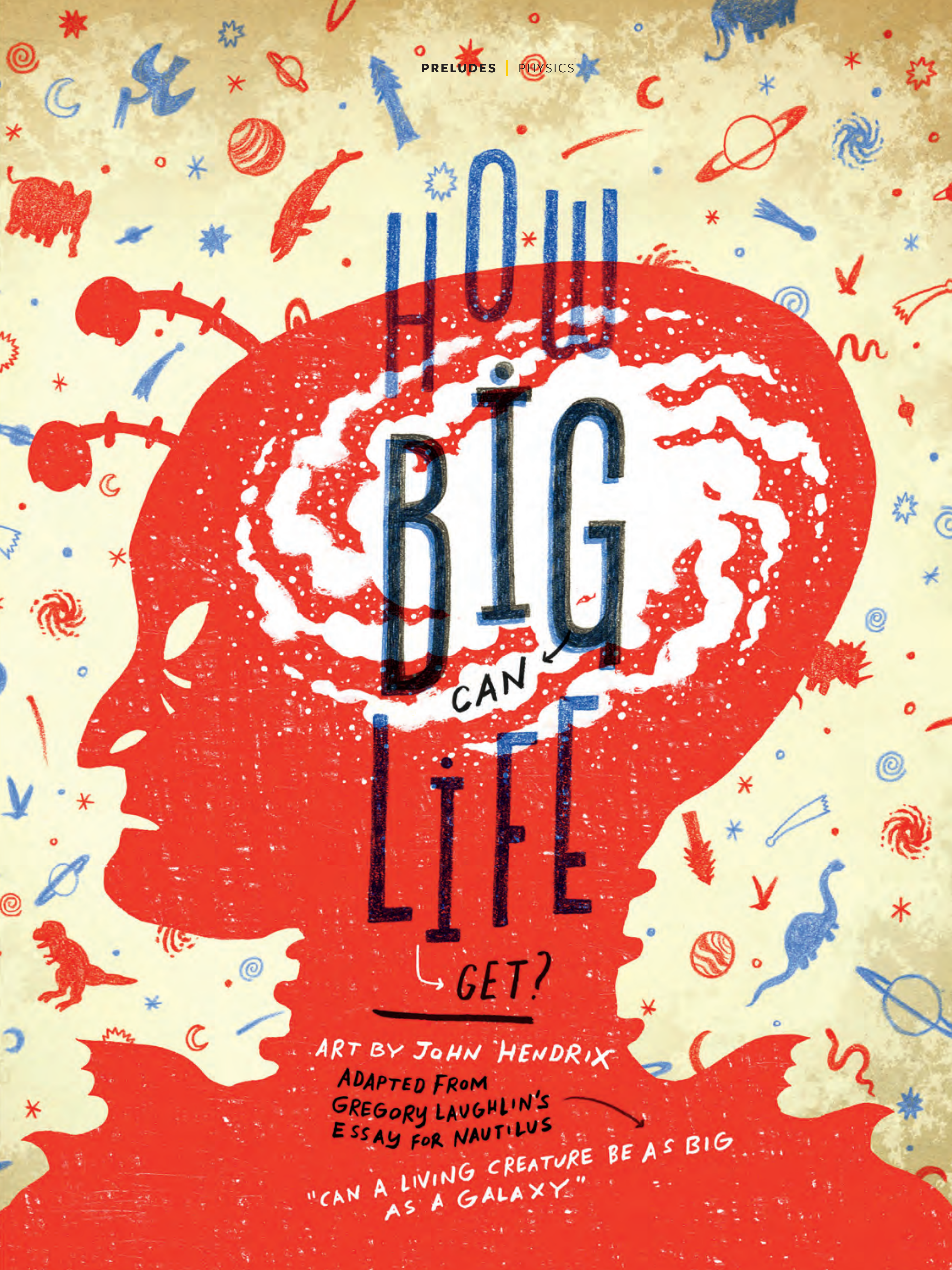
Are your trolls threatened more by your Internet presence or your prospective career in science?
Definitely the Internet. No matter what field other women I know write about, they get flak, just for existing on the Internet. It sucks, but you deal with it how you can. You can curl up and cry—which is a pretty viable option. But once you're done crying, you can fight back.

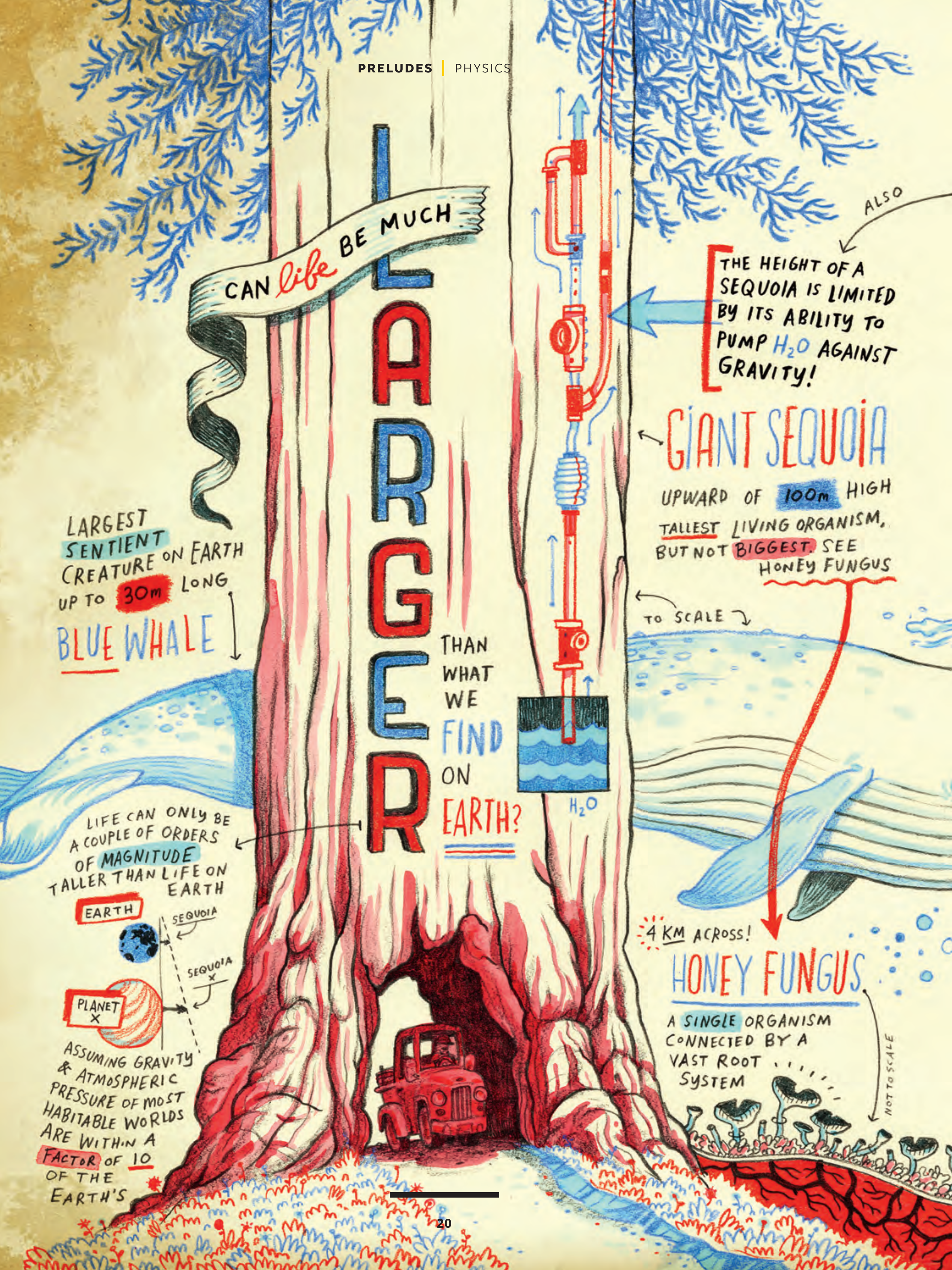
"I took my life philosophy from a French monk."

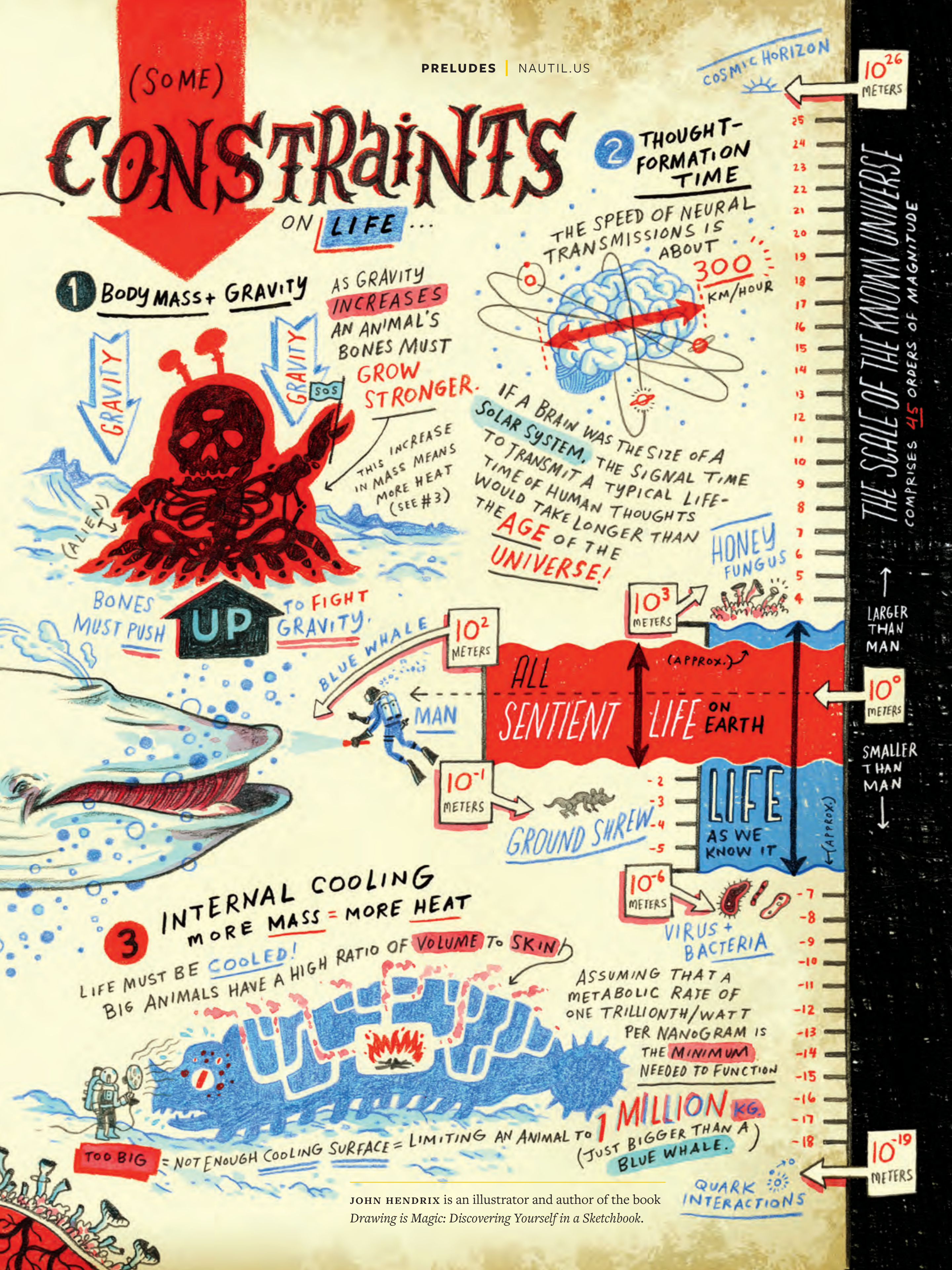
How has it felt to receive media attention for your work?
It's been super weird. I don't do what I do for attention, obviously, so it's been very weird to have people noticing what I do and think it's cool. Because I'm a total geek, you know? I took my life philosophy from an 11th-century French monk, Bernard of Clairvaux! He once said something that goes like this: "There are those who seek knowledge for the sake of knowledge; that is Curiosity. There are those who seek knowledge to be known by others; that is Vanity. There are those who seek knowledge in order to serve; that is Love."

Why do you keep writing the Wikipedia articles?
For me, Wikipedia is a labor of love. I'm seeking knowledge to give it to others. It's nice—now I'm getting to spread the word of women scientists, spread the word for people to join and write about them. That's my lifelong goal, to get people to care about women scientists.

—*Susie Neilson*


HOW BIG CAN LIFE GET?
ART BY JOHN HENDRIX
ADAPTED FROM GREGORY LAUGHLIN'S ESSAY FOR NAUTILUS
"CAN A LIVING CREATURE BE AS BIG AS A GALAXY"


CAN life BE MUCH LARGER THAN WHAT WE FIND ON EARTH?
ALSO
THE HEIGHT OF A SEQUOIA IS LIMITED BY ITS ABILITY TO PUMP H_2O AGAINST GRAVITY!
GIANT SEQUOIA
UPWARD OF 100m HIGH
TALLEST LIVING ORGANISM, BUT NOT BIGGEST. SEE HONEY FUNGUS
TO SCALE
H_2O
LARGEST SENTIENT CREATURE ON EARTH UP TO 30m LONG
BLUE WHALE
LIFE CAN ONLY BE A COUPLE OF ORDERS OF MAGNITUDE TALLER THAN LIFE ON EARTH
EARTH
SEQUOIA
SEQUOIA x
PLANET x
ASSUMING GRAVITY & ATMOSPHERIC PRESSURE OF MOST HABITABLE WORLDS ARE WITHIN A FACTOR OF 10 OF THE EARTH'S
4 KM ACROSS!
HONEY FUNGUS
A SINGLE ORGANISM CONNECTED BY A VAST ROOT SYSTEM
NOT TO SCALE



JOHN HENDRIX is an illustrator and author of the book *Drawing is Magic: Discovering Yourself in a Sketchbook*.

The Father of Modern Metal

The creation of stainless steel took equal parts metallurgy and perseverance

BY JONATHAN WALDMAN
ILLUSTRATION BY EDWARD KINSELLA III

SOMETIME IN 1882, a skinny, dark-haired, 11-year-old boy named Harry Brearley entered a steelworks for the first time. A shy kid—he was scared of the dark, and a picky eater—he was also curious, and the industrial revolution in Sheffield, England, offered much in the way of amusements. He enjoyed wandering around town—he later called himself a Sheffield Street Arab—watching road builders, bricklayers, painters, coal deliverers, butchers, and grinders. He was drawn especially to workshops; if he couldn't see in a shop window, he would knock on the door and offer to run an errand for the privilege of watching whatever work was going on inside. Factories were even more appealing, and he had learned to gain access by delivering, or pretending to deliver, lunch or dinner to an employee. Once inside, he must have reveled, for not until the day's end did he emerge, all grimy and gray but for his blue eyes. Inside the steelworks, the action compelled him so much that he spent hours sitting inconspicuously on great piles of coal, breathing through his mouth, watching brawny men shoveling fuel into furnaces, hammering white-hot ingots of iron.

There was one operation in particular that young Harry liked: a toughness test performed by the blacksmith. After melting and pouring a molten mixture from a crucible, the blacksmith would cast a bar or two of that alloy, and after it cooled, he would cut notches in the ends of those bars. Then he'd put the bars in a vise, and hammer away at them.

The effort required to break the metal bars, as interpreted through the blacksmith's muscles, could vary by an order of magnitude, but the result of the test was expressed qualitatively. The metal was pronounced on the spot either rotten or darned good stuff. The latter was simply called D.G.S. The aim of the men at that steelworks, and every other, was to produce D.G.S., and Harry took that to heart.

In this way, young Harry became familiar with steelmaking long before he formally taught himself as much as there was to know about the practice. It was the beginning of a life devoted to steel, without the distractions of hobbies, vacations, or church. It was the origin of a career in which Brearley wrote eight books on metals, five of which contain the word steel in the title; in which he could argue about steelmaking—but not politics—all night; and in which the love and devotion he bestowed upon inanimate metals exceeded that which he bestowed upon his parents or wife or son. Steel was Harry's true love. It would lead, eventually, to the discovery of stainless steel.

HARRY BREARLEY WAS BORN on Feb. 18, 1871, and grew up poor, in a small, cramped house on Marcus Street, in Ramsden's Yard, on a hill in Sheffield. The city was the world capital of steelmaking; by 1850 Sheffield steelmakers produced half of all the steel in Europe, and 90 percent of the steel in England. By 1860, no fewer than 178 edge tool and saw makers were registered in Sheffield. In the first half of the 19th century, as Sheffield rose to prominence, the population of the city grew fivefold, and its filth grew proportionally. A saying at the time, that "where there's muck there's money," legitimized the grime, reek, and dust of industrial Sheffield, but Harry recognized later that it was a misfortune to be from there, for nobody had much ambition.

The house Harry grew up in was sparse and tight; the living room measured 10 feet square, with two bedrooms above it. The kids ate standing up because there were not enough chairs. There were no books, or pictures, or toys; there was no space for a desk. The Brearleys were heartily poor but not starving, yet they weren't far from the breadline. Harry wore jackets that had been made from his father's trousers. He helped deliver coal in a wheelbarrow in return for sweets. After school, he bundled sticks, earning a penny for a dozen bundles. He used to walk along

THE PRINT COLLECTOR/PRINT COLLECTOR/GETTY IMAGES nearby railroad tracks, collect lumps of coal that had fallen from passing trains, and bring them home to his mother. He once borrowed a book from the library, and copied it—the whole thing—by hand, because he couldn't afford to buy a copy. In 1882 his parents moved down to Carlisle Street, beside the railroad tracks—a place said to be separated from hell by only a sheet of tissue paper. It was filthier, dustier, smokier. But Harry loved it, on account of the increased color and variety. There was a pigsty and stables to poke around in, and more adult conversation to pick up. On account of his curiosity, he was regularly late for school; he found too much to look at on the way. He got away from school, at age 11, with his "brains unshackled and his curiosity undimmed," and was then free to work, according to the law, in nonfactory conditions.

He was unhappy in his first jobs. He spent three days in Marsland's Clog Shop, blacking boots and carrying things from 8 in the morning until 11 o'clock at night, and hated it. He spent a week in Moorwood's Iron Foundry, painting black varnish onto kitchen stoves, before being discharged on account of labor regulations. He spent six weeks helping a doctor, but was disheartened by the subservience the man required. Finally his father took him to work in the Thomas Firth & Sons steelmaking factory, where he worked as a nipper, or cellar boy, moving clay stands and covers wherever needed in the dark, hot ashes of the cellar, and skimming the slag from the steel. Everybody, including his father, thought he was too small and weak for the job, but he spent three months at Firth's, working long, sweaty days, before he was once again discharged on account of violating labor regulations.

He was then hired as a bottle washer by James Taylor, the chief chemist in a laboratory of the same steelmakers. Harry hadn't ever heard the word laboratory before and, when he first showed up, was so overwhelmed by the amount of glassware that he figured it was a place people came to drink. At first, he found the work tedious, but his mother encouraged him to stay there, as it was undoubtedly better than the melting furnaces in the steelworks. Harry was only 12; he would become Taylor's protégé.

Taylor started his training by teaching Harry arithmetic (Harry had to buy the book himself) and then, a couple of years later, algebra (Taylor bought him the book, a gift Harry brought home to show off, and never forgot). Taylor bought

EPICS / CONTRIBUTOR

Harry a set of drawing instruments too. Taylor was not social, not a drinker, not a smoker, not a swearer. He didn't even speak in the Sheffield dialect. But he was thrifty and handy, and the set of skills he displayed was formative for Harry. Under Taylor, Harry learned to join wood, paint, solder, plumb, blow glass, bind books, and work with metal. While his friends were out playing, Harry was learning new skills. This knowledge later inspired Harry to make his own furniture, stitch his own sandals, and try writing. His first attempt, an article for *Windsor* magazine, described the nature of various inks in creating inkblots, of which he made a few hundred; the next was titled "Bubble-Blowing as a Physical Exercise." Some hobbies. He also attended night school, on Taylor's urging, studying math and physics a few nights a week.

> He was so overwhelmed by the amount of glassware that he figured it was a place people came to drink.

By the time he was 20, he was proficient in most crafts, even though, technically, he was a bottle washer. The lab suited him; at work, one assistant sometimes sang opera or recited poems, while Taylor regularly discussed food, economics, education, politics, and social welfare. In this context, Harry grew comfortable in the presence of educated people. Despite, or perhaps because of, Harry's reverence for his boss—which bordered on idolatry—Harry's mother by then was encouraging him to find a job in a factory, one with a better salary, and more of a future.

HIS MOTHER DIED the next year. Brearley moved in with his older brother Arthur. That same year, Taylor left for work in Australia, and Brearley was promoted to lab assistant. Contemplating life ahead, he had a sudden conversion, and decided more schooling was not for him. He recognized that he had no tolerance for things he didn't want to do. He was hardening, like steel.

He also fell in love, and began courting his future wife, Helen, chatting her up at Sunday school. At age 24, they married; he'd been promoted to an analytical chemist at the lab, and was earning two pounds a week. Together they had a total savings of five pounds. They lived on bread, onions, and apple pie, in a simple cottage south of Sheffield, but he never mentions it, or his wife, in his autobiography. He barely mentions his only son, Leo Taylor Brearley (named after James Taylor), who was born two years later. But he mentions love: "I was in love with my work, and could think of few better things than the privilege of living to continue it." He enjoyed it so much that he said it made him feel drunk.

So he drank: He spent the next six years reading everything he could about metallurgy, starting with periodicals and journals about chemistry, barely stopping for a lunch of bread and dates. Next he read about manganese, and every process by which it could be detected in steel. Then he read about every other steelmaking element; all the while he kept index cards detailing what he had learned from each book. He developed his knowledge carefully, procedurally, accumulating as much as he could. Lab protocol stipulated that anyone who figured out how to save time could enjoy his savings as he wanted. Brearley got his day's work done in a couple of hours, and spent the rest of the day reading and experimenting.

In his late 20s, Brearley started writing technical papers on the analytical chemistry of metals for publications such as *Chemical News*. Taylor wrote from Australia, offering him a job assaying gold and silver. He turned it down. He was developing a reputation as a steel problem solver, and enjoying it.

On Saturdays, for fun, he met up with Fred Ibbotson, a professor of metallurgical chemistry. Ibbotson would give him samples of metals, and challenge him to determine, in 10, 20, or 30 minutes, how much of a given element they contained. What happened to blowing bubbles? On Sundays, he hung out at the lab with his brother Arthur (who'd walked 3 miles to get there), and together they analyzed enough steel to get proficient at it. This was the beginning of a lifelong working relationship with his brother. Twenty years later, the two co-wrote *Ingots and Ingot Moulds*; Brearley thought it was his best work. Two years after that, when he won the Bessemer Gold Medal, the highest award conferred by the Iron and Steel Institute, for outstanding contributions to the steel industry, he credited his brother generously. His sixth book, *Steel-Makers and Knotted String*, was dedicated to Arthur, as "playmate schoolmate and workmate." In it, he called his brother "a better workman, a better observer and a more resourceful experimentalist than I."

In 1901, at age 30, Brearley was hired at Kayser, Ellison & Co. as a chemist to work on high-speed tool steels, which had been discovered three years earlier by a consultant for Bethlehem Steel named Frederick Winslow Taylor. Sidetracked from production problems, Taylor had begun looking at steels used to plane and bore ship plates and cannons. Ideal forging temperatures were still measured by color, and he found that steel, heated to just below dull cherry, came out strong, but the same steel, heated above that point, became weak. To his surprise, he found that if he heated it further—to salmon and yellow—the steel got superhard; so hard that machinists could run their cutting tools two or three times as fast as before, until the blades glowed red, at 1,000 degrees Celsius. It was so dramatic that at the Paris Exhibition of 1900, Taylor set up a giant lathe in the dark, so that the glowing-red cutting edge, as well as the stream of blue chips, was visible.

In 1902 Brearley co-wrote his first book with Professor Ibbotson. It was called *The Analysis of Steel-Works Materials*. That same year, he teamed up with his old operatic lab mate, Colin Moorwood, and started a company, the Amalgams Co. He'd developed a unique claylike material, and they profited selling it to a local business. He and Moorwood spent every evening and weekend toying with new materials, and made a mess of one room in his house. Within a year, he'd written his second book, *The Analytical Chemistry of Uranium*.

Steel business was good, and in September 1903, Brearley's old employer, Thomas Firth & Sons, bought a steelmaking plant in Riga—Russia's second largest port, on the Baltic Sea—in order to produce steel for the massive Russian market without having to pay export tariffs. On Moorwood's recommendation, Brearley was hired to be the chemist. Arthur Brearley would join them too, probably on his brother's recommendation. Moorwood would be the general manager. Together Brearley and Moorwood traveled there in January 1904, in the dead of winter.

Brearley saw himself as steel's savior, its priest.

His style was casual. Men swapped roles, worked as a team, and were free to divulge their opinions. There was no organizational hierarchy. No mechanical precision. No engineered plan drawn up on paper. Moorwood OK'ed the arrangement, and agreed not to interfere. Under such management, Brearley found that he preferred novice steelmakers. They weren't biased by previous experience, or hamstrung by any preconceived notions. In time, he credited the Latvian peasants with skills rivaling those of his Sheffield pals.

Within the year, he was promoted to technical director, and put in charge of building a crucible furnace. He ordered some plans. The plans were wrong, but his furnace was right. He was also put in charge of selling high-speed tool steel. He surprised many customers by stripping from his business attire and working in the furnace, just like any of the other men, to demonstrate his product. Who was this Brearley: a technical director or a technician? With his long, boyish face, and big, dark, owlish eyes, Brearley still looked like a teenager. He was cleanshaven, with short black hair parted down the middle. He wore wire-frame spectacles. His ears were not lacking in prominence. By now, his adult persona had emerged: He was deliberate and devoted; confident but not dictatorial, and definitely not greedy. He was earning plenty of money, but he remained thrifty, never yearning for a big house or fancy cars or fine food. He was certainly no public speaker, and had no stomach for politics. He wasn't much of a salesman, as he had no ornamental graces, and few cultural graces. But he was good at his work.

The Russian Revolution came in 1905. The political and cultural revolt didn't bother Brearley so much; in fact, he wasn't especially repelled by socialism. (He'd joined the International Labor Party in England.) But the strikes made it impossible to produce steel, and this bothered him. The furnaces had to run constantly, or not at all. He couldn't start and stop them as the vagaries of politics demanded.

An impromptu public meeting was held on a vacant floor of the factory. Two thousand men showed up. Before the meeting started, revolver cartridges were distributed. Not long after, the foreman blacksmith was murdered outside his apartment. A half dozen factory workers were arrested and imprisoned. The state of affairs terrified many; three engineers fled the country. So did Moorwood. Brearley took his spot as general manager and kept it for three years. He sat in Moorwood's chair, at Moorwood's big horseshoe-shaped desk, in Moorwood's clothes, smoking Moorwood's cigars. It was the most extravagant thing he ever did.

With Brearley in charge, new equipment was in order. He bought a microscope, a galvanometer, and a thermocouple, and spent weeks toying with the latter instrument in a cellar. The cellar became the Friday-evening meeting-place for people who wanted to talk about steel rather than the revolution. During a strike, with nothing better to do, the cellar crew made a temperature recorder out of an old clock and a biscuit tin. They collected pieces of steel that had been hardened at different temperatures, fractured them, and compared them. They savored the mysterious specimens. They sought bewilderment for the sake of discussion. They argued into the night. Cut off from England and its supplies during the long winters, they were forced to adapt, innovate, or use substitute materials. In this way, they gained experience, and what remained in Brearley of any old steelmaking dogma faded away.

Brearley surprised many customers by stripping from his business attire and working in the furnace.

When Brearley returned to England in 1907, he was offered a position running the Brown-Firth Research Laboratories, a new joint operation run by John Brown & Company, which built battleships, and Firth's, which was working on armor plates. Notably, as research director, Brearley was given great freedom; he and his employer agreed, before he took the job, that he could turn down any project that didn't interest him. More importantly, on account of Brearley's interest in Amalgams Co., they also agreed to split ownership of rights to any discoveries.

BREARLEY WOULD SOON BE a dinosaur. But, as a quasi-free-agent analyst at Firth's, his knowledge surpassed that of many other analysts. Other steelmakers described good steel as having "body," attributing it to the type of clay in the crucible, or the source of the water, or the mine from which the ore came. Good steel was therefore mysterious, requiring interpretation. (One Sheffield crucible steel recipe called for the juice of four white onions.) When one steelworker, Henry Seebohm, suggested introducing colored labels to denote the carbon content of steels, Sheffield steelmakers objected. It was too scientific; it eliminated them as translators of intrigue.

Brearley knew qualitative descriptions were bogus misapprehensions, leftover ignorance from an age when science offered little insight. He staked out his turf, relying on skill and science—but not to the exclusion of experience. He ordered two of the earliest Izod notched-bar impact testing machines, each of which, with a calibrated pendulum, quantified the blacksmith's biceps. (The machines are still used today.) He didn't talk about body. He talked about Krupp-Kanheit, the result of cooling a nickel-chromium alloy too slowly, leaving it liable to fracture with a brittle, crystalline face.

Brearley saw himself as steel's savior, its priest. He valued depth over breadth. He examined details, concerning himself with quality. But he missed the big picture, and at Firth, had the wrong priorities. Firth cared about volume. Scale. Margin. Market.

Brearley knew that, as far as physical properties of steel go, there's no difference between an axle with 0.035 percent sulfur and one with 0.05 percent sulfur. But he missed the point: the difference, a manager told him, was £2 a ton. It was a lesson in politics as much as commerce; it didn't matter if the steel was no better. It only mattered that people thought it was better, and were willing to pay more for it.

But the lesson didn't stick; if anything, the business of modern steelmaking only hardened his resolve that it was all hogwash. "Time was," he lamented later, "when a man made steel, decided what it was good for and told the customer how to make the best of it. Then, with time's quickening step, he just made the steel; he engaged another man, who knew nothing about steelmaking, to analyse it, and say what it was good for. Then he engaged a second man, who knew all about hardening and tempering steel; then a third man who could neither make steel, nor analyse it, nor harden and temper it—but this last tested it, put his OK mark on it and passed it into service." It was a disgrace.

In May 1912 Brearley traveled 130 miles south, to the Royal Small Arms Factory in Enfield to study the erosion of rifle barrels. He examined the problem, then wrote, on June 4, "It might be advisable to start a few erosion trials with varying low-carbon high-chromium steels at once ..." He spent most of the next year making crucible steels with chromium from

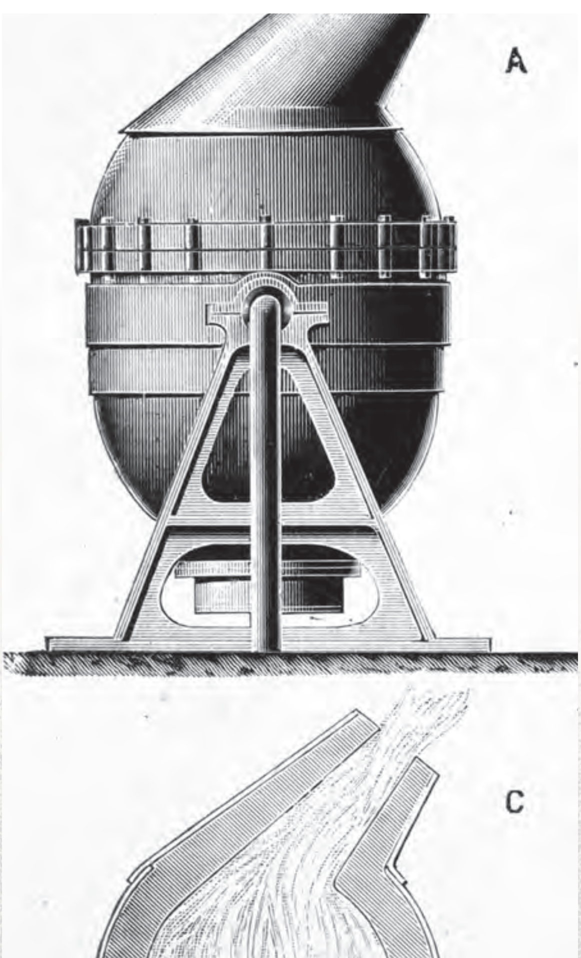
CHRIS WARE / STRINGER

6 percent to 15 percent, but they didn't stack up. Then, on Aug. 13, 1913, he tried the electric furnace, probably grudgingly. The first cast was no good. The second cast (number 1008), on August 20, turned out better. It was 12.8 percent chromium, 0.24 percent carbon, 0.44 percent manganese, and 0.2 percent silicon. He made a 3-inch square ingot and then rolled it into a one-and-a-half-inch-diameter bar. It rolled easily and machined well. From that, he made 12 gun barrels, which he sent to the factory.

The factory didn't like them.

Brearley noticed that cut samples of the metal he'd sent had funny properties. He later recalled that, suddenly remembering a date to the theater with his wife, he left some samples in water overnight, and found them unstained the next morning. He studied the metal by polishing it, then etching it with a solution of nitric acid dissolved in alcohol, and looking at it under a microscope. It wouldn't etch, or, rather, it etched very, very slowly. It reacted to vinegar and lemon juice the same way. He compared a polished sample of carbon steel to a polished sample of the chromium steel, and was amazed to find after 12 days that while the former had rusted, the latter remained shiny and bright.

Brearley wrote a report, and gave it to his boss. The new metal didn't excite anybody, as far as ordnance was concerned. Brearley couldn't let it go. He wrote another report for Brown's, highlighting the noncorrosive nature of the metal. Ditto for Firth's. He suggested that the metal might be advantageously used in cutlery, which, at the time, was made of carbon steel or sterling silver. (The former rusted, as he well knew; the latter was expensive and still tarnished, which really means that the copper, constituting 8 percent of the alloy, corroded.) The response was not even lukewarm. He didn't let it go. By the end of 1913, he couldn't stop talking about the utility of the new metal for cutlery. That he thought of cutlery first isn't surprising. He'd spent enough time as a kid helping his mother with domestic chores that he knew the toil associated with cleaning and drying forks, knives, and spoons. Sheffield had also been the center of the cutlery industry since the 16th century. He sent samples off to two Sheffield cutlers, George Ibberson and James Dixon. A few months later, a report came back: The steel wouldn't forge, grind, harden, or



SCIENCE & SOCIETY PICTURE LIBRARY / CONTRIBUTOR polish—and wouldn't stay sharp. It was useless for cutlery. Ibberson wrote back: "In our opinion this steel is unsuited for Cutlery steel." The cutlers called him "the inventor of knives that won't cut."

Still, Brearley wouldn't drop it; he said the cutlers were wrong, and said so impolitely. He suggested to his bosses that they sell heat-treated knife blanks. They said no. He suggested a patent. They said no. He continued to make a nuisance of himself.

In June 1914 Brearley met a cutlery manager named Ernest Stuart, of the cutlers Robert F. Mosley, whose persistence rivaled his own. Brearley and Stuart had gone to school under the same headmaster. Stuart doubted that a rustless steel existed but recognized that such a thing would be worth bothering about. He bothered by testing a piece in vinegar, after which he reportedly said, "This steel stains less." Stuart was the one who first called it stainless. He took a small sample. A week later, he returned with some cheese knives. He declared them rustless and stainless. But the steel was too hard, and had dulled all of his sharpening tools. He swore. He tried again, and the knives came back very hard, but very brittle. On the third try, Brearley was invited along to watch, even though he knew nothing about knife making. But he knew the temperature at which the steel hardened, and he helped make a dozen knives.

On Oct. 2, 1914, Brearley wrote another report for his bosses, when he realized that this new stainless steel could be useful in spindles, pistons, plungers, and valves—in addition to cutlery. If anything, it was this tenacity—this quasi-insanity—that set him apart from earlier discoverers.

Firth's soon recognized the industrial value of Brearley's steel for use in engine exhaust valves, and had begun marketing it as F.A.S.—Firth's Aeroplane Steel. In 1914, the company produced 50 tons of the steel; over the next two years, Firth's produced 1,000 tons more. Brearley bought 18 bars of it—125 pounds total, for 6 pounds, 15 shillings, 5 pence through Amalgams Co. He made knives and gave them to his friends. He gave them to Stuart's friends. He instructed them to return the knives if, upon contact with any food, they stained or rusted. No knife was returned. Stuart knew he was looking at the future, and ordered, over a few weeks, seven more tons of the metal.

Success brought immediate animosity, because Brearley had one vision, and Firth's had another. Firth's omitted Brearley's name. Firth advertised itself as the discoverer, inventor, and originator of stainless steel, in ads, posters, and labels on bars of steel. Brearley complained and got a bitter letter in response. Yet he insisted. He told his boss, Ethelbert Wolstenholme, that he'd given Firth's a commercial opportunity, and that it had agreed to share any discoveries. But he'd also proven the company wrong and was to suffer for it. He was ignored, cast aside, told to deal with underlings. Annoyed and suspicious, he wrote a tactless letter to his boss. This led to a conference with Firth's three directors, who told him plainly that he had no rights in the matter. A few days later, on Dec. 27, 1914, feeling wronged, more sad than angry—convinced that "workmen are often much wiser than their masters"—he resigned.

What's more, Harry Brearley didn't know it then, but the stuff he cast from the electric furnace at Firth's on Aug. 20, 1913, was nothing new. At least 10 others had created it, or something like it, before; at least half a dozen had described it; and one guy even explained it, and explained it well. Others had patented it, and commercialized it. Before Brearley got around to it, at least two dozen scientists in England, France, Germany, Poland, Sweden, and the United States were studying alloys of steel by varying the amounts of chromium, nickel, and carbon in it. Faraday had tried as much nearly a century earlier. It's not like Brearley was exploring unknown territory. That he is credited with discovering stainless steel is due mostly to luck; that he is credited with fathering it is due mostly to his resolve.

The early alloyers of steel had a difficult time commercializing their discoveries. Robert Hadfield, who made the first real, commercially valuable alloy, called Hadfield's manganese steel, had to wait a decade for it to take off. In his lab journal, on Sept. 7, 1882, he described the peculiar nature of his alloy: It was soft but tough, and tempering it made it softer and tougher still; and even though it was 80 percent iron, it wasn't magnetic. It astonished him. He wrote, "Wonderfully tough, even with a 16lb hammer could hardly break it ... Really grand. Hurrah!!!" It was bad for tools. It was bad for horseshoes. It was bad for fire pokers and car wheels. Hadfield grumbled in a letter to his American agent, "The material is being tried for a considerable variety of purposes but the people are so slow on this side & inventors here have so many prejudices." Finally, 10 years after he made it, it was found ideal for railroad tracks. It lasted almost 50 times longer than carbon steel, and became the standard for heavy-duty rails. With a new silicon steel Hadfield discovered in 1884, the situation was nearly the same. That time, he had to wait two decades before commercial viability became evident.

Commercial success demanded blending science and marketing; a steelmaker had to recognize not just the value of a new alloy, but its potential use. Benno Strauss, of the Krupp Works, later spoke about recognizing the potential of his stainless steel in plumbing, cutlery, medical equipment, and mirrors. He, like Brearley—who realized his stainless steel would be useful in spindles, pistons, plungers, and valves—was focused. Other steelmakers followed suit. Where the first alloys were named after the discoverer—Hadfield's manganese steel, R. Mushet's Special Steel, Firth's Aeroplane Steel (FAS)—later discoveries were marketed with an ear toward popular usage: Rezistal, Neva-Stain, Staybrite, Nonesuch, Enduro, Nirosta, Rusnorstain. In the naming of his alloy, Brearley owes a great debt to Stuart. He made FAS sound better than D.G.S. He made it sound like a miracle, and it worked.

A month after Brearley resigned, news of his stainless steel reached America. On Jan. 31, 1915, *The New York Times* announced the discovery:

> A NON-RUSTING STEEL; SHEFFIELD INVENTION ESPECIALLY GOOD FOR TABLE CUTLERY.
>
> According to Consul John M. Savage, who is stationed at Sheffield, England, a firm in that city has introduced a stainless steel, which is claimed to be non-rusting, unstainable, and untarnishable. This steel is said to be especially adaptable for table cutlery, as the original polish is maintained after use, even when brought in contact with the most acid foods, and it requires only ordinary washing to cleanse.

Here's another reason why Brearley is credited as the discoverer of stainless steel: Reporters at *The New York Times* weren't reading the metallurgical trade magazines. They didn't know about Monnartz and Strauss. The first American ingot of Brearley's stainless steel was cast 31 days later and sent directly to a knife maker.

Years later, a paragraph from Brearley's memoir would describe his outlook this way:

> The range of the mind's eye is restricted by the skill of the hand. The castles in the air must conform to the possibilities of material things—border-line possibilities perhaps; or, if something beyond the known border is required, the plan must wait until other dreams come true.

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AGING MAY BE the only universal process. Everything does it: living things, rocks, maybe even protons (we're not sure yet). Despite that—or because of it—we humans have long dreamt of conquering it. Even the hero in our oldest known piece of literature, the *Epic of Gilgamesh*, seeks and fails to find eternal life, "for when the gods created man, they let death be his share."

As modern science has peered into the clockwork behind aging for the first time, the old narratives persist, even if in new guise. The "Immortality Drive" aboard the International Space Station, which contains the DNA sequences of Lance Armstrong and Stephen Hawking, must be one of the more speculative efforts at NASA.

But science has also tempered our tilting at windmills. We understand today, better than ever, how aging is ingrained into the fabric of things, creating as much as it destroys, and intersecting with deeper currents like complexity and entropy. It's certainly not a breathless lust for immortality that we see on the pages of Don DeLillo's brand-new *Zero K*, which cocks an eyebrow at modern cryonics. Do we really want to "rewrite the future, all our futures, and [end] with a single empty page?"

Our relationship with aging is a window onto our true nature, because through it we confront the most dramatic of consequences. And like all good relationships do eventually, it is growing up.

Welcome to "Aging."

—MS

Nautilus *is excited to produce this issue in partnership with the Glenn Foundation for Medical Research.*

"The fact that most of Louisiana is sinking away illustrates just how short-lived this mature stage of the delta can be."

JUSTIN NOBEL
"The Birth and Death of a Landscape" p.54

Aging

THE UNIVERSAL PROCESS

Learning Chess at 40

What I learned trying to keep up with my 4-year-old daughter at the royal game

BY TOM VANDERBILT

MY 4-YEAR-OLD DAUGHTER and I were deep into a game of checkers one day about three years ago when her eye drifted to a nearby table. There, a black and white board bristled with far more interesting figures, like horses and castles. "What's *that*?" she asked. "Chess," I replied. "Can we play?" I nodded absently.

There was just one problem: I didn't know how. I dimly remembered having learned the basic moves in elementary school, but it never stuck. This fact vaguely haunted me through my life; idle chessboards in hotel lobbies or puzzles in weekend newspaper supplements teased me like reproachful riddles.

And so I decided I would learn, if only so I could teach my daughter. The basic moves were easy enough to pick up—a few hours hunched over my smartphone at kids' birthday parties or waiting in line at the grocery store. It soon became apparent, however, that I had no concept of the larger strategy. The chess literature was dauntingly huge, and achingly specific, with several-hundred-page tomes devoted to unpacking single openings. The endgame literature alone could drown a person.

So, time-starved and not wanting to curse my daughter with my ill-formed knowledge, I hired a coach to teach us both. We soon sat down to weekly sessions with Simon Rudowski, a Brooklyn-based Polish émigré whose Old World formality—and hint of sternness—lent what I thought was an appropriate gravity to the task.

It wasn't long before it struck me that chess seemed to be a game for the young. When my daughter began doing scholastic tournaments, I would chat up other parents and ask whether they played—usually the reply was an apologetic shrug and a smile. I would explain that I too was learning to play, and the resulting tone was cheerily patronizing: *Good luck with that!* Reading about an international tournament, I was struck by a suggestion that a grandmaster had passed his peak. He was in his 30s. We are used to athletes being talked

ILLUSTRATION BY ALEXANDER GLANDIEN

about in this way. But a mind game like chess?

Although it scarcely occurred to me at the time, my daughter and I were embarking on a sort of cognitive experiment. We were two novices, attempting to learn a new skill, essentially beginning from the same point but separated by some four decades of life. I had been the expert to that point in her life—in knowing what words meant, or how to ride a bike—but now we were on curiously equal footing. Or so I thought.

I began to regularly play online, do puzzles, and even leafed through books like *Bent Larsen's Best Games*. I seemed to be doing better with the game, if only because I was more serious about it. When we played, she would sometimes flag in her concentration, and to keep her spirits up, I would commit disastrous blunders. In the context of the larger chess world, I was a *patzer*—a hopelessly bumbling novice—but around my house, at least, I felt like a benevolently sage elder statesmen.

And then my daughter began beating me.

THE AGE QUESTION IS HOARY in chess. Indeed, one of the earliest discussions of the now-universal player ranking system called the "Elo rating" (named for its inventor Arpad Elo) was in a 1965 article in *The Journal of Gerontology*. Using his novel statistical analysis, Elo found that the peak age for master-level chess performance was around 36, with a slow steady decline after that.

That was then. Today, chess is only getting younger. Neil Charness, a professor of psychology at Florida State University, has long studied the question of chess and performance. "Bobby Fischer became a grandmaster at age 15," he says. "Then Judit Polgar beat his record." And then Sergey Karjakin beat Polgar, by doing it in 2002 at age 12. "The record of the youngest age to achieve grandmaster status," Charness tells me, "keeps getting beat." More recently, the 13-year-old Wei Yi became the youngest to rise above a 2600 rating. Magnus Carlsen, the world's current top-ranked player, was the youngest player to reach number one, at age 19. In a process akin to the "Flynn effect," or the global rise in IQ scores over much of the last century, chess ratings have risen over time. Charness notes that "younger players are getting skilled faster than they used to," thanks, in part, to better tools and better feedback:

> As we get older, there is one thing at which we get worse: Being a novice.

Sophisticated computer engines, databases, the ability to play players of any level at any time of the day.

Chess—which has been dubbed the "fruit fly" of cognitive psychology—seems a tool that is purpose-built to show the deficits of an aging brain. The psychologist Timothy Salthouse has noted that cognitive tests on speed, reasoning, and memory show age-related declines that are "fairly large," "linear," and, most alarming to me, "clearly apparent before age 50." And there are clear consequences on the chessboard. In one study, Charness had players of a variety of skills try and assess when a check was threatened in a match. The more skilled the player, the quicker they were able to do this, as if it were a perceptual judgment—essentially by pattern recognition stored up from previous matches. But no matter what the skill, the older a player was, the slower they were to spot the threat of a check.

It's not just that age slows you—you need to begin young, too. Charness points to research by Nicolai Krogius, a Russian grandmaster and psychologist, that shows a positive correlation between the age at which one first learns the game and later success in tournaments. This idea now seems so ingrained that Carlsen is held as a fascinating outlier; "at 5 years old," one account marvels, "an age by which any aspiring grandmaster should at least have made a start—Magnus Carlsen showed little interest in chess." Starting later, Charness tells me, seems to be a handicap. Even when adjusted for total experience, those who start earlier are more likely to reach an international level. "It's not just that you haven't accumulated the required amount of deliberate practice, but rather," he said, "there may be a plasticity thing here."

FRANCESCO IZZO

UNFAIR ADVANTAGE? My daughter en route to another victory.

As we get older, there is one thing at which we get worse: Being a novice. Charness, in one study, had subjects of various ages learn a novel word-processing application; some were experienced with similar programs, others were novices. The older the novice, the longer it took them to learn. "If you're talking about two novices," Charness said, when I asked him about my daughter, me, and chess, "your daughter would probably pick things up about twice as fast as you could." My daughter is, in effect, learning chess like a *first* language, whereas I am learning it like a second language.

Her brain, like a chessboard at the beginning of a game, is still full of infinite possibility, bristling with countless synapses that have yet to be "pruned." As the neuroscientist Peter Huttenlocher noted in *Brain Research*, a 7-year-old, like my daughter is today, has a brain that is almost fully formed, but has a "synaptic density" some 36 percent higher than the adult mean. She is, in a sense, still making sense of the world, and as she does, those synapses are closed—like emptying one's hard drive of little-used applications in order to help optimize overall performance.

What was happening in my brain-as-chessboard, by contrast, seemed more like a cagey, defensive middle-game battle, in which I was trying to hold onto pieces in the face of a closing denouement.

Denise Park, the director of research at the University of Texas' Center for Vital Longevity, described what was happening to me in unsettling terms. "As you get older, you actually see clear degradation of the brain, even in healthy people. Your frontal cortex gets smaller, your hippocampus—the seat of the memory—shrinks." My brain volume is atrophying annually, my cortical thickness dropping some 0.5 percent a year.

Where my daughter's brain was hungrily forming new neural connections, mine could probably have a used a few new ones. "You don't want to be pruning synaptic connections, you want to be growing them," Park told me. My daughter's brain was trying to efficiently tame the chaos. "For older adults," Park said, "there's not nearly *enough* chaos."

Back at the board, there seemed to be plenty of chaos. For one, my daughter tended to gaily hum as she contemplated her moves. Strictly *Verboten* in a tournament setting, but I did not want to let her think it was affecting me—and it certainly wasn't as bad as the frenetic trash talking of Washington Square Park chess hustlers. It was the sense of *effortlessness* that got to me. Where I would carefully ponder the board, she would sweep in with lightning moves. Where I would carefully stick to the scripts I had been taught—"a knight on the rim is dim"—she seemed to be making things up. After what seemed a particularly disastrous move, I would try to play coach for a moment, and ask: *Are you sure that's what you want to do?* She would shrug. I would feel a momentary shiver of pity and frustration; "it's not sticking," I would think. And then she would deliver some punishing pin on the Queen, or a deft back rank attack I had somehow overlooked. When I made a move, she would often crow: "I knew you were going to do that."

I would sometimes wander into the room when coach Simon was there, watching him present her with some puzzle on the board. I would struggle toward some solution, feeling smug, only to find I had completely botched it. My daughter, meanwhile, swiftly moved the right piece into position. He would shoot me a look, beaming at her precociousness. I was proud, I was frustrated. There are surely fewer greater parental satisfactions than to see one's progeny doing well at something. But there is altogether different feeling—a sobering slap of pathos, a vague sense of alarm that some genie had been let out of a bottle—when they exceed you on the same task. When a person who still cannot always successfully tie her own shoes, who has yet to do long division, can beat me at the royal game. She was Big Blue, and I was the human race, being slowly outmoded.

I RESISTED THE IDEA that I was just too old. I was stubbornly proud, competitive, but also curious. Was it just age, or was my daughter just an inherently better player?

I returned to the experts for reassurance. Park told me I was most likely at the peak of my cognitive power. For all my daughter's seemingly spritely processing power, I had higher-order capacities I could draw upon. "If you're younger, you can process information superfast," she told me, "but you may not know what to do with that information as you process it." She cautioned she was "oversimplifying" things, but I was happy to take it.

> The house took on the atmosphere of a war-room.

There are, I learned, two forms of intelligence: "fluid" and "crystallized." As first theorized by the psychologist Raymond Cattel, fluid intelligence is, basically, being able to think on one's feet, to solve new problems. Crystallized intelligence is what a person already knows—wisdom, memories, metacognition. Even if I was only learning chess for the first time, I had a lifetime of play behind me. Fluid intelligence is generally seen to favor the young, with the crystallized variety rewarded by age (though there are many exceptions). Old mathematicians doing their best work are as rare as young Supreme Court Justices. Chess, especially played at the top levels, can encompass both fluid and crystallized intelligence—one needs the firepower to quickly think through a novel position, but it also helps to draw upon a deep reservoir of past games (grandmasters like Carlsen can often identify a historical game with a glimpse at a single position).

Of course, my daughter, like most children her age, has not memorized a huge library of games; nor does she consciously think in terms of higher-level strategy. "I think I'll go with the Rubenstein Variation to the French Defense" is not a thought she will have. She seems to play with some brute instinct, pure fluid intelligence. As Daniel King, a London-based retired professional chess player who now analyzes and commentates chess matches, tells me, "children just kind of go for it—that kind of confidence can be very disconcerting for the opponent." Lacking larger representational "schema," the psychologist Dianne Horgan has noted, children players rely more on simple heuristics and "satisficing," choosing the first good-looking move.

Indeed, my daughter often makes a rapid-fire move, after which I invariably ask: "Do you want to take a little more time?" She rarely does. Experts, curiously, make similarly rapid intuitive judgments. Magnus Carlsen, for example, has described how he often makes a move quickly in his head, then spends a great amount of time verifying it is the correct one.

When I asked Rudowski, my daughter's coach, about the differences he sees in trying to teach beginner children and beginner adults, he said: "Adults need to explain to themselves why they play what they play. Kids don't do that. It's like with languages. Beginner adults learn the rules of grammar and pronunciation, and use those to put sentences together. Little kids learn languages by talking."

Here was my opening. I would counter her fluidity with my storehouses of crystallized intelligence. I was probably never going to be as speedily instinctual as she was. But I could, I thought, go *deeper*. I could get strategic. I began to watch Daniel King's analysis of top-level matches on YouTube. She would sometimes wander in and try to follow along, but I noticed she would quickly get bored or lost (and, admittedly, I sometimes did as well) as he explained how some obscure variation had "put more tension in the position" or "contributed to an imbalance on the queenside." And I could simply put in more effort. My daughter was no more a young chess prodigy than I was a middle-aged one; if there was any inherited genius here, after all, it was partially inherited from *me*. Sheer effort would tilt the scales.

The house took on the atmosphere of a war-room. I gravely analyzed opening lines and tried to keep on my toes with intense online blitz matches. She played in tournaments on chesskid.com but seemed as interested in being awarded little iconic trophies (like "Chess Marathon," for playing a game with more than 100 moves) as in actually beating other kids. When I asked her one day who she thought was a better player, she answered in a cheekily engineered way that both hinted she had picked up on the research I had been doing, and that she wanted to get under my skin: "I am. Because I'm younger and my brain is faster, and still growing."

Then, just a few weeks ago, months into her winning streak, I beat my daughter at chess twice in a row. Even if I had to work twice as hard to do it.

I learned that, as good as my daughter is at launching aggressive attacks, at almost clinically probing my weaknesses, she has a blind spot: What *I* am doing. She played, in those games, as if I were just some lower-level chess engine making haplessly random moves. Indeed, when I made my moves, her eyes would often drift elsewhere—as if what I was doing was almost inconsequential to the larger game. She failed to spot that my seemingly minor, unthreatening moves were all part of a larger strategic purpose. Against her onrushing fluidity, I was laying in a minefield of crystallized traps.

Both matches also went to the endgame, where I was able to draw upon my greater capacity for attention and pure endurance. And lastly, I noticed that even when it became clear (to me) she was going to lose, she wanted to press on. I had noted a similar tendency with her in playing poker: She always wanted to keep betting, to the bloody end, with the most marginal of hands, even as other players were showing strong cards. She was lacking that larger, strategically metacognitive sense, that Bayesian ability to use probability to change one's beliefs.

It was, in the end, a Pyrrhic victory. Not only has she since beaten me many times, but there was the look in her eyes as I checkmated her a second time. For whatever the games had taught me about brains young and old, about the different ways we learn and deploy our cognitive resources, they also taught me that the only thing harder than losing to your daughter in chess is winning against her.

TOM VANDERBILT writes on design, technology, science, and culture, among other subjects.

How to Survive Doomsday

The high technology that could help us live through the sun's inevitable transformation

BY MICHAEL HAHN & DANIEL WOLF SAVIN

LET'S BE OPTIMISTIC AND ASSUME that we manage to avoid a self-inflicted nuclear holocaust, an extinction-sized asteroid, or deadly irradiation from a nearby supernova. That leaves about 6 billion years until the sun turns into a red giant, swelling to the orbit of Earth and melting our planet. Sounds like a lot of time.

But don't get too relaxed. Doomsday is coming a lot sooner than that.

The Earth is, in some ways, in a precarious spot in the solar system. There's a range of orbital distances inside which a planet can have both liquid surface water (which is believed to be necessary for life) and enough atmospheric CO_2 to carry on photosynthesis. This range is called the photosynthesis habitable zone. The Earth orbits barely within the sun's zone. Some scientists estimate that the inner edge lies just 7.5 million kilometers away, which is only 5 percent of the distance between the Earth and the sun.

And that inner edge is moving out. Our sun is a massive ball of gas held together by its own gravity. At its center, the intense pressure and heat fuse hydrogen nuclei together to form helium. It takes four hydrogens to make one helium nucleus. As the number of nuclei in the core of the sun decreases by three with each helium nucleus formed, the outward pressure of the core also decreases (because the pressure is proportional to the number of nuclei per volume). In response, the outer layers of the sun squeeze the core harder, increasing its pressure, temperature, and fusion rate, leading to a 10 percent growth in brightness every billion years.

The Earth responds to this increasing brightness, in part, by decreasing the thickness of its warming blanket, which is provided by atmospheric CO_2. Rising temperatures on Earth speed up reactions between water and silicate-rocks, which in turn draws CO_2 out of the atmosphere. Sort of like changing your winter down comforter for a cotton sheet in the summer, this helps to keep the surface temperature of the planet habitable.

ILLUSTRATION BY SOPHIA FOSTER-DIMINO

LAST PLANT STANDING When atmospheric CO_2 falls below 150 parts per million, C_3 plants like wheat and rice will die off, leaving C_4 plants like corn, millet, and weeds.

Eventually, though, the warming sun will cause CO_2 levels to fall so low that plants will start to die. First to go will be the C_3 plants, so called because their photosynthesis process involves a molecule containing three carbon atoms. Most plants are of the C_3 type, including wheat, rice, barley, oats, soybeans, peanuts, coconuts, bananas, potatoes, cotton, and most trees. In about 200 million years, when the CO_2 concentration drops below 150 parts per million (it is at 400 today), C_3 plants will disappear.

Civilization relies mostly on C_3 plants, which make up about 85 percent of global agricultural production by dollar value. Another class of plants are C_4 plants, which employ a form of photosynthesis that involves four carbon atoms and is more efficient under many conditions. Although C_4 plants make up only about 3 percent of plant species, they account for about 25 percent of the total photosynthesis on Earth. In order to survive the die-off of C_3 plants, we will probably turn to genetic engineering to expand the list of C_4 plants. Today, C_4 plants include corn, sorghum, millet, and sugarcane, as well as some grasses and weeds.

Efforts are already underway to convert rice from a C_3 plant into a C_4, which would result in about 50 percent larger harvests under present-day conditions. At 100 ppm CO_2, the only rice on Earth would be C_4 rice. C_4 plants are thought to have evolved in response to the ongoing depletion of CO_2. It is likely that as C_3 plants die off, C_4 species will continue to expand naturally to fill the newly opened niches in the ecosystem.

Unfortunately, about 300 million years after C_3 plants disappear, C_4 plants will die out too. When the CO_2 concentration drops below 10 ppm, neither type of plant will remain.

Once plants disappear and cease replenishing atmospheric oxygen, animals will begin to die out. Currently, there are no known significant non-biological sources of oxygen on Earth. Once the plants are gone, oxygen will be a non-renewable resource. Large animals would probably asphyxiate within a few million years. Smaller and hardier creatures might last longer. Some types of microbes will probably survive by using metabolic reactions that do not rely on carbon dioxide or oxygen, but instead use materials such as sulfates or iron.

So that's the number: In a paltry 500 million years or so, no humans will remain on the surface of the

SHUTTERSTOCK

Not even cockroaches will survive.

Earth—at least, not outside of some hypothetical controlled environment. And things get worse from there. After the atmospheric CO_2 is gone and no longer able to regulate Earth's surface temperature, things will start to get very hot. In about a billion years, the average surface temperature will increase to above 45 degrees Celsius from the current 17 degrees Celsius. Important biochemical processes turn off at temperatures above 45 degrees Celsius, leaving most of the planetary surface uninhabitable. Animal life will need to migrate to the cooler poles to survive; but by 1.5 billion years from now, even the poles will be too hot. Not even cockroaches will survive.

Now, there are a few things we can do to stay our execution. We could, for example, move the Earth's orbit. If we fired a 100 km wide asteroid on an elliptical orbit that passed close to the Earth every 5,000 years, we could slowly gravitationally nudge the planet's orbit farther away from the sun, provided that we don't accidentally hit the Earth. As a less precarious alternative, we could build a giant solar sail behind the Earth with enough mass to drag the planet away from the sun. Such a sail acts like a kite, where the photons from the sun are the wind and the gravity between the solar sail and the Earth acts as the string. The sail would need to have a diameter 20 times that of the Earth but a mass only about 2 percent that of Mt. Everest, a mere trillion metric tons. Strategies like these could, in principle, keep the Earth in the habitable zone until the sun expands into a red giant. (If some other civilization has already built such a large solar sail, we could detect it using the same photometric techniques that are currently used to find exoplanets.)

Another survival choice is more complicated—or simpler, depending on your perspective. The future Earth will actually be a pleasant home for non-biological life—better than it is today. For one thing, the brighter sun will provide more abundant solar power. The space weather will also be nicer. The sun is a dynamo spinning on its axis about every 24 days, generating giant magnetic storms that disrupt communication networks, overload power grids, and damage orbiting satellites. Robots today need fear that their circuits could be fried by a solar storm, such as the large solar storm in 1989 that caused a power failure across most of Quebec. Currently, such storms are estimated to occur about once or twice per century. But as the sun ages, this rotation slows down and the magnetic storms will abate.

Given these facts, we humans might simply decide to upload ourselves into machines, which would be relatively comfortable on the dystopic future Earth. This would require advanced computing resources and a deeper understanding of neuroscience than are currently available, but there is no known fundamental reason why we could not exchange our biological hardware for robotic replacements. We could probably figure it out in the next few hundred million years.

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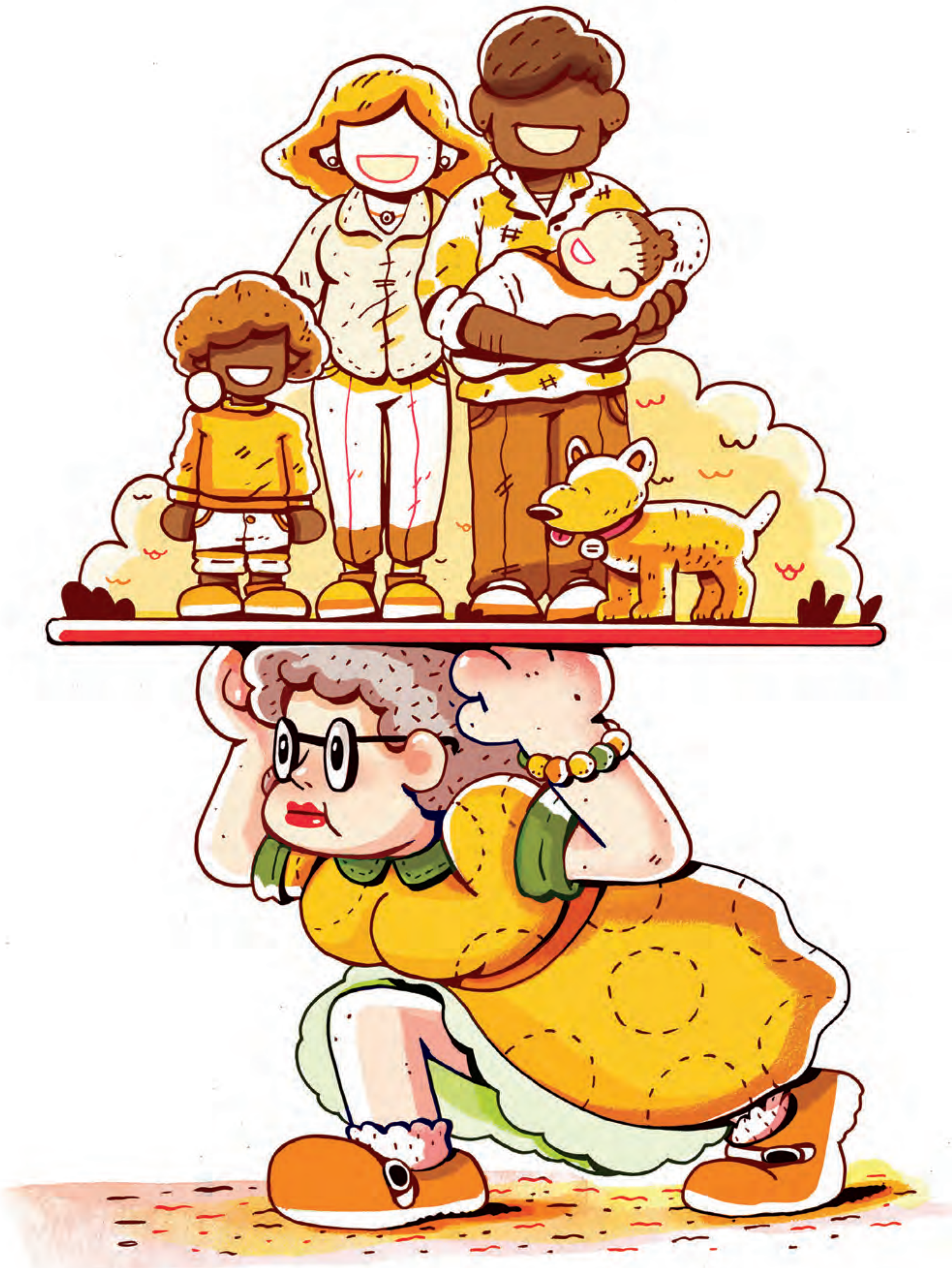

What Good Is Grandma?

The growing importance of grandparents in raising children is actually in line with human biology

BY DAVID P. BARASH

GRANDPARENTS ARE BUSY THESE DAYS. The number of juveniles in the United States under 18 living in a grandparent's household rose from 4.6 million in 2005-07 to 5.2 million in 2008-10, probably because of economic stress associated with the Great Recession.[1] Thirteen percent of grandparents provide regular care for at least one grandchild, and 62 percent have provided financial support of some kind to their grandchildren within the past five years.[2]

These circumstances can be stressful for youngsters, their parents, and their grandparents. But there is another way of looking at it: Today's grandparents are doing exactly what their biology has prepared them for.

In pretty much all other species, individuals reproduce until they can't anymore, and nearly always, this coincides with the end of their lives. Human beings are extraordinary, by contrast, in that long after we've stopped reproducing, we just keep on living. In particular, we appear to be the only animals in which half the population loses the ability to reproduce, through menopause, while they still have roughly one-third of their lives ahead of them, much of it quite healthy.

Natural selection rewards reproduction, and the mathematics show that a woman who produces an additional child will be favored over one who stops ovulating. (Reproduction offers the biological equivalent of compound interest; having just one more offspring means the potential of a whole lot of enhanced fitness, so selection should always favor giving it one more try, even if the would-be mother dies in the attempt.) As a result, the existence of menopause as a species-wide trait presents a species-wide mystery. Why don't people, like other perfectly good mammals, keep on reproducing until they die? Or, another way of looking at it, why do women stop reproducing in late middle age, and yet keep on living? The answer that is emerging from a productive confluence of evolutionary

ILLUSTRATIONS BY JACKIE FERRENTINO

theory and anthropology is that these old people—too old to reproduce, too young and healthy to kick the bucket—are highly biologically relevant.[3]

WHY, SPECIFICALLY, DO OUR BODIES begin wearing out so early compared to their potential lifespan, and why is women's reproductive function particularly targeted? Why don't kidneys similarly give up and shut down at age 50? Or lungs? The targeting of reproduction is especially perplexing since evolution rewards breeding above all else. Baby-making should be among the last things to go. Not only that, but modern techniques of artificial fertilization have made it possible for women in their 50s and even 60s to sustain pregnancy and bear healthy babies, showing that an aging female body can be up to the task.

> We're left with the likelihood that menopause is almost certainly adaptive.

Maybe women stop ovulating and menstruating around age 50 because they simply run out of eggs. After all, every girl is born with about 400 eggs, which are ovulated—roughly one per month—for approximately 35 years. But each XX embryo starts off with about 6 million primordial germ cells, and natural selection has generated all sorts of remarkable adaptations in other respects. There's no reason to think that evolution wouldn't be capable of endowing a woman with 500 or even 1,000 viable eggs if she could make good use of them.

Or maybe old is new and evolution just hasn't had a chance to keep up with our newfound longevity. After all, the average lifespan during most of our evolutionary past was considerably shorter than it is today. The truth is more complex, however. Most of the increased average lifespan that modern human beings enjoy today is a result of reductions in infant mortality. If one baby died at birth for every one who made it to age 60, the average lifespan would be 30, but there would still be plenty of 60-year-olds. Even some octogenarians. Moreover, for contemporary hunter-gatherer-forager people today, life expectancy at age 20 is about 70 years, two decades or so *after* menopause.[4] Almost certainly, there were old people in our past, just as there are today.

If only by process of elimination, we're left with the likelihood that menopause—the persistence of non-reproductive, elderly life—is not an illness, or something random, or a consequence of long modern lifespans. Nor is it testimony to evolution's lack of foresight, with natural selection somehow forgetting to fill 'er up with enough follicles. Rather, it is almost certainly adaptive, something that has been produced by natural selection because it benefits its possessors. But what's the payoff?

Consider, first, that natural selection isn't simply focused on producing as many children as possible. "Fitness" is a matter of projecting genes into the future, or, to put it more accurately, genes successfully promoting copies of themselves. Putting those genes in one's offspring is an efficient route, but so would be employing other bodies, with the importance of such bodies decreasing as they are more distantly related. This is the basic principle underlying "inclusive fitness theory," first clearly articulated by the late William D. Hamilton, and now one of the cornerstones of modern evolutionary biology.

Even if we consider only traditional Darwinian fitness—offspring—the issue isn't simply how many a woman generates, but how many are actually successful. Successful at what? Reproducing. Accordingly, offspring are evolutionarily important insofar as they, in turn, make their own offspring—that is, grandchildren. (Of course, this keeps going indefinitely into subsequent generations—but for the sake of understanding the process, grandchildren are enough.)

Let's consider, now, one of our great-great-great ... grandmothers. She is middle-aged, having produced, say, four children of whom two have survived to young adulthood. These two children are now about to become parents. What is the best, most fitness-enhancing thing that our middle-aged ancestral woman, their mother, can do? One possibility is that she could keep on having more children, which is what essentially all other mammals do. They breed 'till they drop. A problem with this strategy is that pregnancy,

FIRST FAMILY Marian Robinson (center), Michelle Obama's mother, is a live-in grandmother to Malia (far left) and Sasha (second from left). She lives in a suite on the third floor of the White House, one floor above her family.

OLIVIER DOULIERY- POOL/GETTY IMAGES

childbirth, and lactation are physiologically taxing, stresses that younger individuals can usually deal with quite well, but that generate increased morbidity and mortality as any would-be mother ages. (Even with the benefit of modern obstetrics, a woman over the age of 40 has a seven times greater risk of dying in childbirth than a 20-year-old does.)[5] So, our middle-aged momma could keep at it, maybe succeeding and maybe dying in the attempt. A naive view, based simply on reproductive arithmetic, suggests that she's better off (more fit, evolutionarily) if she tries than if she doesn't, simply because sometimes she'd succeed. But she might not just die trying; her loss might also mean that any of her young, dependent offspring would be deprived of her mothering, and this would actively diminish her fitness compared to a mother who refrained from having just one more child.

Among Jane Goodall's famous chimpanzees, the gloriously maternal Flo produced a youngster, Flint, in her old age. Flint wasn't quite weaned when Flo did it yet again, becoming mother to Flame. Shortly after, Flame died and so did Flo, perhaps because of the stress pregnancy and lactation imposed on her. In any event, Flint was left an orphan and he died within a month of losing his mother.

Flo wasn't an evolutionary failure. She had already produced three flourishing offspring, themselves reproductive. But she would have been even more successful if her body had "just said No" after Flint and before Flame. Primatologist Sarah Hrdy contemplated the sad case of Flo and her too-persistent reproduction, coming up with the "Prudent Mother Hypothesis." It suggests that menopause is a way that natural selection ensures that human beings, at least, don't make the same mistake. "Stopping early," according to Hrdy, "guarantees that old mothers who give birth to one last baby will care for it long enough to see this reproductive enterprise through to a successful conclusion." [6]

But why does evolution impose this order only upon human beings, and not chimpanzees, or other primates? These days, evolutionary biologists are increasingly convinced that the answer has a lot to do with another special characteristic of our species: our very long period of childhood dependency, which, in turn, is associated with how much we have to learn. Part of being a prudent mother, if you're of the species *Homo sapiens*, is that your job isn't done simply when you've popped out some offspring. Moreover, it isn't finished when those offspring have grown up, or even when they've begun to have their own children. Rather, those children—your grandchildren—also need to be successful, and for that, it evidently helps if someone (beyond the biological parents) is around to help rear that next generation.

The Grandmother Hypothesis helps make sense of a recent and intriguing finding: A particular variant of the immunoregulatory receptor gene known as *CD33* has been adjusted in human beings (compared with chimps) to be protective against late-onset Alzheimer's disease.[7] It seems reasonable that the chimpanzee equivalent of this illness, if it existed, would be disadvantageous to chimps, too, as it is in human beings. But chimpanzees don't experience a prolonged post-reproductive lifespan like we do, and so, they haven't undergone comparable selection to ameliorate the devastating effects of Alzheimer's or its parallel among chimps. A fundamental evolutionary insight is that selection is relaxed after reproduction has been achieved, and indeed, this helps make sense of the phenomenon of senescence generally.

Why don't people, like other perfectly good mammals, keep on reproducing until they die?

Natural selection is less potent as aging proceeds, simply because older individuals are less relevant as they have less reproductive future. This is almost certainly true for human beings, too, but apparently less so for us than for other critters. And according to the Grandmother Hypothesis, this is because, more than for other critters, old people can make a contribution to their own fitness by enhancing that of their offspring, via their grandchildren. By the same token, the fact that our species has apparently experienced selection that is at least somewhat protective against the ravages of old age suggests that even the elderly are valuable enough—purely in evolutionary terms—to warrant keeping them functional.

THE HADZA ARE HUNTER-GATHERERS currently living in modern-day Tanzania. Although there aren't many Hadza left (perhaps 1,000 or so), they've persisted in a lifestyle in which women gather and forage, while men hunt—harkening back, to some extent, to what paleo-anthropologists believe our ancient ancestors did for millennia on the African savannah. Kristen Hawkes, an anthropologist at the University of Utah, and her colleagues have found that among the Hadza, women bring in considerably more calories by foraging than men do by hunting. Not only that, but the hardest-working foragers—the ones who bring in the most calories of all—are post-menopausal women.

It's the grandmothers who provide edible roots, who gather more than their share of fruit, and who obtain gobs of honey, which is especially valued.[8] Teenagers and newly-weds forage for roughly three hours per day; married women with young children pitch in at an average of four and a half hours (it's difficult to dig and forage when you're also carrying a baby, never mind nursing as well). Grandmothers tip the scales at seven hours. The resulting "income" is far more than they need for themselves, and not surprisingly, they share the bounty with their children and grandchildren. Also not surprising: The body weight of grandchildren increases in proportion as their grandmothers contribute. Moreover, among the Hadza studied by Hawkes and her team, every nursing mother is supported by a post-menopausal helper, nearly always her mother or mother-in-law.

What's true of the Hadza isn't necessarily true for all people currently living a traditional lifestyle. Furthermore, it isn't guaranteed that today's gatherers and hunters offer an unobstructed view of how our early ancestors functioned. But it's the best that we currently have, and it strongly suggests that natural selection has favored mandatory non-reproduction among middle-aged women so that they could invest in their grandchildren.

For today's shrinking and increasingly stressed middle class, it seems that extended families are more needed than ever, as Mom and Dad have to work full time, leaving the grandparents to take up at least some of the slack when it comes to child-rearing: a modern day Hadza scenario, right here in high-tech America. The silver lining is that, in a sense, this is a return to form for the grandparent. According to the Pew Research Center, older Americans report that the best part of growing old, by far, is spending more time with family, especially grandchildren.[9] A 2013 study by Boston College found that emotionally close relationships between grandparents and grandchildren are "associated with fewer symptoms of depression for both generations."[10] There's also a growing granny labor pool: the numbers of U.S. grandparents are at record highs, and growing faster than the general population. By 2020, they are projected to represent nearly 1-in-3 adults.[11] They are also close by, with 69 percent living within 50 miles of their closest grandchildren.[12]

Thank goodness that they aren't burdened with their own young children and are available to pitch in, Hadza-style.

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The Birth and Death of a Landscape

A trip to a Louisiana river delta reveals an ecosystem that is growing up

BY JUSTIN NOBEL
PHOTOGRAPHS BY BEN DEPP

TO REACH THE YOUNGEST LAND in the United States you need a boat. Robert Twilley still vividly remembers the first time he made the trip. The Louisiana State University coastal ecologist piled into a 24-foot Boston Whaler with a bunch of geomorphologists from Minnesota and motored out to an arc of spongy islands along the central coast of Louisiana called the Wax Lake Delta. It was the best place to learn about how a delta develops. The way the land eventually stabilizes and becomes home to a unique ecosystem that changes as the delta gets older is a process that ecologists call succession. "Succession is one of the most fascinating concepts in ecology," said Twilley, "though one of the hardest to study. But in the Wax Lake Delta you can see it all. Biologic communities link up A to Z; it is the holy grail of ecosystem succession."

What is remarkable for scientists like Twilley is that with good muck boots, a small boat, and a non-aversion to intense sun, freak thunderstorms, biting insects, and devastating humidity, the aging process of this new land can be studied in a human lifespan. In just over 40 years, the Wax Lake Delta has grown from nothing to an area twice the size of Manhattan. Meanwhile, since the European settlement of North America, the Mississippi River Delta has lost approximately one-third of its original wetland area. A delta that was once about twice the size of Delaware and on maps resembled a head of cauliflower now looks more like a string bean. The slow death of the Mississippi River Delta has severe consequences, including reduced hurricane protection for cities like New Orleans. Not only an important food source for humans and wildlife, this rich habitat also helps filter pollutants and absorb excess nutrients that would deplete the oxygen in the Gulf of Mexico's water.

As one delta dies, another one grows. The budding Wax Lake Delta has allowed Twilley and his team of researchers to study how a delta ages. First, the nascent delta takes shape as lobes of sediment accumulate below the water. The delta is born when it breaches the surface of the water. Colonized by plants that gradually enhance the soil's organic content and raise its elevation, it rolls through childhood. And eventually, it grows into a landscape able to support large shrubs and black willow trees. "The delta is almost like an organism," says Twilley, "There is a birthing, there is an aging process, and there is a death."

Birth

Like many births, the Wax Lake Delta was something of an accident. In the 1930s, Morgan City, Louisiana was the economic hub of Cajun Country, where muskrat trappers, moss pickers, frog hunters, shrimpers, and lumbermen came in from the swamps to sell their wares and swill their profits. Meanwhile, back in the swamps roamed by bears and gators, a reddish brown liquid, which a century prior had been worthless, was beginning to be siphoned out of the muck—oil. As it was unearthed, this marshy metropolis boomed.

But there was a problem. Morgan City was perched on the lower reaches of the Atchafalaya River—a distributary of the Mississippi, branching off from the mighty river in central Louisiana and taking its own path south to the Gulf—and it flooded regularly. In 1941, to alleviate the flooding, the U.S. Army Corps of Engineers dredged a shortcut to the Gulf of Mexico called the Wax Lake Outlet, diverting about one-third of the Atchafalaya's flow.

> "The delta is almost like an organism," says Twilley. "There is a birthing, there is an aging process, and there is a death."

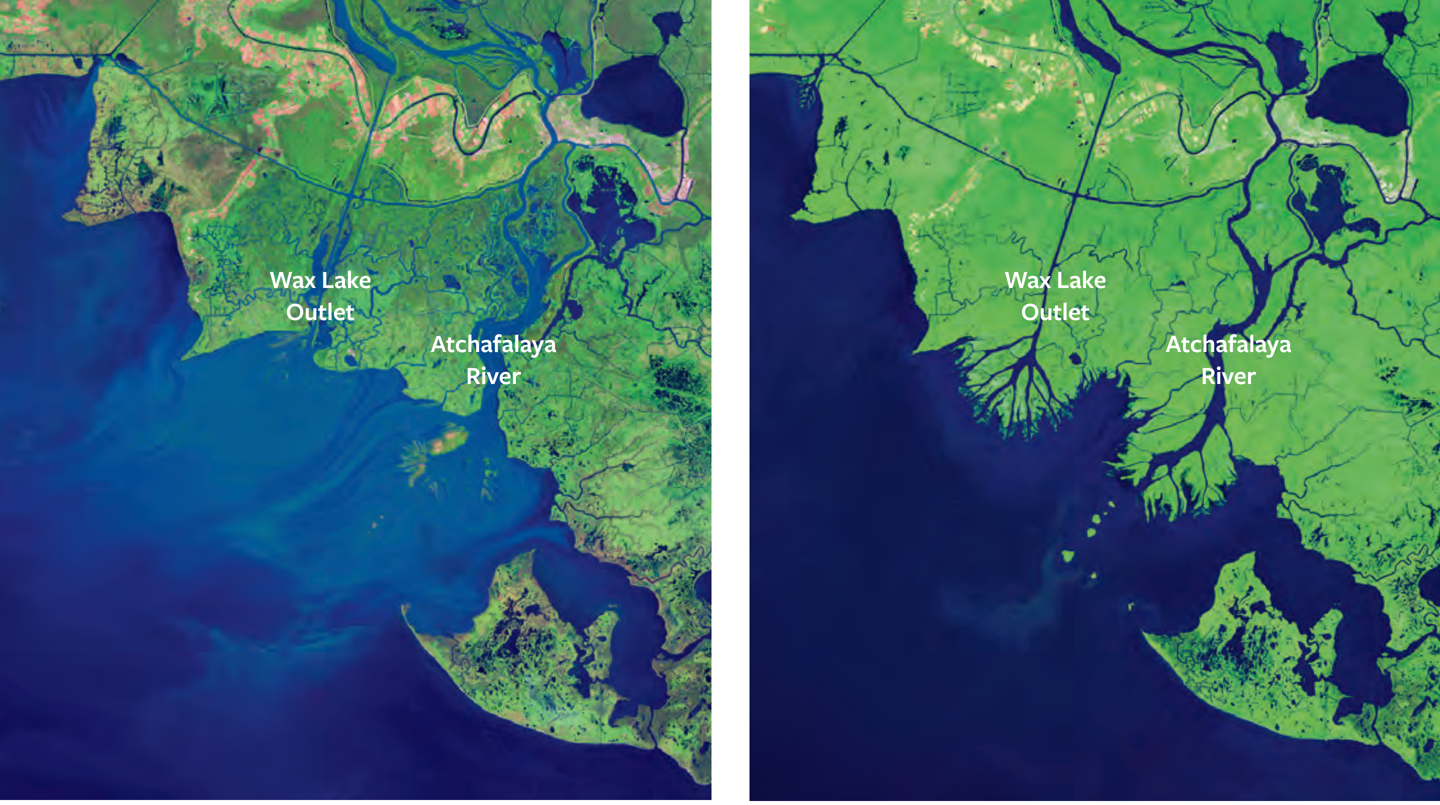
The Atchafalaya has been a Mississippi distributary for at least 450 years, though for centuries its entrance was choked off by a 20-mile-long logjam, likely accumulated from trees swept regularly into the river from eroded banks. In 1839, local residents attempted to remove the blockage by setting it on fire. They destroyed, according to a government report, an "immense mass of timber" and "thousands of alligators"—but the logjam remained. Finally, during the early 1840s, the state cleared the epic jam with barges specially designed for the task, called "snagboats." The Atchafalaya blossomed, and for the next century it continued to steal water and sediment from its parent river. "A steadily enlarging Atchafalaya River," warned a 1952 U.S. Army Corps of Engineers report, "may eventually capture the entire Mississippi." Such an event would have spelled disaster for cities like Baton Rouge and New Orleans, major port towns that suddenly would have lost their river, or at least a large part of it. To prevent that from happening, the Army Corps installed a system of floodgates in 1963.

Through the 1940s, '50s, and '60s, both rivers were depositing fine silts and clays into the bay, but the deltas had not yet breached the water's surface. For that they needed sand. While it takes about 90 days for a drop of water to travel the length of the Mississippi, and a particle of fine sediment can make the trip in about a year, for a grain of sand to run the length of the river can take a century. That's because silts and clays are carried suspended in the water, while coarser particles like sand are rolled, bounced, and jumped along the river bottom. Extreme flood events, though, can move a lot of sand quickly, which is exactly what happened during the Mississippi River flood of 1973.

"Dead animals were everywhere," read one newspaper article, "some in trees, mostly deer and cows, and other critters too weak to fight the rapidly rising water." Some 33 people also died, and there was more than $1 billion in damage. At the flood's peak the flow rate of the Atchafalaya quadrupled, and the sediment load doubled, a boost that made its way into the Wax Lake Outlet, too. Where the waterway entered the Gulf, lobes of sandy land emerged. As Twilley sees it, this was the delta's birth.

Adolescence and Maturity

On an early March morning a squall line is approaching the Louisiana coast, and I am standing with Edward Castaneda, one of Twilley's research associates, at the foot of a boat ramp beside the Intracoastal Waterway, a 3,000-mile ribbon of water that runs just inland of



SHIFTING SILT While the Mississippi River Delta has been washing into the Gulf of Mexico and receding, just to the west the Wax Lake and Atchafalaya River Deltas (pictured above) are growing. Satellite imagery shows how the deltas have grown between 1984 (left) and 2014 (right).

NASA / JESSE ALLEN

the coast from Texas to New Jersey, intended as a sheltered shipping passage. We are about to depart on a small journey. On a brightly colored map of the Wax Lake Delta, Castaneda lays out our route into the new territory, untrammeled by all, except scientists and hunters—the entire delta is part of a state-run wildlife management area.

Aside from the occasional winter cold front or monster hurricane, the Gulf is relatively tranquil. Because the tidal range is also low, and the discharge rate of the Wax Lake Outlet is high, the Wax Lake Delta remains a freshwater system, with the morphology shaped largely by the flow of the Outlet itself. The delta is fan-shaped, and composed of long arrows of land, separated by channels that have split off from the main outlet. These arrow-shaped islands point upstream, and the tips are the highest, and oldest, parts. They began as sandy lobes that further slowed the river's flow, helping to trap more sediment, and provided habitat for vegetation. Seeds arrived via the river, first subaqueous plants like longleaf pondweed, whose leaves rest on the surface, then lotus and arrowhead, plants with webby root systems that help trap and stabilize additional sediment. The delta's largest plant species are black willows. For Twilley, their emergence represents the beginning of the delta's adolescence.

Castaneda motors the Boston Whaler east along the Intracoastal, busy with barges carrying petrochemical products being pushed by sleek tugs. He is dressed for an excursion into some untrodden jungle, in camouflaged pants and dark shades. But the day's main mission is actually light work: Fix a downed data-recording station on Mike Island, located roughly in the middle of the delta. At a four-way intersection of waterways so perfectly perpendicular I almost expect there to be stoplights, we turn right, and proceed south down the Wax Lake Outlet and toward the Gulf. Here, there's virtually no river traffic. A warm wind buffets the bow;

GROWING UP The Wax Lake Delta was born during a flood in 1973. Now, ecologists keep a close eye on it to monitor how it grows and changes.

the squall line is getting closer, marking the leading edge of a storm system forecasted to last for three days and dump a foot of rain. The Outlet branches into two waterways, with a skein of low islands in the distance—we have entered the Wax Lake Delta.

To call southern Louisiana solid ground is misleading.

To our right is Camp Island, one of the oldest parts of the delta, built atop sand deposited in the Mississippi River flood of 1973. There is a line of tall black willows on the upstream-facing side of the island, which has the highest elevation, and in this tiny forest are rabbits and deer. The land is even stable enough for a much larger type of organism, humans. A row of primitive hunting shacks occupies the island's prime high ground, and fishermen come regularly to hook redfish, bass, and bluegill.

For the time being, the island is part of the delta, but eventually, sediment will choke the waterway separating it from the mainland and Camp Island will fuse with the coast. The mature stage of the delta also includes the formation of new coastal land. This process is what made all of the land in southeastern

Louisiana, including New Orleans, and why graves in New Orleans are above ground and houses tend to list. The city is built not atop solid rock, like say New York City, but squishy deltaic sediments. And the fact that much of southeastern Louisiana is sinking away illustrates just how short-lived this mature stage of the delta can be; if land here is not getting replenished with new sediments, it is wasting away. Maturity, it appears, perhaps much as it is with human beings, is fleeting and precarious, a thin ridge between adulthood and a long slow march toward death.

But Azure Bevington, one of Twilley's doctoral students, does not like to anthropomorphize the delta's succession. "I think describing the delta with these rigid growth stages takes away from the complexity, and I would argue, the beauty of the system," she says. Bevington describes a more chaotic succession, where the different parts don't move with such linearity or purpose. Her research has shown that willows first emerge on the high sandy levees that form on the edges of the delta's river channels during floods. The tip of Mike Island is lined with willows so uniform they look as if they were planted by a landscaper. Bevington believes they were probably seeded during several storms over the past 35 to 40 years. But curiously, as the island grows, new willow trees have not necessarily taken sprout. She thinks it is because the ground the willow seeds are falling on is already too thick with other vegetation, and thus the willow seeds are being outcompeted.

"Willows live to be 50 or 60 years but they are not regenerating themselves," Bevington says. "So when the willows die what I think will happen, and this is purely untested hypothesis, but I think the land will be colonized by more shrubby vegetation."

Maybe willows are not the peak, and like in a human life, physical robustness does not necessarily connote maturity. The climax of the delta, just like that of a human life, is perhaps more amorphous and unexpected. And perhaps aging itself is not a single arc toward a pre-defined destination, but an unsure wobble toward an unknown future.

MUCKIN' AROUND Ecologist Edward Castaneda approaches a damaged data-recording station (opposite page) on Mike Island, part of the Wax Lake Delta. The island barely rises above the water's surface and it is mostly made up of nutrient-rich muddy sediment.

Death

We are approaching Mike Island. The water is choppy and tinted orange, what I now know to be due to bits of clay, silt, and sand that have eroded off land somewhere upriver, potentially on the final leg of its journey to a new deltaic home.

Traveling with the sediments are nutrients, including nitrate fertilizer that runs off farms in Iowa, Illinois, and other Midwestern states each summer and is carried by the Mississippi into the Gulf of Mexico. There, it helps spawn algal blooms that use up oxygen supplies and can help cause a "dead zone" of oxygen-poor water that can grow to be the size of Connecticut and Rhode Island combined. These nitrates flow down the Wax Lake Outlet and into the Wax Lake Delta, where Twilley believes that the nitrates may actually be enhancing the growing vegetation on the delta. This is a good thing, he explains, because the more nitrates that get clogged up in the delta, the less are available to flow out into the Gulf and exacerbate the dead zone. One more largely unknown ecosystem service the delta is performing for us.

As the clouds are thickening, Castaneda ties up to a Spanish moss-draped black willow near the tip of Mike

Island. We have moored just beside a small tidal creek, one of many that help funnel sediment from a main outlet channel into the island's watery interior. This one happens to contain a baby alligator. Jumping off the bow of the boat I half-expect to sink right through the nascent island, born about 1990, but instead am greeted by spongy ground that sucks at my muck boots as I walk. Further proof that to call southern Louisiana solid ground is misleading; ground here is born of deltas, built upon layers of squishy sediments that, without continual replenishment, will eventually sink back beneath the waves.

That, of course, is exactly what is happening with the Mississippi River Delta, which continues to fray, eroding from wetland into the watery grave of the Gulf of Mexico. Presently, the Wax Lake Delta is growing faster than it is subsiding, though that could change in the near future, if subsidence, combined with sea level rise, outpaces the rate at which sediment is building up the delta. But sea level rise represents an unknown. "Certainly there is a tipping point," said Twilley. "But I am not sure what it is, and I don't think we will know until these phenomena play out."

Later we get back in the boat and continue south toward the open Gulf, the island's fringing line of willows slowly turning to marshy clumps. "All of this is still Mike," says Castaneda, pointing to the petering-out island. Smooth massive logs stuck in the channel indicate that not just sediment has made the long trek from way upstream. And the sky continues to darken. The orange-tinged river glows electric against the stormy sky, and is now rippled with white caps. Raindrops begin to fall. The long-predicted storm has finally arrived. But for the Wax Lake Delta, that may be a good thing. Rain upriver means erosion, which means new sediment, and for the delta, that means growth. The youngest land in the United States will get even bigger.

JUSTIN NOBEL's magazine articles on science and culture have been published in *Best American Science and Nature Writing 2014* and *Best American Travel Writing 2011*, and *2016*. This summer he will journey the Gulf and Atlantic coasts, documenting lifestyles and landscapes in the face of rising seas.

Yes, Life in the Fast Lane Kills You

New insights into mitochondria reveal how life expends energy

BY PHILIP BALL

NICK LANE IS AN EVOLUTIONARY biochemist at University College London who thinks about the big questions of life: how it began, how it is maintained, why we age and die, and why we have sex. Shunning the habit of our times to regard these as questions for evolutionary genetics, Lane insists that our fundamental biochemical mechanisms—particularly those through which living cells generate energy—may determine or limit these facts of life.

Lane has been steadily constructing an alternative, complementary view of evolution to the one in which genes compete for reproductive success and survival. He has argued that some of the big shifts during evolutionary history, such as the appearance of complex cells called eukaryotes (like our own) and the emergence of multicellular life forms, are best understood by considering the energetic constraints.

Lane's book *Life Ascending: The Ten Great Inventions of Evolution* was awarded the 2010 Royal Society Science Books Prize, the top prize in the United Kingdom for books on science. His 2015 book *The Vital Question: Why Is Life the Way It Is?* has been described as "game-changing" and "brimming with bold and important ideas." It offers a new, detailed model for how life might have begun by harnessing the incipient chemical energy at deep-sea vents. Bill Gates called *The Vital Question* "an amazing inquiry into the origins of life."

Nautilus caught up with Lane in his laboratory in London and asked him about his ideas on aging, sex, and death.

In your book *Power, Sex, Suicide* you ask, "When did the drive for sex become punishable by death, and why?" What do you mean?

Sex evolved with complex cells. If we go back to bacteria, they don't do sex as we know it. They do something similar—they swap genes, which is essentially what sex is doing: It's moving genes around. But we're combining them in different ways. The complex, eukaryotic cells, which include us, plants, fungi, and so on—all have sex. And that in itself is quite remarkable. But we don't really know what the advantage of sex is. This is something that arose in evolution in this large group of complex cells. It seems to be necessary, and it's linked tightly to death. The more we focus our resources on producing offspring, the better we will do in evolutionary terms. So if I focus all my resources on having sex,

ILLUSTRATION BY ALEXANDER GLANDIEN

then effectively I take resources away from longevity. I take them away from surviving for longer, and so I shorten my lifespan almost deliberately in evolutionary terms.

What do you mean that sex is linked tightly to death?
Death in that sense is a specific process called programmed cell death. It's controlled by the genes, it costs energy, and it's very deliberate. Cells that have become damaged kill themselves and remove themselves and are often replaced with pristine new cells from the stem-cell population. Sex is doing that at the level of individuals by recombining genes. What that's doing, in terms of natural selection, is increasing the differences between individuals. It's increasing the variability in the population, and that aids natural selection. And what natural selection is seeing as the differences between people is back to sex again. How many offspring are you leaving? For us, that particularly means men. Selection is very biased toward a relatively small proportion of men leaving far more children.

You mean that some males do well and some do poorly?
Yes. What sex is doing at the level of selection is enabling the best genes to leave more copies of themselves. It's increasing the variance in the population. So you have some very effective males and some fairly ineffective males, and it's giving the opportunity to the more effective males. It's not a very pleasant way of seeing the world from a human point of view. But that's basically what evolution is doing.

You trace energetic processes down to a part of the cell called the mitochondrion. Where did mitochondria come from?
They were bacterium that got into another cell. There's still argument about what that other cell looked like or was, but almost certainly it was quite a simple cell. And in the end the mitochondria became the power packs of our cells. So all the energy that we need to live is coming from the mitochondria.

How does this relate to aging?
There's a cost to living; there's a cost to doing everything. That cost depends on the speed at which we're living, to some degree. If we are living our lives at a very fast rate, we tend to wear out sooner. There is a strong relationship between metabolic rate—the rate at which we're taking in oxygen and burning up food—and lifespan. Under good conditions, we focus most of our resources on sexual maturation. I'm speaking not so much about humans as animals in general. But this goes beyond the animal kingdom.

There seem to be, in an evolutionary sense, almost no limits to longevity.

We focus resources on sexual maturation and leaving offspring. But if the conditions are unfavorable, if we're starving, there's a kind of switch from gearing up for sex and protein synthesis and bulking up to gearing up for survival: battening down the hatches and waiting out the bad times. This genetic switch has been the focus of most work on aging over the last decade or so. It relates not exactly to metabolic rate, but to flux, to the way in which we are focusing our resources. We're either focusing them on sex or we're focusing them on survival. Various genetic mutations can double or triple the lifespan of very simple organisms. It's much harder with something as complex as us.

All the same, we have an extraordinary desire for extending our lifespan. What are the best strategies? Some studies on calorie restriction in mammals seem to suggest this is a way to significantly increase lifespan. Is that going to work for humans?
It's pretty equivocal. There have been quite long-term studies, decades long, on rhesus monkeys, which give contradictory results. Some suggest it works quite well, extending lifespan by 30 or 40 percent. Others have suggested that allowing the control group to eat whatever they want, as much as they want, is actually quite destructive to good health, and so they live shorter lives than perhaps they should have. So there's a lot of uncertainties in the experimental design. Besides,

most humans would not wish to restrict their diet by 40 percent or so. There *are* some people who do it, but it's not clear if it actually extends their life. I heard of one case of someone who fell over and broke his bones surprisingly easily—it turned out that he'd got osteoporosis. So there are side effects.

What, then, are the real possibilities for human longevity?

There seem to be, in an evolutionary sense, almost no limits. That's what's really striking. Possums that live on an island without predators double their lifespan over five or six generations. And birds live far longer than they ought to if you extrapolate from their metabolic rate. A pigeon will live for about 30 years, even though, based on their high metabolic rate and body size, you would predict a lifespan of only three or four years. That's a tenfold increase. There are good reasons to think the reason that pigeons live a lot longer is that they have been selected for really high aerobic capacity; in other words, they're able to fly. There's a tremendous metabolic cost just to get off the ground, and so they have to have good mitochondria to do that. And part of having those really good mitochondria is that they leak very few free radicals. That seems to be one of the reasons why pigeons live so long.

We hear a lot about free radicals, particularly in relation to diet, and how we should take things with antioxidants to supposedly mop up free radicals and live longer. What do we really know about free radicals?

The free-radical theory of aging, as it was originally stated 50 or 60 years ago, said in effect that mitochondria produce these reactive forms of oxygen called free radicals. A certain proportion of the oxygen we are breathing gets released as reactive free radicals that can damage DNA, mutate DNA, damage proteins, or damage membranes themselves. And over time that damage builds up into what's called an error catastrophe, where the cell is no longer able to support itself. Over the last couple of decades the theory as originally stated has been comprehensively disproved; it's not true. The idea that we can prolong our lives or protect ourselves against age-related diseases, which include cancer and dementias, by taking large antioxidant supplements, is not true either. There have been a lot of studies and large meta-analyses done. And the data show quite convincingly that if anything you're more likely to die sooner if you take large antioxidant supplements.

VITAL QUESTION Why is life the way it is? "I believe the clue lies in the bizarre mechanism of biological energy generation in cells," says Nick Lane.

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Why don't antioxidants work, if oxidizing free radicals do damage our cells?

I think there's a very good and generally accepted reason: They interfere with signaling. We now know that free radicals signal a stress state in the cell. There are all kinds of subtle distinctions, but if something is going wrong, they are behaving like a smoke detector, or at least they are the smoke, and the cell is set up to detect the smoke and react accordingly. The trouble with antioxidants is they're in effect disabling the smoke detector, and that's not a good thing to do. The smoke detector sets off a stress response and that stress response changes the expression of all kinds of genes, which are protective for the cell. So very often more free radicals produces a stress response which is protective, which battens down those hatches and allows a cell to go on living for longer. Messing around with that signal by throwing antioxidants at it really doesn't help.

LIFE IN THE SLOW LANE Giant tortoises have an average lifespan of 100 years. This could be because their metabolic rate is incredibly low.

TREVOR WATCHOUS / EYEEM / GETTY IMAGES

If pigeons can live 10 times longer than their metabolic rate predicts, does that mean we could also do so?
In our case, we are limited by our brains. If we can replace everything—cells, tissues—as we live, then there would be presumably no limits to how long we could live. But if we replace our neurons, we're also rewriting our own experience in the process, and cease to be ourselves. I think that's the real penalty for extending life beyond the natural maximal lifespan of a neuron, which is 120 years or thereabouts. That's where I see the real limit. How do we prevent our brains from effectively losing mass over time, losing neuronal connections, losing synapses, which is where we're storing memories and experiences?

If we could regenerate neurons to replace damaged ones, do they come in a pristine state, ready to be imprinted with experience? Or are they conditioned by the neural pathways already present? And which parts of the brain are we talking about regenerating? Those associated with memory? Cognitive processing?
Neurons don't become imprinted with experience. But a single neuron may have 10,000 synaptic connections as part of a neural network, and we don't yet understand their contribution to the network as a whole. Cognitive processing seems inherently simpler to replace than memory; if synaptic connections store memory, how could a newly grown neuron reconstruct all those connections?

There are other interesting problems with replacing neurons. You can take a skin cell, for example, and reprogram it to become a stem cell. Amazingly, that works quite well. You can then induce this stem cell to become a neuron, and maybe use it to replace neurons dying off in the brain. If this new neuron can successfully establish the right connections, an important question is: What happens to its mitochondria? When you reprogram a skin cell, its mitochondria revert to look like those in stem cells—they become rounded and lose their electrical charge. But we don't yet know what happens to their DNA. Does it retain the damage it incurred in its former life in skin cells, or is it somehow cleaned up? If it remains damaged, then this shiny new neuron might be a charade, which will pack up quickly like a cheap plastic replica.

In *Power, Sex, Suicide* you write, "to live longer and to rid ourselves of the diseases of old age, we will need more mitochondria." Why do we need more?
If we think about lifespan and look to reptiles, to tortoises, they live an awfully long time. And the reason is they've got an extremely low metabolic rate; they hardly move at all, and so they live a long time just because their cells are not really under any real stress. At the other end of the spectrum, we see birds, which have a faster metabolic rate than we do. They have a higher body temperature, they consume more oxygen, and yet they live longer than mammals of equivalent size and metabolic rate. And they seem to have done that by selecting high-quality mitochondria and having lots of them, so they've ramped up the function of the entire system. So there's an almost U-shaped curve of longevity versus metabolic rate that I find really intriguing.

Where do we fall on that curve?
We are somewhere in the middle. Our lifespan is relatively short compared to either birds or reptiles for our body mass, because we have a fairly high metabolic

rate, but we don't have the high-quality mitochondria that birds have. That's partly a matter of the quality of the individual mitochondria, and partly due to the number of them. We've got 10 times as many mitochondria in our liver cells, for example, as a tortoise. So this seems to mean selecting for high aerobic capacity seems to increase lifespan. This is one of the reasons why birds and bats have very high power requirements: to fly and live a long time. Now, we live much longer than gorillas or chimpanzees. We seem to have been through a phase in early human evolution when we increased our aerobic capacity, our stamina. Whether this was related to chasing gazelles across the plains of Africa or what, I don't know. But we certainly have a high stamina and capacity to keep on being active compared to other great apes.

Do we know when that expansion of aerobic capacity happened in evolutionary terms?

I'm thinking a million years ago, rather than a couple of hundred thousand years ago. It seems to have been a relatively early increase.

Let's go deeper into the evolution of complex cells. Can you tell us more about the early union of bacterium and a host cell?

What's uncertain is what was the host cell that acquired this bacterium, and what was the bacterium that got acquired. We don't really know. But I have a fairly strong view on how this might have happened, strong in the sense that I think it's scientifically more pregnant with possibilities. A lot of evidence points to the fact that the host cell was a simple bacterium-like cell called an archaeon. It didn't have a nucleus to store its DNA and it didn't have sex. It didn't go around engulfing other cells. It acquired, by some kind of fluke accident, a bacterium that got inside and became the mitochondria. So we have two very simple cells involved, and one of them gets inside the other one. All of the traits of eukaryotic cells, which is our own type of complex cell, arose in the context of this interaction. All of this complexity—sex and lifespan and aging—arose in that context. That means that mitochondria, which are often dismissed essentially as a power pack, have been responsible for the evolution of all of this complexity, and are still very much central to it all.

Mitochondria are undersold as mere energy sources, then?

Well, if we're looking at how can we extend human lifespan, we've got to think about the mitochondrion not from the point of view that it's a power pack, but that it was one of two key players that gave rise to all of that complexity and are still absolutely central to it. Whether a cell is going to make a copy of itself, divide, or die, mitochondria are essential to all of that.

How might scientists, then, harness the manifold functions of mitochondria to expand human lifespan?

This is tough. The simplest way to replace bad mitochondria with good ones is to induce selection at the level of the cell—cells with bad mitochondria die, those with good mitochondria survive. So the first thing you need is cell turnover. Exercise can do that, even a good diet: Fruit and vegetables may be good for us in part because they contain toxins that stimulate cell turnover, and have little to do with antioxidants. The age-old advice is good—eat well and exercise. But that won't help us extend our lives much further.

When cells are not being replaced, selection doesn't operate at the level of cells, so bad mitochondria can proliferate. That happens surprisingly easily as we age, and in all kinds of diseases—the worst mitochondria proliferate at the expense of the good ones. Heart muscle fibers (which are not easily replaced either) can become ragged, as mitochondrial mutants take over.

The brain is still the big problem, but may hold a clue to the answer—mitochondrial transplants. I wondered for a long time how neurons could survive for 120 years with a stock of mitochondria they acquired at birth. It turns out that's not what they do; mitochondria can be transferred into them from stem cells down tiny connecting filaments. This sounds like science fiction, but if stem cells can pass on pristine mitochondria to neighboring neurons, it is almost literally an infusion of life. It won't be easy, but regenerative medicine might be the best approach—not replacing neurons directly but reinvigorating the stem cells.

PHILIP BALL is the author of *Invisible: The Dangerous Allure of the Unseen* and many books on science and art.

The Wisdom of the Aging Brain

Tantalizing evidence suggests that, as we age, brain activity shifts to increase wisdom

BY ANIL ANANTHASWAMY

AT THE 2010 CANNES FILM FESTIVAL premiere of *You Will Meet A Tall Dark Stranger*, director Woody Allen was asked about aging. He replied with his characteristic, straight-faced pessimism. "I find it a lousy deal. There is no advantage in getting older. I'm 74 now. You don't get smarter, you don't get wiser ... Your back hurts more, you get more indigestion ... It's a bad business, getting old. I'd advise you not to do it if you can avoid it."

Creaking bones and bad digestion notwithstanding, is that really the only face of aging? Turns out, it's not. At least for the fortunate few, old age may not be Woody Allenesque; instead old age is when they become compassionate and wise. Yes, wise.

While aging diminishes activity in certain brain regions, there's tantalizing evidence this may be compensated by changes in brain regions associated with supportive and social behavior. This shift in brain activity may foster wisdom in some people, a way of being that moves one away from self-centeredness toward emotional equanimity and wider social consciousness. We may even be able to work toward wisdom in old age.

FOR MILLENNIA, PHILOSOPHERS and theologians have been preoccupied with the notion of wisdom (the Greek word *philosophia* means "love of wisdom"). Centuries before the Greeks got into the act, the religious traditions of India and China, such as Hinduism, Buddhism, and Daoism, were thinking about wisdom, emphasizing the regulation of emotion—or emotional balance—as key to it.

Aristotle delineated wisdom into two types. One was the general, god-like, all-knowing wisdom, and the second (more pertinent to us mere mortals) was something called *phronesis*, or practical wisdom, which is the ability to be discerning about one's actions, knowing when and why to act in a pragmatic manner. Ideally, such wise actions—whether involving emotion regulation or reasoning—would balance self-interest against the interests of others and those of society in general.

ILLUSTRATION BY MATTHIEU BOUREL

Despite humanity's fascination with wisdom, it wasn't until about four decades ago that it became a topic of empirical study. Vivian Clayton, who practices geriatric neuropsychology in Orinda, California, was a graduate student in the 1970s when she began to seriously think about operationalizing, or defining and measuring, wisdom. Her study of both ancient and modern literature led her to define wisdom as judicious behavior, often involving social situations—behavior born of knowledge, imbued with thoughtfulness, reflection, and compassion.

By the 1980s, other psychologists got into the act. Swiss psychologist Jean Piaget, in the 1930s, had put forth an influential model of cognitive development, the final stage of which endowed us with the ability for abstract thought. Piaget saw this stage as the height of cognitive development, the highest form of reasoning one can achieve. But Woody Allen's bemoaning aside, is this the pinnacle of human ability? Psychologists speculated that there was more: the "more" being wisdom that came with life experience, and was potentially associated with getting older.

Such questions led German psychologist Paul Baltes, along with psychologist Ursula Staudinger, to start the Berlin Wisdom Project in the 1980s—a pioneering effort to pin down wisdom. "It was an interest in this notion of wisdom [as] an ideal endpoint of human development," says Staudinger, who today is the director of the Robert N. Butler Columbia Aging Center, at Columbia University.

Baltes and Staudinger defined wisdom as "expertise involving deep insight and sound judgment about the essence of the human condition and the ways and means of planning, managing, and understanding a good life."

Intuitively, the ability to be wise seems as if it should grow with age, but their research showed that it's not enough to get older to get wiser. Other processes that come with aging could hamper the emergence of wisdom. Aging diminishes what Baltes and

SPLIT WISDOM Legend has it that King Solomon had the wisdom to settle complex debates, like a child's parentage, but had a rather unwise private life.

There may be a specific neurocircuitry of wisdom.

Staudinger called the “mechanics” of the mind—which depend on the biology of the brain, such as the number of neurons, the connectivity, metabolism, and the speed at which the brain can process new information. The mechanics of the mind reach their peak around the age of 25 to 30, and then decline steadily.

Many studies have shown that the aging brain gets slower. For instance, the ability to carry out mental operations definitely declines. As does our capacity for episodic memory and executive function (which is necessary for planning, multitasking, and verbal fluency, among other tasks), due to dysfunctions in the medial temporal lobe memory system and the frontostriatal networks, important for executive function.

But all’s not lost. “What doesn’t go down is reasoning and cognition that is based on knowledge and experience,” says Staudinger. This ability, which reaches its peak between the ages of 40 and 50, and then stays stable and declines only during the final years of one’s life, could contribute to wisdom, as long as we stay mentally active and engaged. Evidence from studies of rhesus monkeys supports this observation. This involves structures called dendritic spines, which protrude from one neuron’s dendrite toward another neuron’s axon. These spines have a neck and a head. Those with long necks and small heads decline with age, but the shorter, stubbier “mushroom spines,” hypothesized to be “locus of long-term memories,” don’t decline. That potentially explains why our ability to learn new things suffers as we age, yet abilities that depend on lifelong learning (such as playing a musical instrument) don’t.

Following Baltes’ death in 2006, Staudinger has come to differentiate between so-called general and personal wisdom. She has found that while general wisdom—the ability to make wise decisions about others—stays more or less stable over one’s lifespan, it’s much harder to be wise about one’s own life. Personal wisdom is not easy.

Nothing illustrates this more than the story of King Solomon of Israel, whom both Christians and Jews regard as an exemplar of wisdom. When two women came to him with a baby, each claiming the baby was hers, Solomon suggested cutting the baby in half. When one woman cried out that the baby should be spared and given to the other woman, Solomon identified her as the real mother. Solomon demonstrated general wisdom. “At the same time, Solomon had a private life that was completely unwise,” says Staudinger.

Igor Grossmann, who studies wisdom at the University of Waterloo in Ontario, Canada, thinks that the ability to be wise about one’s own life has a lot to do with one’s sense of self. “In Western culture, there is this

Wisdom comes from a balance of activity in brain regions.

idea that the self is kind of an independent entity, that everybody has a very clear-cut independently-defined concept of who he or she may be," says Grossmann.

And that often makes a person vulnerable. "What you find is that if you put people in a situation where their self is threatened, then people are not very good in engaging in any form of wise reasoning. They want to quickly defend their self," says Grossmann.

Grossmann's cross-cultural studies have revealed that in cultures where the self is seen as more interdependent, more reliant on relationships with other people—such as in Japan—people are less threatened by perceived dangers to one's self, and are more able to engage in wise reasoning.

But studies show that even for those of us who take offense easily, it's possible to boost the ability to reason wisely by creating some distance between you and, well, your self. Clinical psychologists call this process decentering: You take an observer's view of something that's happening rather than being a participant.

Grossmann says that loosening the hold of the self can help with wise reasoning, even as we age. One way to decenter as you age is to live in an interdependent manner, surrounded by people, so that you don't feel alone and threatened.

"Old age is not necessarily a time when everything declines," says Grossmann. "Many of these types of processes are flexible, and you can train them." Via meditation, for example. "Many of the meditative practices include this type of third-person perspective, where you detach from the immediate self, you become an observer," says Grossman.

There's plenty of evidence that meditation induces neurobiological changes. Sara Lazar's lab at the Harvard Medical School in Boston has shown that even eight weeks of meditation can increase gray matter density in brain regions associated with executive function, working memory, and—importantly, from the perspective of wisdom—empathy, compassion, and self-distancing. In another study, her team showed that certain regions of the prefrontal cortex were as thick in 40- to 50-year-old meditators as they were in 20- to 30-year-old meditators and control subjects.

THE BRAIN'S PREFRONTAL CORTEX especially interests Dilip Jeste, a former president of the American Psychiatric Association and director of the Sam and Rose Stein Institute for Research on Aging at the University of California, San Diego. He speculates that it may be part of a network of brain regions responsible for wisdom.

To understand wisdom and its possible

neurobiological underpinnings, Jeste and his colleagues took a multipronged approach. The first was an extensive literature survey, to identify what researchers mean by wisdom. Second, they put together a panel of experts, and canvassed their opinions on a list of traits. (Jeste considers wisdom a personality trait; not everyone does.) The experts responded anonymously, tagging each trait as necessary for wisdom, intelligence, or spirituality—a trait could belong to one, two, all three, or none of them. Each expert was then sent the panel's average response, and the process was repeated. "It was clear that the experts viewed these three as slightly overlapping, but largely independent concepts," says Jeste. For example, "wise people are intelligent, but intelligent people are not necessarily wise."

The researchers went further. They interviewed hospice care patients, who were nearing the end of their lives, about what they thought about wisdom. Finally, they addressed an issue that confounds wisdom research: cultural specificity. With help from a medical anthropologist and some special software, Jeste analyzed *The Bhagavad Gita*, a spiritual treatise that is considered the philosophical cornerstone of Hinduism, dating back to the last few centuries B.C. "We looked at wisdom and its synonyms, like sagacity, and antonyms, like foolishness, folly," says Jeste. "We wanted to find out how many times those words were used and more importantly in what context in the *Gita*."

Their analysis was revealing. "What was really striking and surprising was that the components of wisdom looked at in these different ways are surprisingly similar," Jeste says.

The team identified six components of wisdom: having pragmatic knowledge of life; emotion regulation; pro-social behavior, which would entail compassion, altruism, and empathy; knowing one's strengths and limitations; decisiveness; and finally, acceptance of uncertainty.

More striking was the consistency over time. "Why should the concept of wisdom not have changed from thousands of years B.C. to today?" says Jeste. "To me it suggested that it should be biologically based. If it is biologically based, then where would it be based? Obviously in the brain, but where in the brain?"

Jeste's team went back to the literature. They looked at studies on brain imaging, genetics, neurochemistry, and neuropathology that targeted these individual components of wisdom, and their opposites; for example, the opposite of emotion regulation is impulsivity, and the opposite of pro-social behavior can be found in the actions of anti-social personalities.

Case reports of patients with brain damage, either due to injury or strokes, were enlightening. Jeste recalls reading the published case of an intelligent young soldier in his 20s, competent, well-adjusted, and happily married. One day the Jeep he was riding in went over a landmine. The resulting brain injury transformed his personality. He would divorce and remarry—three times. He barely managed to hold down a job as a newspaper delivery man. The damage to his brain was localized to the prefrontal cortex.

Further clues emerged from a form of neurodegenerative disease called behavioral frontotemporal dementia (bvFTD), in which the damage is again restricted more or less to the prefrontal cortex. People suffering from bvFTD often start making bad decisions, show lack of insight, become impulsive, passionate, and sometimes anti-social. "If you look at the symptoms, they are the exact antithesis of wisdom," says Jeste.

In a recent retrospective study of 2,397 patients seen at the Memory and Aging Center at the University of California, San Francisco, researchers found that those diagnosed with bvFTD were far more likely to engage in criminal behavior compared with those suffering from Alzheimer's disease (AD). "Common manifestations of criminal behavior in the bvFTD group included theft, traffic violations, sexual advances, trespassing, and public urination in contrast with those in the AD group, who commonly committed traffic violations, often related to cognitive impairment," the researchers wrote.

For Jeste and colleagues, the evidence was enticing. "Based on all of those, we suggested there is a neurocircuitry of wisdom," says Jeste. This circuit involved the dorsolateral prefrontal cortex (responsible for rationality, discipline, and self-preservation), the ventromedial prefrontal cortex (associated with "kind, supportive, social, and emotional behavior needed for survival of species"), the anterior cingulate (which mediates conflicts between parts of the prefrontal cortex), and the striatum with amygdala (part of the reward circuitry).

According to Jeste, wisdom comes from a balance of activity in these brain regions. "In some way, wisdom is balance. If you are very pro-social, you give everything to other people, you won't survive. But of course, if you don't give anything to others, the species won't survive. You have to have balance."

When we are young, we like our jokes to be bizarre.

Despite such evidence, Jeste is cautious. "It'd be unwise of us to say that this is *the* neuro-circuitry of wisdom," he says. "We don't know that. It is a hypothesis. Empirical research may show that it is totally wrong and something else is right. That's fine."

And what does this have to do with aging? Jeste points out that aging is associated with a shift in brain activity. For instance, there's something called Hemispheric Asymmetry Reduction in Older Adults (HAROLD)—a phenomenon in which the half of the prefrontal cortex that is less active in youth (which half depends on the individual) shows increased activation during old age, increasing overall activity in the prefrontal cortex. There's also a shift in activity during old age from the occipital lobes, which is associated with sensory processing, to the prefrontal cortex (the so-called posterior-anterior shift with aging).

None of this is to suggest that older people are wiser by default. "Wisdom and aging are not synonymous," says Jeste. "You see young people who are very wise for their age and you see old people who are very unwise. Having said that, it's more likely that with aging you can become wiser."

But why? Jeste has often asked himself the same question. As we get older, we develop infirmities, diseases, and disabilities. "If we are supposed to live long with disabilities without contributing to the species, it doesn't make sense, unless something improves with aging to compensate," says Jeste. "The idea is that this is wisdom."

Another association of old age with wisdom comes from studies of humor. Turns out that when we are young we like our jokes to be bizarre, incongruous. As we get older, we find jokes funnier if they don't merely have incongruous punchlines but also have an overall coherence. "You could make a loose connection between that and perhaps wisdom, where if you think of wisdom as being more interested in how things fit together, and less interested in what is bizarre or different," says neuropsychologist Hiram Brownell of Boston College.

Staudinger worries that we risk diluting the essence of wisdom by taking too broad a view. Sure, there are things we do better as we age, but she thinks that's more to do with leading an adjusted, well-balanced life. It's well known that older adults are better able to focus on positive emotions and avoid negative emotions—something that can be seen as wise. But according to Staudinger, that tells us that we are becoming more socially competent and well-adjusted as we age—but not necessarily wise.

Wisdom, says Staudinger, includes being able to handle negative emotions and "actually stick to the negative emotionality just long enough to learn from it, and not do away with it or avoid it altogether." Often, she adds, "we really have to be exposing ourselves to very unpleasant states," if we are to grow rather than adjust.

Staudinger and her colleagues have carried out over 1,200 "wisdom interviews" since the 1980s, of people ranging in age from 12 to 95. She thinks less than 1 percent of those interviewed displayed levels of insight and judgment necessary for wisdom according to her team's definition—a capacity to tolerate negative emotions and learn from them, a penchant for thinking about the next generation and the common good over one's immediate needs. "Very few people develop the ability to transcend their body, transcend their own self," says Staudinger.

While it's clear that our definition of wisdom makes it more or less likely that we'll achieve that exalted state as we age, it's also clear that those who do live wise lives benefit not just themselves but humanity itself.

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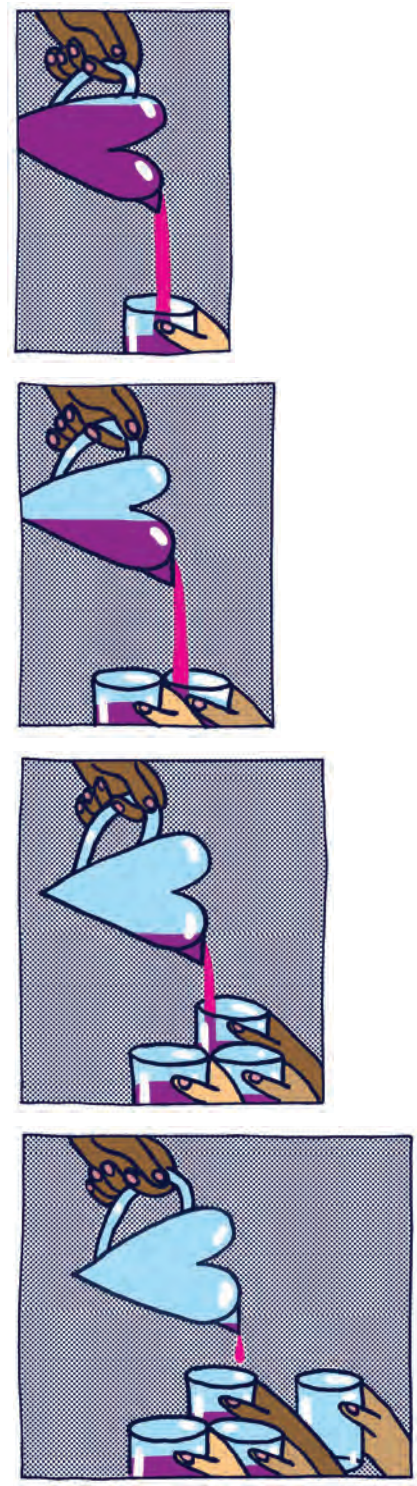

ILLUSTRATION BY **HANNAH K. LEE**

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THERE IS A MILES-LONG solitary wave trundling its way across an ocean right now. It will travel for days on end without changing its shape, before dissipating its billions of joules of energy onto some unseen shore or trench. If you had traveled with it, it would have seemed like the ocean is moving backward, and it is standing still.

Before the 1800s, so-called soliton waves were unknown to science, and they remain imperfectly understood today. They are testament not just to the weirdness of non-linear physics, which works against the linear dispersion that would normally lead to the wave's quick dissipation; but also, simply, to the surprising ability of distant things to come near.

From motes of methane pushed by distant starlight, to words smuggled out of a silent place—our world is full of unseen currents that carry us along.

Welcome to "Currents."

—MS

"I felt more than saw the huge shelf cloud, a wall of black striped with electricity, surge forward over the ridge of the Allegheny Mountains."

SARAH SCOLES
"The Strange Blissfulness of Storms" p.78

Currents

DISTANT TRUTHS

The Strange Blissfulness of Storms

Is there a biochemical reason that extreme weather makes us happy?

BY SARAH SCOLES

ILLUSTRATION BY RED NOSE STUDIO

I **FELT PRETTY SURE SOMETHING** was wrong when the deer began running toward me. I knew something was wrong when a pine branch flew by my head. The air went dark and a noise like a train barreled through the forest, the actual wind coming after the sound of itself. The trees all swayed in the same direction, and then came the slap of thunder.

I felt more than saw the huge shelf cloud, a wall of black striped with electricity, surge forward over the ridge of the Allegheny Mountains overlooking Green Bank, West Virginia. A sharp line against the blue sky, it looked less like weather and more like a Rothko. I lived in this remote town, and I was on my usual afternoon run, picking my way across the trails that led from my house to the National Radio Astronomy Observatory, where I worked. Adrenaline told me I needed to fly, faster.

I ran two miles in 12 minutes, a pace I'd never maintained before and never have since, hurdling downed trees and power lines. When I got back to my house, surprised to be safe, I dragged my dog down to the farmhouse basement. After a restless 30 seconds, though, I bolted back upstairs, threw the door open, and stood on the porch. A wall of wind hit me. Lightning struck like a strobe. I felt awakened, alive, engaged. As the edge of the front pushed forward, the force seemed to clear the air and charge the whole scene with yellow-lit significance.

I'm not the first to feel this way, or write about it. "It was his impression that not just he but other people too felt better in hurricanes," wrote Walker Percy in *The Last Gentleman*, a novel published in 1966. Today, people crowd around Weather Channel broadcasts and cross their fingers that storms will strengthen. They get giddy over thundersnow. Percy, a philosopher as well as a novelist, was intrigued by the phenomenon. In one of his earliest essays, published in the 1950s, he asked, "Why do people often feel bad in good environments and good in bad environments?"


W
E

Why hurricanes elevate our mood—lifting us out of a malaise we might not even know we're sunk in—is a rich question for philosophers, novelists, and people who like philosophy and novels. It's deepened by the fact that our giddiness often comes spiked with guilt, and a revulsion at ourselves for hoping for, and enjoying, something so destructive.

But the thrill of storms may not just be a psychological phenomenon. A branch of science called biometeorology attempts to explain the impact of atmospheric processes on organisms and ecosystems. Biometeorologists study, among other topics, how the seasons affect plant growth, how agriculture depends on climate, and how weather helps spread or curb human diseases. For decades now, a faction have looked at how charged particles in the air, called ions, might alter our psyches as they wing in on the wind.

Explanations of the environment's impact on us sometimes crash at the intersection of science and pseudoscience. The idea that electrically charged molecules affect humans has led to dubious cures like negative air-ionizing therapy. But recent, rigorous studies have hinted at compelling links between ions, physiology, and psychology. The collision of that work with the science of storms could bear a message of connection for us all.

> A wall of wind hit me. Lightning struck like a strobe. I felt awakened, alive, engaged.

SCIENTISTS FIRST ATTEMPTED to unweave the web between air ions—whose composition changes with weather and environment—and human mood in the mid 20th century, when ion-generating machines and ion counters became more standardized and available. Ions, natural or ginned up inside a device, are electrically charged particles: Negative ions have an extra electron, and positive ions are missing an electron. Positive ions get their spark when some force—like the scrape of air over land or shear from water droplets splashing—strips an electron from them. That electron goes on the rebound and attaches itself to a nearby oxygen molecule, which then becomes a negative ion.

In the wild, people encounter the greatest densities of negative air ions in pleasant, hydrated places and during summer months. Breaking ocean waves and falling water—dropping from the sky or flowing over a rock ledge—release a rash of negatives into the air. So do bolts of lightning. Positive ions—often associated with pollutant particles like smoke, smog, and dust—are more prevalent indoors, in urban areas, and in the winter. The leading edges of storms and hot, dry winds like the Santa Anas in California also blow them in.

Medical doctor Daniel Silverman of New Orleans and Igho Kornblueh of the University of Pennsylvania in Philadelphia were first to test whether the shifting tides of ions do anything to the human body or mind. Is either polarity good or bad, or are they both neutral? In 1957, they gave subjects 30-minute treatments with air ions from ion-generating devices.

During the treatment, Silverman and Kornblueh watched patients' electrical brain activity on electroencephalograms. Their long, slow, alpha waves looked calm and relaxed when they were surrounded by negative ions, positive ones, or both at once (not exactly conclusive). Another research group later confirmed chilled-out brain activity and sharper perception, when they treated patients with negative air ions. Their results weren't definitive, but three other studies in the '50s and '60s looked at how ions changed self-reported perceptions of comfort and restlessness. According to this research, some subjects felt negative feelings with positive ions, and some reported positive feelings with negative ions.

That correlation soon became the standard wisdom: Positive ions hurt, raising crime rates, asthma attacks, and your hackles. Negative ions help and make you happy. But the experiments themselves were not robust enough to prove either of those connections, with researchers using mixed methods, unstandardized measurements, and questionable controls.

Between 1981 and 1987, 13 more studies looked into ions' psychotropic effects. Eleven claimed significant effects, leaning toward the same conclusion: Positive is bad; negative is good. Still, the experiments varied in dosage, design, and quality control, and so couldn't point to a definitive conclusion.

STORM INSIDE Negative ions released in a thunderstorm, foreboded by a massive shelf cloud over a plain, might affect us in a way that explains the emotional rush we feel in extreme weather.

At the time, and still today, scientists were unsure how ions changed biochemistry, if they did at all. The prevailing idea for a time was the "serotonin hypothesis," advanced by A.P. Kreuger and E.J. Reed of the University of California, Berkeley, and Felix Sulman of Hebrew University. They claimed that positive ions created an excess of serotonin, a neurotransmitter, or chemical messenger, normally associated with feelings of pleasure and happiness. But high levels cause problems, later called "serotonin irritation syndrome." Positive ions, according to the authors, keep serotonin floating in the blood. Negative ions reverse this imbalance, stripping nitrogen-based molecules called amines from the neurotransmitter, and so sliding serotonin levels back where they should be.

Other scientists, however, believed the serotonin hypothesis had problems. "The so-called serotonin hypothesis focused on blood concentrations rather than brain neurotransmitter availability, two distinct systems," says Michael Terman, a professor of clinical psychology in Columbia University's psychiatry department, one of the few people currently doing serious research on ions. Chemicals in the blood can't pass into the brain because of a blocker called the blood-brain barrier.

A bigger problem, from many scientists' point of view, came in 1983, when Fred Soyka, a businessman who had "encounters" with "good" and "bad" ions, published *The Ion Effect*, setting off a New Age craze. The book is no doubt the forefather of websites with URLs like negativeionizers.net, negativeiongenerators.com, and alteredstates.net—from companies peddling expensive air-charging devices that will fix all your problems. "For the scientist seeking a solid path toward clarity, the pop claims for air-ion efficacy were an embarrassment," says Terman.

Rigorous work ground to a halt in 1987, when Jonathan Charry and Robert Kavet compiled existing academic papers into a volume called *Air Ions: Physical and Biological Aspects*. In aggregate, the three decades of research didn't add up. Findings conflicted with each other, and scientists offered few biochemical explanations. The denouement after that was steep: According to a meta-analysis of experiments on the topic by principal scientist William Bailey of Exponent's Center for Exposure Assessment and Dose Reconstruction, only a few human research studies were published between 1987 and 1993. But more recent experiments using high concentrations of air ions, like those Terman has done, led Bailey and his team to look again at the research literature. "It had been more than 20 years since the last comprehensive review of air ion research," Bailey says.

TERMAN, WHO IS THE HEAD of the Center for Light Treatment and Biological Rhythms at Columbia Presbyterian Medical Center, did not expect to become an air-ion researcher, or find that small molecules could have physiological effects. He began his work in ion therapy inadvertently: He needed a placebo for another experiment. To test whether bright lights help with depression, his experiment required a control—a group of subjects who didn't receive bright-light treatment but didn't know they were part of the control group. Problematically, most people can see light, so subjects would know they were getting the placebo, potentially skewing the results.

Terman discussed this problem with Larry Chait and Charmane Eastman of the University of Chicago, who had used a powered-down ionizer as a placebo in a similar experiment. At the time, most people had heard—thanks to *The Ion Effect*—that negative ions helped our psychological states. Chait and Eastman reasoned that if they disconnected an ionizer, but made it *look* like it was on, people would believe they were receiving a true treatment. Terman didn't do exactly that. Instead, he kept a negative ionizer on at an extremely low dosage, so low that its trickle counted as placebo. Control subjects could believe they were receiving a treatment, even though they weren't.

He compared patients' responses to a light-box; a low-output, placebo ionizer; and also a high-output ionizer. "I personally had no expectation that the high-density units would actively reduce symptoms of major depression," he says. "I thought both high- and low-density units would act equally as credible placebos. I was suspicious of early claims in the literature, knowing that the research field had virtually collapsed after publication of Charry and Kavet's volume."

But the results shocked him. When patients had 30-minute, high-dosage sessions for about three weeks, depressive symptoms decreased by more than 50 percent. The low-density ions, though, didn't help much, suggesting that an actual biochemical equation could be in play, just as taking more Tylenol yields greater pain relief. (Bailey, though, notes that in the meta-analysis, longer or more frequent high-density treatments didn't produce better outcomes.)

Terman reported that result in the *Journal of Alternative and Complementary Medicine*. "You can tell I was still nervous about the claim," he says, explaining why he went with a publication that's not as mainstream or high-impact as others. But he later replicated the results for the *Archives of General Psychiatry* (now *JAMA Psychiatry*) and the *American Journal of Psychiatry*, the field's most competitive journals.

The jury is still out on how the biochemistry of this mood-lifting might work. The serotonin hypothesis remains a possibility, although better and brain-based testing is needed to rule it out or in. Another idea, Terman has written, is that negative ions land on the skin and neutralize positive charges that have built up there, which would decrease depressive symptoms if positive ions are, in fact, bad for the brain. Breathing in the ions could also activate the vomeronasal organ, a piece of nose anatomy thought to detect pheromones, and somehow send a positive message to the brain.

On the lookout for biological mechanisms that might explain the effect of air ions, Terman came across a study in which doctors dosed the lungs of ICU patients, who had just had surgery, with negative air ions. Their blood's lactic acid, built up from stress, dove down. The same could happen in the veins of people with seasonal affective disorder (SAD), an environment-induced depression. Terman was intrigued by the study, but says he wouldn't "claim that increased oxygenation of the blood is the mechanism of action" in ions' effect. Another study is underway to see if SAD patients receive bumps in their bloods' O2 levels during negative-ion treatment. If they do, researchers can step forward, figuring out how negative ions oxygenate the blood and why that makes people feel better.

Catherine Harmer of the University of Oxford has also recently worked on double-blind, rigorous research—in which neither the scientist nor the subject knows which treatment patients are receiving—into how ions affect the mind. "We had seen published studies supporting negative ion administration as a treatment for seasonal depression, which were intriguing," she says, referring to Terman's studies. "No one knows how this treatment works."

She set out to see if ion treatment produced some of the same psychological changes as prescriptions like Zoloft or Abilify. "When people are depressed, they tend to focus on and remember more negative things than positive things," she says. That's one of the first mental processes that drugs reconfigure.

In a 2012 experiment, Harmer gathered people with SAD and gave them a battery of standard emotional-processing tests, like recognizing positive and negative facial expressions and recalling negative and positive personality characteristics. The depressed were biased toward recognizing and remembering the negative, but healthy people in her experiment did not have this same bias.

When Harmer gave the patients a high-density negative ion treatment and then repeated the tests, they showed the kinds of emotional-processing improvement—like increased ability to recognize and recall those happy faces and words—as people who take medication. But it wasn't just the SAD patients who got better. In most measures, the healthy control group did, too.

Both Terman and Harmer caution against overgeneralizing their findings to the stormy world outside the lab. The weather and waterfalls of the world don't deliver precise, ultra-high densities of negative particles in known, controlled settings. Still, the scientists are willing to speculate a little. "It's possible that natural increases in negative ions, like camping near a waterfall, might have similar effects," says Harmer. "However, this hasn't been tested using the same methods as we did in our study so it is unknown." And small shifts in ion concentration, she cautions, would likely lead to small physio- and psychological shifts.

Looking to the world outside the lab, Terman also points to the work of a colleague, Phillip Mead of the University of Idaho. Mead found that the air in a typical bathroom shower had negative ion densities comparable to those that came from Terman's industrial ionizer (which has higher output than most commercially hawked ones). "Whether this explains why people enjoy long showers, or begin to sing loudly, I don't know," Terman says. "But it is probably safe to extrapolate to rainstorms and their short-term aftermath, as the old pop literature claimed. Conceivably, if you showered every day for 30 minutes after waking up, there would be the same kind of antidepressant action I measured in our clinical trials."

WHEN I WOKE UP after the storm, I was still buzzed, though the world was once again still. Maybe, like a shower or a waterfall-centric campground, the big meteorological event changed the air ion concentration enough that the weather literally got under my skin, changing my brain or blood or both. Like lying in a field on a new-moon night, the storm had made me feel like I was part of the universe—an insignificant, crushable part, but a part nonetheless.

When I opened my front door, it led to a new world, one with a lot fewer upright trees and utility poles. None of them had fallen on my car or house. But I soon saw that others hadn't been so lucky.

The storm, I learned, had been a hurricane-force phenomenon, with winds that screamed up to 100 miles per hour. Meteorologists christened it the North American Super-Derecho. It did $3 billion of damage and left approximately 4.2 million people without power.

My town had no electricity—and so no water, which came from wells—for two weeks. The Red Cross showed up with tents, dinner, and hydration. A police officer stood next to the one generator-fed gas pump and rationed what little was left. The line stretched a mile.

Morning showers, like rainstorms, could have an antidepressant effect.

An older woman who lived out of town was found dead in her house, killed by carbon monoxide. A man died of heat exhaustion while trying to clean up debris, another because he couldn't get to a hospital quickly enough.

But it wasn't all bad, and the vivifying and devastating effect of the storm banded people together, like magnetized iron filings. In Green Bank, people gathered to share slowly spoiling food, drag branches from each other's yards, and invite each other to nightly debris-combusting bonfires. They brought each other barrels of potable water, biked to the store to get neighbors cold cans of stew bought on credit, and shared "Where were you when it hit?" stories.

After a while, though—after the power came back and we went back to work and illuminated, fully plumbed homes—we each stripped ourselves from the tight group. We again became isolated and unbonded. But just as an ejected electron will seek out and bind to another molecule, humans, too, will always clump back up. After all, the future is full of catastrophes, threatening to draw us back together.

SARAH SCOLES is a writer based in Denver, Colorado, and a contributor at *Wired Science*.

What Wild Animals Do in the Dark of the Night

Capturing wildlife with flash photography at the turn of the century

BY REBECCA HORNE

GEORGE SHIRAS THE THIRD (1859-1942) was captivated by the waters of Lake Superior at night, when sounds, shapes, and movements seemed more mysterious, more dramatic. Under cover of darkness, he sought out animals that lived along the shore of the lake. Shiras would place a lamp at the bow of a canoe and wait quietly in the shadows at the rear of the boat, until two eyes could be seen reflecting the boat's light back out of the darkness. The "blue, translucent eyeballs" were the signal to quietly slide forward into range, take aim, and shoot his quarry. This was how Shiras took the first photos to show the nightlives of wild animals, over a century ago.

In these early days of photography, Shiras was forced to haul clunky cameras using large-format sheet film on his canoe; the flash was an explosion of magnesium powder that he likened to a mystifying "blowing moon." Shiras described what happened at this critical moment: "Suddenly there is a click and a white wave of light breaks out from the bow of the boat—deer, hills, trees, everything stands out for a moment in the white glare of noonday. A dull report, and then an inky veil of darkness descends. Just a twenty-fifth of a second has elapsed, but it has been long enough to trace the picture of the deer on the plates of the cameras, and long enough to blind for the moment the eyes of both deer and men."

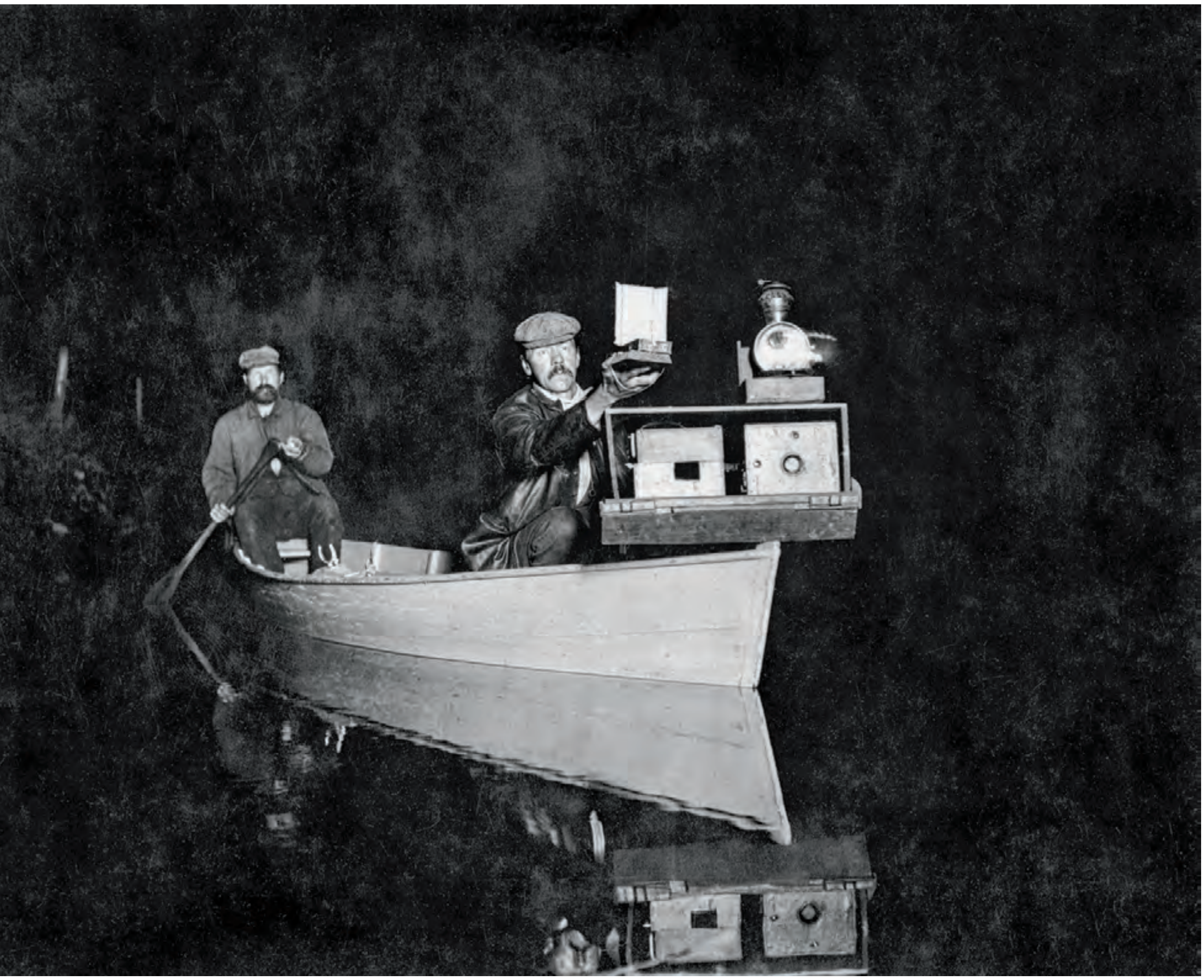
Confused or scared animals would sometimes charge the boat, knocking cameras overboard. Sometimes he used two cameras, one to capture the animal as it quietly watched the light, and another to catch the animal in flight after the first flash. Shiras adapted the flash and camera setup over time, by trial and error.

Shiras' photographic technique was an adapted form of "jacklighting," a hunting practice he had learned from guides belonging to the Ojibwe tribe of Native Americans. Between Shiras's groundbreaking pictures and the articles he wrote about "hunting with a camera" for various publications in the 1890s, he was instrumental in popularizing wildlife photography. Shiras later served in Congress, where he sponsored the first bill meant to protect migratory birds.

A new book, *George Shiras: In the Heart of the Dark Night*, rediscovers photographs from his night prowls, presenting them for the first time in a monograph. Perhaps what makes these images seem so fresh even now is the relative lack of compositional control in the experimental process. The animals are transfixed by the boat's light—sometimes they pause in their nocturnal routines to stare, other times they turn and run. The images are documentation of an intervention, records of human and animal interaction. What we see is not nature as it is, or nature idealized, but rather nature observed.

REBECCA HORNE is a California-born, Brooklyn-based artist, writer, and multimedia producer.

PHOTOGRAPHY BY GEORGE SHIRAS



PREVIOUS PAGE Lynx on the shore of Loon Lake, near Lake Wanapitei, Ontario, Canada, July 1902.
OPPOSITE PAGE Moose on misty lake, Minnesota, 1909.
ABOVE George Shiras with his assistant John Hammer on Whitefish Lake in a canoe outfitted with jacklighting equipment. Lake Superior region, Michigan, 1893.

Three white-tailed deer running,
Michigan, 1893-1898.

PREVIOUS PAGE Raccoon, Whitefish Lake, Michigan, 1903.
ABOVE An elk walks in marsh grass on the shoreline of Lake Superior, 1898.

Bacteria Are Masters of Tai Chi

The remarkable science that helped me understand what it means to be a physicist

BY MADISON KRIEGER

W**HEN I BEGAN STUDYING** how animals swim, I didn't feel much like a physicist. I'd just finished my bachelor's in physics during which time I'd been taught that physicists work on one of a handful of buzzwords: quantum mechanics, cosmology, gauge theory, and so on. To see if graduate school was right for me, I shadowed a friendly research group at the University of California, San Diego—but they didn't study any of these buzzwords. They used high-powered mathematics to understand things like the locomotion of snails, worms, and microorganisms.

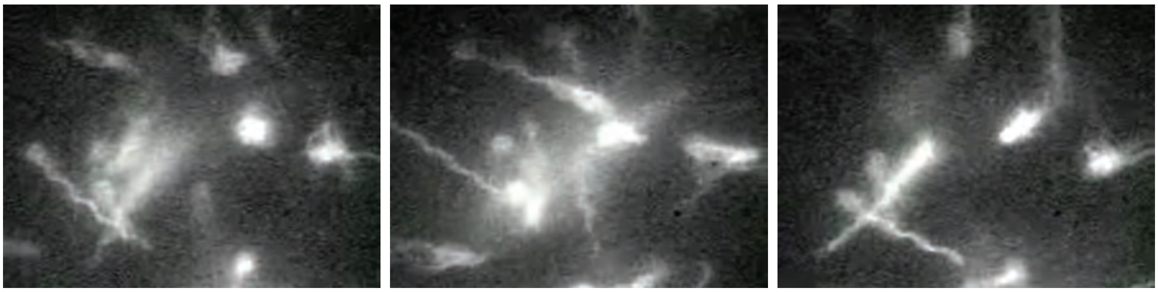
I was grateful for the opportunity, and I thought the problems they studied were beautiful and interesting—just not fundamental physics. As I became more involved in the group, this distinction grew into an identity crisis. Theoretical physicists are kind of like artists, or athletes: If you feel yourself drifting further from Klee or Peyton Manning, it can seem like a catastrophe. I thought I could feel Einstein and Feynman looking down at me and frowning as I took a turn down the wrong path.

It would take some impressive feats by microorganisms to convince me that they were as sexy as smashing atoms together—and they did not fail to deliver. Some are capable of shooting small needles, or even segments of their DNA, which accelerate about 1,000 times faster than a space shuttle launch; others share genetic information with their unrelated neighbors, forming an Internet many millennia older than ours; many outlive us, despite being 1 million times smaller. Even more interesting was that microorganisms do not obey Newton's laws, which govern basic motion and are a pillar of classical physics.

These remarkable facts changed not only how I perceived bacteria, but how I defined what it meant to be a physicist.

MICROORGANISMS EXPERIENCE their fluid environments in a radically different way than we do. We experience water as we do only because we are a certain size, and swim at a characteristic speed. Physicists and engineers describe how water might "feel" with the Reynolds number, which compares the relative

ILLUSTRATIONS BY JUN CEN



WEE BEASTIES The world's most famous bacterium, *E. coli*, in motion.

HOWARD BERG, HARVARD UNIVERSITY

importance of inertia and viscosity (drag) for a given liquid flowing at a given speed. The larger this number is, the more important inertia is relative to drag. Turbulence (the white, choppy, bubbly water you see around speedboats) kicks in when the Reynolds number is big, at least a few hundred.

By this you can infer that human swimming is characterized by a number that is somewhere less than a few thousand for wimpy swimmers like me, and somewhere more than that for Olympians. For bacteria, the Reynolds number turns out to be roughly 0.001. That means inertia is almost 1 billion times less important to them than for us humans.*

To recreate the experience of a bacterium in water, a human of average size would need to be immersed in molasses and swim at about 1 centimeter per minute. If they suddenly stopped, they would coast less than a millimeter before coming to a halt; that is, the coasting distance would have to be measured with a microscope. The time spent coasting would also be miniscule, somewhere on the order of microseconds, which is the time between flashes in a strobe light. Similarly, a bacterium that was traveling at top speed and suddenly stopped would coast one-tenth of an angstrom, about the size of a single atom. In a low-Reynolds-number world, lazily performing the backstroke over the course of a year gets you as far as if you complete the stroke in one second.

When inertia no longer matters, terms like mass, acceleration, and force lose their meaning. Statements like Newton's second law (force equals mass times acceleration) are moot. Newton's second law for a bacterium is zero equals zero. There is no such thing as acceleration, since bacteria attain their steady swimming velocity nearly instantly upon beginning to swim, and lose it instantly when they stop. Newton's first law, that objects in motion remain in motion until acted upon, becomes absurd; all bacteria know is that if you are not swimming, you're standing still. No microorganism gets to move for free. Newton's third law, that every action has an equal and opposite reaction,

*In exposing the subject I shamelessly follow its most classic text, the Nobel laureate E.M. Purcell's lecture notes "Life at Low Reynolds Number," [1] though I draw on my own experience as a doctoral researcher in this field.

For a bacterium, there is no such thing as acceleration.

becomes something of a tautology, for there are no longer any actions.

In bacteria-world, physics is better described by Aristotle, who denied the existence of inertia.

I was surprised by the ability of bacteria—which their discoverer, van Leeuwenhoek, called "cavorting wee beasties"—to break one of the cornerstones of classical physics. Seeing this, the head of the group I was shadowing guided me to a set of articles written in the 1990s by Nobel Laureate physicists.[2,3] The articles proved that the physics governing swimming microorganisms were identical to the physics governing the quantum mechanics of certain subatomic particles. They even described something simple and concrete—the speed and trajectory of a certain alga—with gauge theory, one of the buzzwords with which I had been inculcated as an undergraduate. The fact that bacteria are governed by a gauge theory is precisely what allows them to move without forces and circumvent Newton's laws.

That was another big lesson for me, not only in physics and mathematics but in sociology and identity. I determined that physicists are not constrained to study certain *objects*, but rather apply certain tools and modes of thinking to any kind of object in any field of interest. Gauge theory was not just for quantum mechanics, it could also be for microorganisms and other objects closer to our own size.

With immense help from the group at UCSD, I got into a Ph.D. program at Brown University. My new colleagues appropriated beautiful tools from theoretical physics to study macroscopic topics such as swimming, the wrinkling of window drapes, and the formation of trees and bones. Learning to recognize structures of theoretical physics in unusual places prepared me for my discovery that, like microorganisms, human beings are also capable of transcending Newton's laws.

In my first year at Brown, I started learning tai chi to dissipate the stress of graduate school. I'd become obsessed with the problems I was working on, and had become like a cartoon scientist who manically pulls out his hair whilst staring at an immense blackboard filled with scribbles. Tai chi advertised the ability to let go, as well as a certain mysticism and appeal to the athletically inept.

During the initial training, I did indeed learn to relax and forget about my work. But I received an entirely different benefit when I was introduced to the common two-person tai chi exercise known as *tuishou*, translated as "Push Hands" (or "Pushing Hands"). It can be performed either collaboratively, for the purpose of relaxation, or competitively. The objective of competitive Push Hands is simple: Competitors face one another and attempt to unbalance each other without the use of strikes, grabs, and without pushing below the waist or above the collarbone. The rearrangement of the two competitors is expected to be smooth and continuous, lacking the muscle-against-muscle overtures of other grappling disciplines.

The key to Push Hands training is learning how to not seize up when muscled, but rather loosen and lead an opponent "into emptiness": manipulating the opponent's alignment so that their incoming push or pull is redirected safely away from the practitioner's center of mass. In the beginning stages it's difficult to identify which components of the body are tight and which are loose, even in oneself—it can take years of studying and practicing tai chi routines to do so. This is an absolutely essential component of training, as any tension provides a direct line to one's center of mass: It's like having a steel rod (the tight limb or joint) precariously attached to a leaning structure (the torso). Because the rod doesn't stretch or bend, anybody can pull the structure down by pushing or pulling on the rod.

Next, a prospective Push Hands competitor must learn to recognize these tightnesses in another person by touch and by sight. This is normally facilitated by pre-arranged, cooperative Push Hands drills which train the skill of *ting*, which means *listening*—learning to interpret an opponent's intention and body alignment haptically through the points of mutual contact. The value of this skill is so great that participants are discouraged from ever breaking contact.

Push Hands challenges you to move and deform your body to dissipate incoming force. No force means no inertia. When there is no inertia, there is an ambiguity in defining terms related to mass. Concepts such as a "center of mass" become ill-defined. If you cannot feel a mechanical connection to your opponent's center, you can't say for sure where their center is—it could be in their head, their left pinky, or anywhere else.

All of this left me overwhelmed with a sense of déjà vu. The recognition of something familiar peeking out from behind the mask was immediate, but it took me a while to process, because for the first time I was not thinking about my research with pen and paper—I was feeling it with my arms, hands, fingers, feet. Finally, I realized: Bacteria were masters at tai chi.

LIKE AN EXPERT TAI CHI PRACTITIONER, bacteria also effectively lack a center of mass. If you are a bacterium and crash into another bacterium, the motion is the same whether you think the center of mass is in your head or your flagellum. When two bacteria are in contact they stick and adhere, and move around without exerting a force on one another. Sometimes to neutralize these forces they need to remain together for very long times, almost indefinitely. Somehow the bacteria "know just how to move" in order to not exert force on one another. They are masters of neutralization.

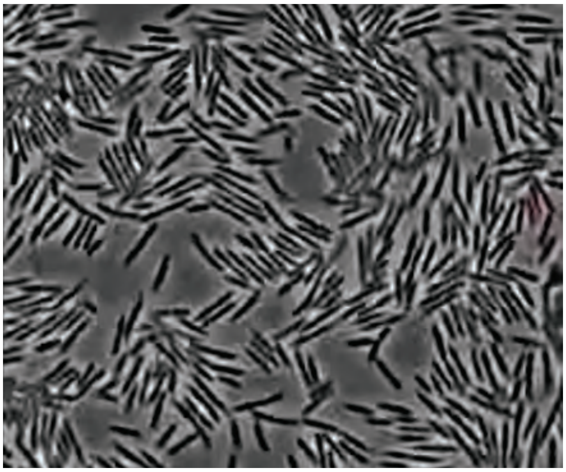
They are also, like Push Hands practitioners, doing the seemingly impossible: neutralizing every force, while still achieving some kind of motion. They speed up and slow down, and change directions on a dime. Newton forbids this to happen in the absence of forces.

This discourse between force and motion taught me the one difference between bacterial swimming and Push Hands. In Push Hands we eventually exert large forces after gaining an advantageous position. Similar strategies can be seen outside tai chi, like Muhammad Ali's "rope-a-dope" technique of adhering to and riding out punches using the elasticity of the ring ropes to dissipate the incoming energy, which leads to huge forces in the subsequent counter-punch. In a phrase, *the bacterium-like motion of the practitioner was to be abandoned precisely when it would maximize an advantage.*

This led me to wonder—did microorganisms stand to learn anything from tai chi practitioners? How would they behave if they, too, were suddenly allowed to exert force in a timely and strategic manner? To understand this, I had to introduce them to some new physics; the gauge theory of swimming which at first had so excited me was now the chief obstacle in teaching my wee beasties to use force on one another.

This unexpected motivation from martial arts

I wasn't thinking about my research with pen and paper—I was feeling it with my arms, hands, fingers, feet.



GENTLE RUSH *E. coli* cells act as a swarm without exerting forces on one another.

became a major thrust of my doctoral research. I set out to study novel environments for bacteria in which their physics are slightly different. In these environments—like simple fluids in unusual geometries, or unusual fluids in simple geometries—bacteria could do useful work for humans, including assembling and towing small batches of medicine or powering tiny engines. This becomes possible when we break up the conventional physics in a pre-programmed way, much like the Push Hands practitioner breaks the rules of neutralization when the advantage has been won.

Ideas like these are now percolating in many directions and will eventually lead to the fabrication of useful microscopic devices. The ability to trigger forces which allow bacteria to separate from objects after sticking and adhering could let them tow cargo, for example a payload of chemotherapeutic molecules directly to a tumor, delivered without bombarding healthy tissue. (Bacteria are capable of separating themselves without our help, but the mechanism is a bit obscure and involves secreting a lot of different chemicals.) Or small swimmers (natural or manufactured) could manipulate and assemble particles of medicine or other small molecules in intricate patterns, even at a distance, due to the flows they create when they exert force. A bacterium could, in this way, not only assemble anti-cancer medications from some basic ingredients, but also carry them to a tumor, release it, and repeat the process until therapy is complete.

Studying tai chi did more than guide my research—it transformed how I do research. Western philosophy tends to separate the universe into the observer and the observed, with little interaction between the two. Seeing bacteria and tai chi mutually inform one another gave me a perspective on a more egalitarian way of doing physics, by focusing on *connections.*

THERE IS A FAIR AMOUNT of naiveté in finding connections between bacteria and Chinese martial arts. But this kind of naiveté is central to how theoretical physics is done, and giving in to it for a moment led me to something deeper. I began to write drafts and drafts of *something*, some crazy idea of physics pedagogy using body techniques. I started ranting to my friends and colleagues about a "physics *from* the body."* To me the connection between tai chi, bacteria, and the mathematical idea of gauge theory seems deeper than random connections between my interests or suggestive little ideas that guided my research to big problems.

I've come to appreciate the body as a *vector* of knowledge, a source separate from the eyes that read books and the ears that hear lectures. In that sense, it is the most accessible vector we have; everyone possesses a body, but not everyone has access to books or lectures. I really believe that obscure ideas which are now thought of as the provenance of mathematicians can be made universally accessible, at least through analogy. If you can connect the reasons why a subatomic particle behaves a certain way to why you and your body behave a certain way, then perhaps it will help you understand the world you live in a little bit better, even if the tiny details get swept under the rug. Or, even better, perhaps it will make you *want* to understand this world better.

*Meant as an analogy to Loïc Wacquant's popularized idea of a "sociology from the body."

MATTHEW COPELAND, UNIVERSITY OF WISCONSIN, MADISON

Recognizing this connection has also made me feel like I have a certain place or role, which isn't necessarily described by the term "physicist." That word has a rocky and tenuous definition rooted in sociology and popular opinion, and had led me to doubt myself. The kinds of things that scientists are interested in now have long eclipsed such terminology, and the field today deserves a change in mindset and terminology. This new mindset should have a new name: "Thinker" is entirely too pretentious, so I will choose "connector."

A connector is somebody who notices the connection between things. Connecting is perhaps the most valuable skill for physics, and one possessed by many of its heroes—the folk literature is full of adages about Feynman discovering principles of quantum electrodynamics by spinning plates in the Cornell dining hall and Einstein discovering aspects of his Brownian motion theory by playing with soup. Scientific discoveries are wrapped in a personal narrative—sometimes it is something as boring as staring at a blackboard for hundreds of hours, but more often there are small breakthroughs that occur in the shower, while bowling, while watching the patterns birds form as they fly.

These small connections rarely make it into publications, are rarely discussed in Nobel acceptance speeches. But in a sense are the most important part of the story not only because they are the most humanizing and accessible, but because they reflect the nature of scientific development. And if that's true, then our quotidian activities are not so different as we might think from smashing atoms together to guess how the first stars were born. Like yin and yang, they usually go hand-in-hand, whether we notice or not.

MADISON KRIEGER recently received his Ph.D. in engineering from Brown University and is currently a postdoctoral researcher at Harvard's Program for Evolutionary Dynamics.

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The Surprising Importance of Stratospheric Life

The science of bacteria in the upper atmosphere is getting its moment in the sun

BY CHELSEA WALD

R**IPPLING LIKE A JELLYFISH,** a helium balloon big enough to envelop the Empire State Building lofted over the New Mexico desert. Its passengers, suspended below in a boxy white gondola, were hardy specimens: millions of cells of a remarkably resilient bacterium known as *Bacillus pumilus* SAFR-032. NASA scientists had first collected the strain more than a decade ago in the *Mars Odyssey* assembly facility, where the bacteria had survived sterilization. Before sending the pill-shaped cells into the sky last October, researchers starved them until they morphed into endospores, an armored dormant state.

Higher and higher the wee wayfarers rose: to 17,000 feet, the maximum altitude at which trees grow; to 24,000 feet, the upper limit of the highest-flying migratory bird, the bar-headed goose; to 60,000 feet, where atmospheric pressure is so low that water in bodily tissues would boil away. At last, at 100,000 feet, the balloon reached its destination. Here in the stratosphere, above the troposphere and most of Earth's protective ozone layer, conditions are extreme: cold as an Antarctic winter, drier than the driest desert, and flooded in ultraviolet rays. "Mostly, it's eventual death," says Cindy Morris, a microbial ecologist at the French National Institute for Agriculture Research.

Yet scientists are finding that a rich variety of life—archaea, bacteria, and single-celled eukaryotes—can thrive at high altitudes. In the troposphere, where day-to-day weather happens, each cubic meter of cloud contains on average tens of thousands of microbial cells. Even above the clouds in near space—as high as 250,000 feet, according to a 1978 Soviet study—rocket and balloon missions have collected hearty voyagers. "We're not just finding corpses that are blown up there and preserved," says Brent Christner, a microbiologist at the University of Florida. "Some fraction of these organisms is still alive."

Lacking wings or pressure suits, these Lilliputian aeronauts have devised ways to protect themselves from irradiation, desiccation, and severe cellular

ILLUSTRATION BY TIANHUA MAO

stress, and find food in the bleakest of food deserts. Their unique set of survival skills has allowed them to soar the skies, dispersing to some of the harshest environments on Earth. And perhaps beyond: If *B. pumilus* cells can live through a balloon ride to the stratosphere, what's stopping them from hitching a lift to Mars? "If organisms are blowing around in the stratosphere, and we took them and we put them on the Mars surface," Christner says, "they wouldn't even know the difference."

OF COURSE, MICROBES DON'T NEED balloons to fly. Some fungal spores catapult from cannon-like structures in their parent. Wind or sea spray can similarly launch cells into the air. But most simply levitate, Mary Poppins style, in a passing updraft. "There's always upward movement of air because the Earth is always heating the atmosphere," Morris says. "It's impossible for a particle that small to not get incorporated in these currents."

Once airborne, the tiny drifters ride a complex and ever-shifting network of "highways in the sky," says David Schmale, an aerobiologist at Virginia Tech. With engineer Shane Ross, he is developing ways to predict these turbulent routes. By pairing fluid dynamics modeling with data from air-sampling drones, the team has identified atmospheric features as large as countries, called Lagrangian coherent structures (LCSs), that behave "like waves moving through the atmosphere," Schmale says. As an LCS moves over the landscape, it morphs much like an ocean swell, shuffling microbes along various air masses, like plankton along eddies.

Depending on their size and aerodynamics, microbes can stay aloft in the atmosphere for days to weeks—long enough to jump a continent, or an ocean, in one go. Analyses of meteorological data, for instance, suggest that transatlantic winds carried fungal spores from West Africa to the Americas, spreading sugarcane and coffee leaf rusts to New World plantations in the 1970s. Bacteria kicked up by dust storms in Africa's drought-plagued Sahel appear to be making a similar leap to the Caribbean, where they are killing coral reefs. And in China, at the start of every growing season, spores causing wheat yellow rust migrate hundreds to thousands of miles from plants in the western provinces of Sichuan and Gansu to recolonize the country's main wheat belt further north.

Most of this globetrotting happens in the troposphere because the air there rarely mixes with air in the stratosphere above. But there are ways to catch a lift to loftier locales, including transport via thunderstorms, volcanic eruptions, and deep tropical convection.

What would happen if hardy microbes stowed away in a dark crevice on a lander?

A GIANT LEAP FOR LIFE Bacterial cells attached to the gondola (left) of a NASA research balloon (top) took a ride to the stratosphere in October 2015. If they can live in this extreme environment, they may be able to survive similar conditions on Mars.

NASA / DAVID J. SMITH

Microbes that make it to the stratosphere get swept along in its steady horizontal currents, allowing them to sail swiftly over vast distances, Christner says. "It's a ticket to anywhere on the planet."

No known organism can survive high altitudes indefinitely. Scientists estimate that even the fittest microbes probably last no longer than a week in the stratosphere, and around a couple of weeks in the troposphere. Eventually they "get fried by radiation," says David J. Smith, a NASA microbiologist who led the October balloon mission testing the stamina of *B. pumilus* cells. As a result, some high-flying species may have evolved a method to get down fast: hijacking the weather.

Microbial matter typically falls from the sky in rain or snow. To precipitate, clouds must grow ice crystals big enough to outweigh air, but pure water vapor won't normally freeze above -36 degrees Fahrenheit—unless it gets help from an "ice nucleator." Most often, airborne particles such as salts or mineral dust provide this service. By supplying a seed around which water molecules can arrange themselves, a nucleator enables ice to form at temperatures up to 5 degrees. Some microorganisms produce proteins that catalyze the process in even warmer conditions, up to 28 degrees in a laboratory. Scientists have yet to prove this happens in real clouds. But if it does, it's a handy trick: Not only have these microbes found a way to encase themselves in an icy escape capsule, but they may be able to make it drop from the sky when it otherwise wouldn't.

According to one model, possessing these icemaking powers could help shorten a microbe's time in the sky to about a twentieth of what it would be if it couldn't nucleate ice at all. "The ones that are not ice-nucleation active have a little more trouble getting out," Morris says. From a microbe's perspective, she explains, the atmosphere is like a subway system. "There are people there all the time, but the metro is not a place to live—it's a place to move."

IF EARTH'S ATMOSPHERE IS a microbial metro, it's an especially brutal one, and commuters have evolved various means to survive the trip. Some, like the *B. pumilus* cells in the NASA balloon, form endospores. "Sporulation is like hibernation for bacteria," Smith says. "They shrivel down, dehydrate all of their innards, and wrap their DNA. They remain in that state until water and nutrients arrive, and then they flip the switch and germinate, and go on living."

Other longest-distance travelers sequester themselves in protective dust plumes. Researchers have collected deposits of African dust from all over the world, and "they're just loaded with microbes," Schmale says. Shade from dust can cut UV radiation by half. And as the plumes cross water bodies, they pick up particulates such as pieces of algae or phytoplankton, which "can provide wetting, moist environments for microbial populations to sustain viability as they trek across the ocean."

Microbes can also make a temporary home in clouds. Atop the 5,000-foot peak of Puy de Dôme, in central France, microbial ecologist Pierre Amato sucks up cloud water with a droplet impactor—"a vacuum cleaner, basically," he says. He then takes the samples back to his lab at the National Center for Scientific Research, in Aubière, where he extracts living bacteria and cultures them in flasks. Some specimens can subsist on formaldehyde and other organic compounds commonly found in cloud water, suggesting they can metabolize, and perhaps even reproduce, in clouds. "They eat some very strange things," he says.

The most successful cloud-squatters, Amato has found, are bacteria that spend their terrestrial lives on plants—no surprise, he says, considering that these species are well-adapted to life on the surface of a leaf, where light, temperature, and humidity change rapidly, as they do in a cloud. Many of these organisms have also evolved protections against UV radiation: pigments that act as sunscreens, for instance, or the ability to rapidly repair their own DNA.

Where these widespread adaptations first arose is an open question. Did microbes hone their survival skills on the ground and then use them to take to the skies? Or vice versa? Smith, for one, argues that the arduous conditions of the upper atmosphere likely provided a selective pressure that drove terrestrial life to be as robust as it is. "Think about trillions upon trillions of tiny cells continuously passing through the Earth's deadly upper atmosphere for billions of years," he says. "In that framework, evolved resistance to environmental extremes seems almost inevitable."

Take Antarctica's ice sheets. Some of the most hostile places on Earth, they were once thought to be devoid of life. Yet in the past decade, scientists have discovered microbial species living on and in the ice, and in lakes buried below. "These microbes might not be growing actively—they might just be frozen in suspended animation—but as the climate changes and as these places melt, and as surface water starts to form, you may well see them metabolizing and reproducing," says David Pearce, a microbiologist at Northumbria University in the United Kingdom who is part of an international collaboration to survey microbial diversity over Antarctica. Many ice dwellers, Pearce suspects, probably arrived on the winds: When he and his colleagues analyzed microbial DNA from air samples over a remote research station, they found that almost half of the airborne explorers not associated with human activity had likely originated from soils and other terrestrial sources on other continents. (Incredibly, some of these strains have also been found in spacecraft assembly rooms.)

"The upper atmosphere acts like a pre-selection filter," Pearce says—it ensures that only the hardiest individuals disperse to colonize Earth's remotest and most barren outposts.

THE SAME MIGHT BE SAID for other worlds. If the rigors of air travel can prepare microbes to thrive in Antarctica, why not the atmosphere of Venus, where relatively mild temperatures and pressures may be able to sustain Earthly life? Or the surface of Mars, where conditions aren't so different from Earth's upper atmosphere? If microbes like *B. pumilus* can survive the stratosphere, Smith says, they may be able to persevere long enough on the Martian surface to establish themselves in a more hospitable spot, such as underground, "where it might be warmer and wetter." His team is still analyzing results from the balloon mission, but he says they seem "consistent" with what's already known about these super-survivors, which have endured stratospheric simulation chambers and once lived for 18 months outside the International Space Station while shaded from UV light.

How Earth life might get to other planets is a matter of much debate. Airborne cells can't reach escape velocities great enough to break free of Earth's gravitational pull. Nor have scientists come up with a convincing explanation of how they would survive the long transport times and lethal radiation levels in deep space. But that hasn't stopped astrobiologists from musing about panspermia, the hypothesis that life spreads throughout the universe via meteors and other cosmic vehicles—like, say, spacecraft.

For NASA, this is a very real, and troubling, possibility. The agency has identified hundreds of bacterial strains like *B. pumilus* that have outlived spacecraft sterilization procedures such as peroxide baths, heat shock, and UV radiation. What would happen if these or other hardy microbes stowed away in a dark crevice on a lander, or latched on as it passed through Earth's atmosphere?

"These organisms are really very robust," Morris says, "and they are going places." All they need is a lift.

CHELSEA WALD is a science writer in Vienna, Austria, who writes often for *Nautilus*.

Paving Over the Fossil Record

Why isn't India doing more to protect its rare evolutionary record?

BY SHRUTI RAVINDRAN

EVERY WINTER FOR THE PAST DECADE, paleontologist Kenneth D. Rose returns to Vastan, one of the open-pit lignite ("brown coal") mines in a corner of western India. On this dizzyingly bright March morning, as miners in hardhats and boots tirelessly scoop out tarry chunks of lignite with rumbling earthmovers, Rose and his team sift through a thin layer of sediment with ice picks and brushes. Their goal: piecing together fragments of the most archaic forms of mammals to walk the earth, and unraveling the story of modern mammalian evolution.

The fragments they're seeking date back to the early Eocene epoch, about 54.5 million years ago. Around then, the earth was 12 degrees Celsius hotter, and gripped by the most intense global warming event the world had known. India was a tropical island that had recently broken free of Madagascar, and was headed toward an epic collision with the supercontinent Laurasia; a collision that would compress the ancient Tethys Sea and thrust up the Himalayan ranges. Vastan, a swamp on the edge of the island, lay beside a tropical rainforest teeming with rabbits, bats, snakes, lizards, frogs, birds, ancient relatives of horses and tapirs, and an extinct order of mammals—tillodonts—that resembled saber-tooth bears.

Rose, a professor at the Johns Hopkins University School of Medicine in the Center for Functional Anatomy and Evolution, has recovered remnants of all of these creatures, many of which are archaic forms, and the oldest of their kind to be found in Asia. They provide a tantalizing set of clues to a long-standing evolutionary puzzle. Where did the world's modern mammals come from? How did they evolve? How did they spread? Swiping at a dun-colored wall of sediment with a soft brush, his eyes trained for the promising black gleam of bone, Rose says, "What we're asking, specifically, is how and when did this fauna get on India, how did they get off, and how much did they evolve here?"

The haul from Vastan is uniquely positioned to answer these riddles. "Its importance is its age and

ILLUSTRATION BY GARY TAXALI


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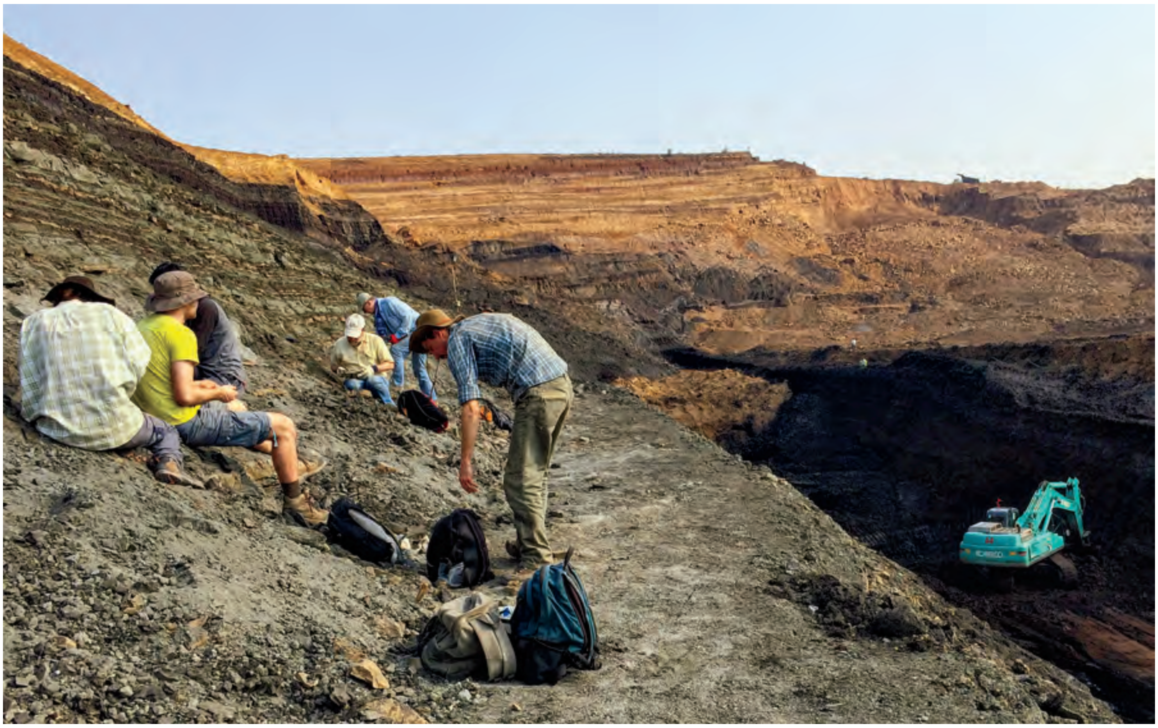
Jaxali



A GOLD MINE FOR FOSSILS American paleontologist Kenneth D. Rose and his team sift through sediment at the Vastan coal mine in India, which has yielded a trove of fossils that help explain the evolution of mammals.

location," explains Jessica Theodor, a vertebrate paleontologist at the University of Calgary. "The earliest Eocene is where we start to see the first appearances of a lot of the modern lineages of mammals." Paleontologists had long been hunting for the lineages of modern mammals, such as cattle and camels, horses and tapirs. Finds at Vastan, says Theodor, suggests the lineage stretches back to India, from where the mammals may have immigrated. "Vastan gives us a window into an early time frame which we hadn't had before," she says.

Paleontologists from around the globe agree the findings from the mines around Vastan are surprising, abundant, and important. "It's no coal mine, it's a gold mine," says Ashok Sahni, a retired paleontologist who worked at the site for a decade. Theodor says Vastan's richness brings to mind Germany's Messel Fossil Pit, the world's best-known repository of Eocene-era treasures. With one crucial difference: That site, a former oil shale mine, ceased commercial operations 40 years ago. Local protests prevented it from becoming a landfill, and the United Nations Educational, Scientific and Cultural Organization declared it a heritage site in 1995.

In India, however, laws to protect Vastan and other fossil sites are rarely enforced and so weak as to be nearly nonexistent. Three years ago, an immense excavation in the Vastan site, 5 kilometers wide and 100 meters deep, streaked with fossils, was closed. Mining itself destroys countless fossils. "Those mine people, they take our best stuff and throw it into the thermal plant, where it burns," Sahni says.

In a recent essay, Naman P. Ahuja, a professor of Indian Art and Architecture at Jawaharlal Nehru University, New Delhi, decries India's disregard of its heritage. "South Asia is encountering a pace of development which is unlike ever in its history," he writes. "As the population rises and more rural areas and hinterlands are being converted into urban spaces, archaeological contexts are disturbed forever."

SHRUTI RAVINDRAN

She was horrified to see shark teeth poking up between rows of planted cotton.

India has a long tradition of scientific excellence. But to Sahni, a Fellow of the Indian Academy of Sciences, and the Academy of Sciences for the Developing World, the country seems at odds with its scientific icons. "Ignorance and the motivation for short-term commercial gain overrides the long-term benefits in preserving our fossil heritage," he says. "Regardless of science or geology, on the ground it's all greed."

Some countries, including the United Kingdom, the United States, and Australia, have done well to preserve their geological sites, says Murray Gray from the School of Geography at Queen Mary, University of London, and author of *Geodiversity: Valuing and Conserving Abiotic Nature*. "But I'm afraid that geological conservation struggles to make its case in every country in the world, particularly in developing countries where losses of important sites probably occur almost every day," Murray offers.

Understanding how one of the world's largest and most populous countries can neglect its rare and important fossil record requires the perspectives of scientists, archaeologists, and government officials. Together they answer the question: Was there ever any chance of keeping the excavators at bay?

A DECADE AGO, as an enthusiastic graduate student of paleontology, Anjali Goswami decided to embark on a road trip to India's most storied fossil sites. Goswami, a paleobiologist at University College London, was accompanied by her future collaborator G.V.R. Prasad, one of the country's foremost vertebrate paleontologists. They decided to revisit sites from the Late Cretaceous, 66 to 100 million years ago. Their itinerary included spots where Prasad made many of his best discoveries in the 1990s, including the first Cretaceous mammal to be found in India. They also planned to visit fossil sites first excavated in the early 19th century. This was the largely accidental heyday of Indian paleontology, when great hauls of fossil bones were unearthed by military officers during lengthy cross-country marches, or by East India Company engineers while supervising landscape-churning work.

For her first pit stop, Goswami decided she couldn't do better than Jabalpur in the badlands of central India, where the British paleontologist W.H. Sleeman discovered the first ever dinosaur to be found in Asia. He did so in 1844, three years before Sir Richard Hunt even coined the term dinosauria. "Besides, it had the added advantage of being close to my *bua's* (father's sister's) house," she recalls with a laugh. When she got there, she was horrified by what she found. "The outcrop was entirely covered in garbage," she says. "You could walk around, but it was pretty gross. Given that such a huge number of dinosaurs come from this site, you'd like to think they'd get some protection."

The rest of her journey did nothing to improve on that inauspicious start. All five sites she visited across the southern state of Karnataka—some first explored by colonial officers, others by Prasad—were given over to farmland. She concluded that what she'd witnessed was the inevitable damage of more than a century. But once she began fieldwork in 2007, she realized just how rapidly the depredations were taking place.

When she first started work on her chosen field-site, the Cauvery basin in the southeast of the country, she worked in shallow ravines surrounded by gently undulating hillocks. During the next six years, while she and Prasad unearthed the remains of turtles, dinosaurs, and a strange snub-nosed crocodilian species between 67 and 100 million old, the hillocks got bulldozed and flattened into cotton fields. When she visited her "best shark site" last year, she was bemused and horrified to see the unmistakable spiky silhouettes of shark teeth poking up between the rows of planted cotton. "That was so frustrating!" Goswami exclaims. "They had survived for 100 million years—and now they're gone. And they're completely irreplaceable." They've since found newer sites to move onto, but everywhere they go, fields, settlements, and quarries are quick to catch up.

The pace and certainty of the destruction made Goswami delay her departures and spend a few days screen-washing—pouring fine gray sediment from the site through running water and scouring the contents for flecks of fossils under an electron microscope. "It's totally out of panic, because I never know how much will remain when I return," she says. "For paleontologists, all our data is unique. And if we don't get it out of the ground quick enough, that's one branch of the tree of life gone forever from human knowledge."

Some roots of life might well be traced back to Vastan. In 2014, Rose and his colleagues identified a small-hoofed creature as the descendant of the original ancestor of modern horses and tapirs. The creature's anatomy, they found, combined the traits of two wildly disparate groups. Its fused jaw resembled that of the first horses and rhinos, but its teeth and limb anatomy placed it further back in time, helping the paleontologists fill a missing gap in the record of archaic hoofed animals.

"These fossils are more primitive than anything that's been found from that order anywhere else in the world," says Rose. "We think it's the great-grandchild of the ancestor of horses and tapirs—an early relic of that radiation." He reckons the creature's presence in Vastan just before island India made contact with Eurasia suggested that the ancestors of horses and rhinos quite likely originated in India.

Vastan has also yielded as many as seven species of bats, belonging to seven separate genera, all of which appear closely allied to European counterparts found in France and Germany. Nancy Simmons, a curator at the American Museum of Natural History, and an expert in the evolutionary biology of bats, points out that the Eocene was a transformative epoch for bats, during which they went from "small scrambling creatures" to ones that glide, enabling their spread and rapid diversification. Simmons says the significance of Vastan's bats is "amazing." Before they turned up, she thought all significant Eocene bats were found "very close together," in South America, Europe, and North Africa. "Suddenly we find this fauna, which has close connections to animals living in North America and Europe, but on this island continent of India that was floating out in the Indian Ocean," she says, with a laugh. "It makes us wonder: What are we missing? Perhaps they diversified much earlier than we thought."

Over the past three decades, a trove of fossils from the mountain ranges across India and Pakistan has helped paleontologists put together a picture of whale

FOUND IN TIME Unearthed in India, this skull and mandible, 54.5 million years old, are from *Cambaytherium thewissi*. The small hoofed creature represents a pivotal link in a lineage of mammals that includes horses, rhinos, and tapirs.

K.D. ROSE & T. SMITH

evolution. Scientists can now see, with the hypnotic clarity of a flipbook, how whales might have transitioned from housecat-sized river-bottom waders to enormous traversers of oceans in the space of 10 million years. In the late 1990s, Sunil Bajpai, a vertebrate paleontologist, found several such tantalizing evolutionary snapshots from Babia Hills in Kutch in the country's northwest border. "It looked like a graveyard of whales!" Bajpai recalls. When he returned to his old field-site a few years ago, he was shocked at what he found. "The whale-bearing horizon was covered with the dark gray overburden from a coal mine," he says. "I had worked there for so many years, and suddenly everything was destroyed. It was unimaginable!"

MANY FACTORS IN INDIA have combined to making the unimaginable inevitable. Everything remotely mineral belongs to the government; specifically, the Ministry of Mines, which caters to extractive interests. The occasional question posed by members of Parliament on behalf of their constituents puts central and state mining ministers on the spot, asking what they're doing to protect a particular geo-heritage site or set of fossils. The lucky few among these cases get graced with a red-tape-redolent "notification and instruction for protection and conservation" from the Geological Survey of India (GSI).

Dhananjay Mohabey, a former Deputy Director General of GSI, admits that monuments can only be "declared," not maintained. "They're in very bad shape because there are no laws to be able to prosecute or take action against builders or offenders," he says. "So all we can do is put up a display board saying: 'This is a unique feature of this or that importance.' "

Such bureaucratic niceties are put aside in an instant when they come up against anything in the "national interest." Take, for example, Varkala-Vizinjam, the country's sole stretch of spectacular laterite cliffs

"Is the state under an obligation to preserve all such places of beauty? Beauty is in the eye of the beholder."

in the southern state of Kerala. Although they were declared a geo-heritage site in 2014, they're about to be lost forever due to the construction of a deep-sea port project that began late last year.

In January, activists opposing the project at the Supreme Court were told to step out of the way, since this was a "project of national importance being set up for the benefit of the country." When the activists pointed out that the cliffs were eco-sensitive, and that their beauty was worth protecting, T.S. Thakur, the Chief Justice of India, shot back: "Is the state under an obligation to preserve all such places of beauty? Beauty is in the eye of the beholder."

The country's lack of concern for fossils can be seen in its ineffective crackdown on thieves and smugglers. Sahni, the retired paleontologist, says he once discovered that fossilized dinosaur eggs that he'd excavated in western India had been ransacked by vandals for trade and even worship. Further, he has seen paleontologists get stymied by the arbitrary application of a vaguely worded law meant to protect antiquities and art treasures. "It doesn't define what is an antiquity or what is a fossil," says Sahni. "But it's so restrictive and draconian that genuine researchers are shooed away and others [smugglers] get away scot-free."

Sahni laments that India doesn't have a major natural history museum for the country's fossils. Other than a repository maintained by the GSI in Kolkata, which extends to colonial finds, most fossil collections under study in the country are maintained by individual scientists and their research institutions. Sahni, for instance, has preferred to maintain "a personal catalogue" throughout his career—for his own "sanity and science." The lack of one centralized repository leads to a second problem: Research takes place concurrently in separate silos.

Mohabey says, "When a [fossil] skeleton is found, one person removes the leg, another the arm. They end up in different places, and it becomes very hard to study." What makes things even harder is that when professors retire, the collections they've amassed over a lifetime have nowhere to go. "They're large fossils," says Sahni. "You can't just carry them around the country."

Sahni has spent the past few years of his retirement trying to do what he can about these limitations. In 2010, he helped a forest officer, Pankaj Srivastava, frame a fossil preservation act in Madhya Pradesh, where some of the country's most important fossils were stolen—including dinosaur eggs and the early hominid *Gigantopithecus*. Srivastava had been frustrated at his inability to do anything about the widespread smuggling and destruction of fossils. "There is nothing in the law to punish those who take dinosaur eggs worth a fortune and sell them for 100 rupees," he says. But despite Sahni's and Srivastava's continued efforts, the bill never made it to the assembly. "The fossil protection law," Srivastava says, "is getting fossilized."

Ahuja, the professor of Indian art and architecture, says the nation's scientists might gain public support through an information campaign, held in conjunction with museums. "If paleontologists created a public interface through a museum, more people would be aware of the value of what they'd be losing," he says. "But if you call for fossil sites to be protected without disseminating information, it's pointless. You'll just be holding off destruction until some other dam or road is made." He adds, "No one is here to forestall progress. But it's shocking how callous the government is toward the country's history."

Sahni agrees, and regrets how far India lags behind other countries in paleontology and preservation. "China has about 40,000 active paleontologists, 17 natural history museums, and laws protecting fossils and fossil sites," he says. "If we had half the support they did, we would be to mammals what they have been to dinosaurs since 2007."

Early this year, in Vastan, tractors and excavators kept roving about, churning up mud and carting away lignite. Rose and his colleagues found an as-yet-unsavaged spot where they could look for fossils, one crumbly handful of sediment at a time. They were excited about an upcoming paper describing a miraculously intact skull they found on a previous trip. Its owner, they're convinced, will soon set the vertebrate paleontology world astir. Unlike its confreres, which vanished in a cloud of brown dust.

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In Which I Try to Become a Swift

The closest I ever got to flying with the birds was on the ground

BY CHARLES FOSTER

THERE ARE TWO CLASSES of words commonly applied to swifts: words about ethereality, and violent words. They are not contradictory. The violence makes the ethereal accessible. Swifts lay open the sky so that we can go there. They slash the veil.

If the swifts didn't come, we'd be stuck with what we've got.

They were very late this year. Panic rose. I'd get up very early, thinking that I'd heard a scream, and rush to the window. There was nothing there but pigeons as ponderous as I am: pigeons who sleep in trees and waddle in the dirt.

And then, as I was lying on my back, they were suddenly there.

"Why are you crying, Daddy?" said Rachel, who was watching my face instead of the sky.

"Because it's all right," I said. "Because the world still works."

"Okay," she said.

They're always suddenly there or suddenly not there.

THE AIR CRAWLS. Up there, like plankton, there are live things drifting in the wind; aphids, other bugs, spiders, beetles. An aphid might be sucked from a grass stem in an English wood, up a gurgling plughole in the air, across the Pyrenees and the Strait of Gibraltar, and into the crop of a zitting cisticola at an oasis in Mauritania.

I've tried to map the vortices. It's best done from quite tall, bald trees with lots of footholds on which you can stand at many heights. It's a happy, mesmeric way to pass the day.

Airborne thistledown's the best marker of the vortices. It probably doesn't weigh much more than an aphid. Near the ground the thistledown is tentative. It moves from side to side, as if testing the worth of all the possible air channels. By four feet up it has decided where to go, though a fleck of down that started in the same flower head might well have chosen differently.

In a wood, or above a field, the vortices are an unseen forest of tangled chimneys. The chimney walls are quite hard. Not much escapes from them. They're often very close together, but they're rarely exactly parallel, and they sometimes even cross. Each has a tight centripetal glug, but they don't just channel

ILLUSTRATIONS BY JENN LIV

straight up. Each has tides and eddies. Bugs and seeds bounce off one another and off the walls: They somersault and arabesque. An aphid that almost made it out beyond the canopy might be blown back down by the fat cheeks of the summer and pass one coming up that started its climb from the undergrowth an hour before.

At the top of the tree line there's a tangled delta. The chimneys swell, start to knot, and disgorge into a flat bowl that spins them together. The flotsam gathers pace; the streams are wider and denser.

The swifts graze the streams. Perhaps there's another delta and another flattening farther up. Certainly by an altitude of a hundred yards or so the pickings are thin. Yet swifts are often very much higher than this, where they're unlikely to be feeding.

It's different in open country. There the sun sucks up the earth hard. Banks of wind surf roll across the land, hit a wall, a ditch, or a ripple, and surge up, becoming mushrooms. The stalks of air are huge writhing rivers of tiny spiders and aphids, sometimes hundreds of yards wide, racing in tumbling spate from the fields to the high clouds. They rasp a hand plunged into them.

The summer sky is, usually, a rigidly stratified bird sandwich. The swifts feed at the top; the martins are below them, and swallows wobble the top of the grass with their wake. But the swifts sometimes slice down into the martins' patch, and when the sky is heavy with

wet electric power, they're pushed farther down among the swallows to the fields and the lakes.

Swifts are selective, fastidious feeders. Although they catch 5,000 or more insects a day, and though they have wide gapes like the mouth of a trawl net, they don't usually trawl. They go for the big, stingless insects. You can see them swing off their course to get them. And their discrimination is nuanced. When they hunt bees they take the stingless drones selectively. Try telling drones from workers at a speed of 50 feet a second. And they're not just responding crudely to insect warning livery: They take plenty of stingless bee and wasp mimics. We don't know how they tell the difference, but it must be visual.

They are hunters—aerial sight hounds—snapping like terriers, and so they have two foveas: a shallow monocular one, and a deep magnifying one. This deep device probably gives them some binocular vision, used for computing the distance of speedy insects. They're like cheetahs or peregrines. When a swift first spots a likely kill, it'll be at a similar distance from it, relative to the size of the prey, as a peregrine would be from a pigeon, a cheetah from a Thomson's gazelle, or I from a deer far across the hill. Identical visuospatial problems have to be solved in each case. Like a peregrine, the swift will nod its head as it bears down, switching between devices—between the big picture and the detail. Both are needed for an efficient kill that won't leave a sting in the mouth.

Though they're mainly trophy hunters in the sky plains, swifts are not above a gulping, glutting feeding frenzy if the chimneys are serving up a fresh hatch.

I was once in the middle of one of these kill orgies. I was dragging a very small child along to day care to be contained for a while, when the air above a wood by the road exploded in black, screeching sparks. The swifts were among a new hatch rising from the treetops; not bothering with hairpin turns, just plowing through, jerking openmouthed heads from side to side to hit the areas of deepest density.

I told the 3-year-old to wait in the stinging nettles, ran across the road, and scrambled up a tree as high as I could get. That was quite high. I swayed in a fork just below the top and pushed my head out into the killing zone of the delta.

I saw a tongue, squat, gray, and dry; I saw myself, pinched and saucer-eyed. I felt the cool electric grace of a downstroke on my face. I snapped a mouthful of nymphs and spat them onto the roof of a brand new Mercedes dropping off a child from a house 300 yards away.

It was the closest I ever got.

But becoming a swift? I might as well try to be God.

I STRAPPED MYSELF INTO A HARNESS and was tugged by a parachute into the sky. It taught me the taste of height—but the taste to a palate designed for 6 feet above the earth, not 6,000. It taught me about the roar of the wind, but the roar in flapping ears fixed on the sides of a big crude block of a head, forced under a gushing tap. It didn't teach me how the temperature changed as I climbed: My face was too flushed with fear and thought to notice, and the rest of my body was wrapped in wool and nylon.

Swifts feel the ground by the shape of the breath it exhales.

They smell their way through the scent columns. They hunt in a reflected image of the earth—an image as dense and sticky as a caramel apple.

I looked down at woods and fields and saw woods and fields. For a swift, woods and fields are pizza delivery joints. You never go to one of those. You just call and speak to a disembodied voice. You don't really have much of a picture of what's there. You've never thought about it. You probably know vaguely where it is. If pressed, you might use its location as part of a set of directions to somewhere else (as a swift may use some terrestrial signposts for navigation). But it has no intrinsic interest other than as the source of your pizza. The swift stays at home in the air, and the earth delivers.

It's not surprising that poets get all ethereal about swifts. If anything can be literally ethereal, swifts are.

The main problem with turning myself into a swift, though, isn't that it's an air thing and I'm a soil thing. It's speed. I'm a terribly slow animal. The difference between our relative perceptions of the texture of the air is vast, but it's as nothing compared to the difference in pace of our lives.

In terms of longevity, a swift is comparable to many humans. Swifts have been known to live to 21. It's the amount of living that they put into each of the years that's the real difference.

Some arithmetic, because there is a type of truth in figures:

Each spring and each autumn they travel around 5,592 miles between Oxford and the Congo: That's 11,184 miles every year—which doesn't begin to account for the flying that they do in their ordinary lives. That's spread over about 66 days in the autumn (30 days of traveling, 36 days of stopover) and 26 days in the spring (21 days of traveling and 5 days of stopover). In autumn they average around 186 miles per day toward the 5,592 miles), and in the spring 266 miles per day. Let's assume that on the migration stopovers they do 47 miles a day feeding, soaring, sleeping, and exulting. Let's say that in the rest of their lives they're doing 62 miles a day.

The balance sheet therefore looks like this:

	Miles	Additional Stopover Miles	Total Distance
Spring Migration	5,592	235	5,827
Autumn Migration	5,592	1,692	7,284
Remaining miles traveled over the Year	16,926 (273 days at 62 miles/day)	-	16,926
Total miles	28,110	1,927	30,037

For 21 years that's 630,777 miles—about 1/150th the distance between the earth and the sun and 2.6 times the distance between the earth and the moon.

Swifts are about 6.5 inches long. I'm about 6 feet—about 11 times the length. If I were to walk proportionately as far in 21 years, I'd have walked almost 1/13 of the way to the sun, or 29 times to the moon. If I kept up the same pace and lived to 84— a realistic equivalent for that long-lived swift—I'd have walked almost a third of the way to the sun and 116 times to the moon.

But it's not all traveling and killing (though think of the millions of individual, assessed, intimately targeted head turns and snaps there will have been). That 21-year-old may well have bred 19 times. The average number of nestlings might be as high as 1.7 per season. That's 32 in its breeding lifetime. Multiply that by four for me: 128.

I followed the swifts with my eyes, despairing as they climbed up to roost in the air.

That's what they do with their time. But what about their perception of what they're doing? If (and yes, it's a big if) they're watching, as we do, a film of their own lives, how fast is it moving? And how frantic are those snapping heads?

If those questions mean anything at all, they must relate in some way, however crudely, to the speed of perception.

Snails move very, very slowly. Only if events are more than a quarter of a second apart will a snail perceive them as distinct. If you wave your finger in front of a snail four times or more a second, it will see a single, stationary finger. Sloth freezes movement: it blurs, simplifies, and integrates, and in integrating it loses a lot of the whole. It obscures the distinct parts of things, if time is an element of those parts, and concocts the lie that it sees things as they really are. It drains time out of our vision. Oversimplification is deceit.

Whereas speed, if you're up to it, can tell you the value of time; can let you see your business with the due contribution from time's perspective; can inject complexity and nuance. If, like some birds, you can hear sounds separated by less than two-millionths of a second, you'll know the baroque complexity of apparently bland birdsong. If you're a human hearing that, you'll fall on your knees. Wonder is a function of the degree of resolution—in birdsong, in optics, in philosophy, in theology. Only those blind to the velvet flow of a caterpillar's legs and deaf to the grunt of a crocus as it noses out of the earth don't worship, and often they can't be blamed.

Another way of putting this is that really fast hardware and software can effectively slow down the world. The acutely discriminating bird hears what I'd hear if I turned the speed of the birdsong right down. I can probably hear two sounds as distinct if they're around two-hundredths of a second apart. The bird's getting in one second what it would take me about two and three-quarters of an hour to hear. If the rest of the bird's tape runs at a similar rate, and the bird (let's call it a swift) lives for 21 years, then, since it has done 10,000 times as much living per unit time as I have, it will die at a real age of 210,000 years—the distance separating us from the time when the first modern humans evolved in East Africa.

Now let's try this with physical speed—which of course entails a lot of attention in many different neurological modalities. The snail can get by as a woefully crude visual discriminator because it moves over ground at a top speed of about a yard an hour.

The highest migration speed recorded for swifts over a long distance is (a plainly wind-assisted) 404 miles per day. The average for the spring migration is 209 miles per day. Measured by tracking radar, the flight speed of swifts on spring migration was 35 feet per second, which, if maintained over 24 hours, would be 573 miles per day. The fastest human runner, Usain Bolt, clocked 34 feet per second over 328 feet (a hundred 100 meters). Then he stopped, panted, was wrapped in a blanket, handed an energy drink, and carried shoulder-high around the stadium. The swifts continue, at about the same pace, 3,483 times farther per day, for the best part of a month, catching their own food and navigating across deserts, seas, and mountains. We, at our very best, are snails.

Of course there are obvious objections to all these nerdishly arithmetical types of comparison. I've been making them myself as I've tapped away. I agree with them all. But even if the comparisons are wholly worthless, it's worth making them in order to demonstrate their worthlessness, and so clear the ground for something else.

The figures might be the grammar of swifts. Grammar is necessary but not sufficient for poetry. I've tried to be prosaic, because when it comes to swifts, all poetry fails.

I CAN'T FOLLOW THE SWIFTS into the air. I'm less like them there than when I'm on the ground. Planes, of course, aren't about the air at all. You're furthest

from swifts in a hurtling tube full of flatus. The view's disembodiedly cartographical.

The air, for me, is necessarily about buckles and ball-crunching harness. I lurch, swing, and churn. At best I'm a huge aphid—a drifting piece of swift-food. At least on the ground I can dodge and roll for whole seconds at a time, and on a mountain path in a gale I can feel secure when wind is blowing around me at the same speed as around the head of a migrating swift. If I strip off my clothes on the path I'll get feedback from my ruffled body hair that's not all that unlike the tingling from the touch receptors of the swift's filoplumes—minute, hairlike feathers that lie alongside the contour feathers, moving with them and letting mission control know where each of the big plumes is in space.

Water's better, I suppose, but still remote. There I'm as buoyant as the swift when it's sleeping 2 miles above the sea. My legs could be its forked tail: they do the same job. I can angle my arms like its saber wings, and they take me down or up. But the water takes away almost as much of the swift-life as it gives. It takes away speed, and therefore swift time. A slow swift is perhaps even less of a swift than a stiff swift.

I'm best at being a swift when I'm on the ground. At least then I can see and smell the source of the air rivers the swifts are fishing, hear the thrum next to my ear of the wasp that will be broken 300 yards up, and slap a fly on my arm at more or less the same speed as the swift's stubby neck will turn and its mandibles close on it.

SITTING ON A BENCH in my Oxford garden, I followed the swifts with my eyes, despairing as they climbed up to roost in the air, beyond all eyesight, beyond all sense, sensibility, and words.

When they left I couldn't bear it. I followed them across the Channel and across France, noting down slavishly—like a bereaved disciple looking for relics—the things that the swifts might have seen or smelled or heard as they came this way. It seemed to matter that the smell of a Picardy bonfire was rendered properly in the notebooks: The birds might have caught beetles that the fire hoisted into a cloud. The chatter in a Pyrenean café was relevant: The same phrases were likely to have been used a fortnight before, at the same volumes, and at the same tables, and so to have ricocheted off the same mildewed whitewash and up into the air over the mountain at the same angles, contributing to the same hum and throb that the swifts knew, and giving a floating aphid the same sort of jerk that caused a swift's head to turn. The wine that night in an Andalusian courtyard had to be described exactly because nitrate from swift dung might have coursed into the grapes, and because insects that fed on the vines might have spiraled up in a fog of lemons and rotting shrimp and been taken by you know what. Or you know who.

The world was a web, fine as gauze, woven of causes—each cause connected to the others, and each traceable ultimately, if you followed things carefully, to the swifts.

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Excerpted from *Being a Beast: Adventures Across the Species Divide* by Charles Foster, published by Metropolitan Books, an imprint of Henry Holt and Company, LLC.

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"Olin gave me the confidence that I could do something unique and innovative. It guided me out of my comfort zone and helped me to become used to taking risks, which is so important for a startup."
- Etosha Cave '06
Olin graduate
Co-founder, Opus 12
Carbon emission-reducing clean energy startup


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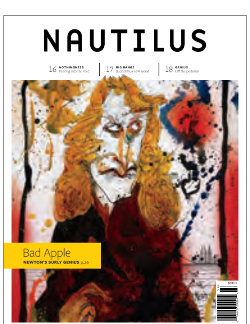

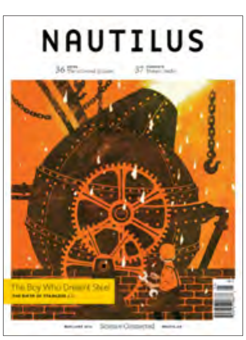

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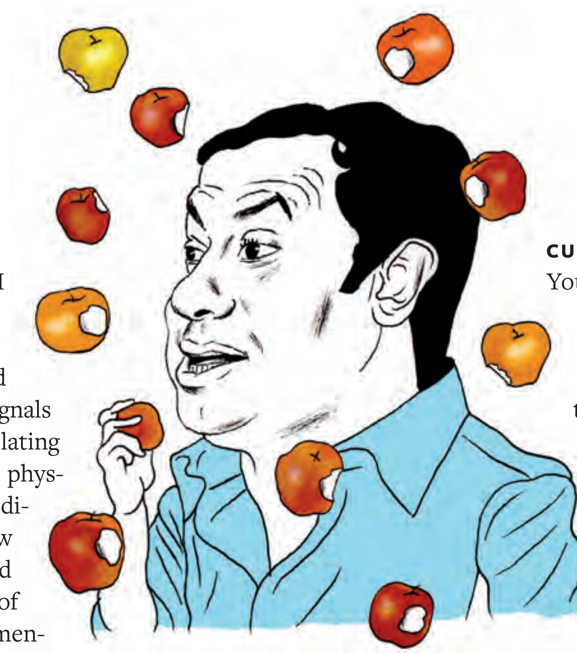
Choukri Mekkaoui

The string theorist turned radiologist reflects on the themes in Nautilus

INTERVIEW BY SUSIE NEILSON



AGING

When I was doing my Ph.D., I formalized, mathematically, all the electrical and nonelectrical signals in your body. I developed a model to project all these signals into one domain. I was translating my background in theoretical physics, specifically M-theory, to medical imaging technology. How so? Imagine I have 11 apples and each apple is one dimension of the universe—there are 11 dimensions, according to M-theory. Like the universe, there are a lot of things going on in the body—temperature, pressure, water motion. Consider that each apple has its own taste. Now imagine we create an apple where, when you eat it, you feel all the tastes simultaneously. When doctors perform a diagnostic test, they use devices that measure different indicators. It's difficult to summarize what's happening when considering all the information separately. You have to consider it simultaneously. Using the multidimensional approach, we're able to examine the water motion, temperature—and other indices from medical scans—in human tissue to pinpoint what's happening. With a heart attack, you can see which part of the muscle is going dead and localize your regeneration efforts. We make the life of the doctor easier because they only have to look at one image.

CURRENTS

You love your mom for her emotional support, her presence. You want to keep her and the eventual memory of her as perfect as possible. What if you could preserve what makes her who she is and how she makes you feel without her body? We may be able to do that one day. Let's apply the multidimensional way of looking at things to the spine. The spine acts like a cable, transferring signals from and to the brain. If we can extract and express the multidimensional content of the mind and somehow store it, we should be able to transfer that information to a robotic system. Since your brain controls your body, it should be able to control something else. Suppose someone has an accident, the spinal nerves are severed, and his arm no longer functions. In the near future, we will be able to restore the connection. Usually, aging is about living as long as we wish. But I'm not sure that's what most people want. They want to live a better life for a longer period of time. And that's what I want to do—increase the quality of life for as long as possible.

ILLUSTRATION BY ANDY FRIEDMAN

Cancer MoonShot 2020

"There are unique times in history when events and advancements in technology converge to elicit a quantum leap in medical care. That time is now for cancer. Our knowledge in the science of genomics, proteomics, immunology and immunotherapy has advanced and converged at an unprecedented speed, making now the right time to accelerate the deployment and to orchestrate the precise combinations of immunotherapy for the benefit of millions of cancer patients. The Cancer MoonShot 2020 Program, the National Immunotherapy Coalition and the QUILT Trial are designed to do just that - to rapidly deploy new immunotherapies by bringing together a diverse group of visionary leaders and stakeholders at the FDA, NCI, Pharma, and Payers. By connecting this actionable information to clinicians at the point of care across the country, we will bring to patients a dramatic improvement in cancer care."

Patrick Soon-Shiong, M.D.
Founder & Chief Executive Officer
NantWorks & The Chan Soon-Shiong Institute of Molecular Medicine

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