

NAUTILUS

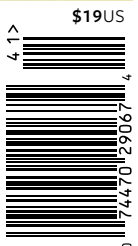
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SPRING 2014

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Monsters

THERE'S SOMETHING ABOUT SPRING and monsters. It was in the spring when John Utterson broke down a cellar door to discover the murderous Mr. Hyde; when Victor Frankenstein saw his own creation fleeing through the woods outside of Geneva; and when Jonathan Harker embarked on his journey to the castle of a certain Transylvanian nobleman. The thawing snows, it seems, have a habit of revealing follies long forgotten but unsettlingly preserved.

The spring 2014 *Nautilus Quarterly* keeps tradition with opening stories about monsters mathematical, animal, and ecological. We are reminded that the objectivity and dispassion of science are sometimes joined by a more urgent and fearful element. And, as with many monster stories, our expectations are opposed. Just as Mary Shelley transforms Frankenstein from an abomination into a sensitive interpreter of Goethe and Milton, so are we surprised at the origins of some of science's monsters—and at how outright useful they can be.

We have happy springtime stories to tell, too, both in the remainder of the *Quarterly* (did you know that wasting time is good for you?), and from our own New York offices. Thanks to you, our enthusiastic readers, the *Nautilus Quarterly* has earned personal subscribers in 46 countries, and is available for purchase in hundreds of bookstores across the United States and Canada. We were also pleased to have been awarded three Folio magazine awards, beating out some industry stalwarts in categories like best general-interest issue and best design—not bad for a magazine that launched less than a year ago!

We therefore greet the season with open arms, for, as Mary Shelley wrote, “The winter has been dreadfully severe; but the spring promises well...”

Welcome to the spring 2014 *Nautilus Quarterly*.

—Michael Segal
Editor-in-Chief

Science

for a complex world



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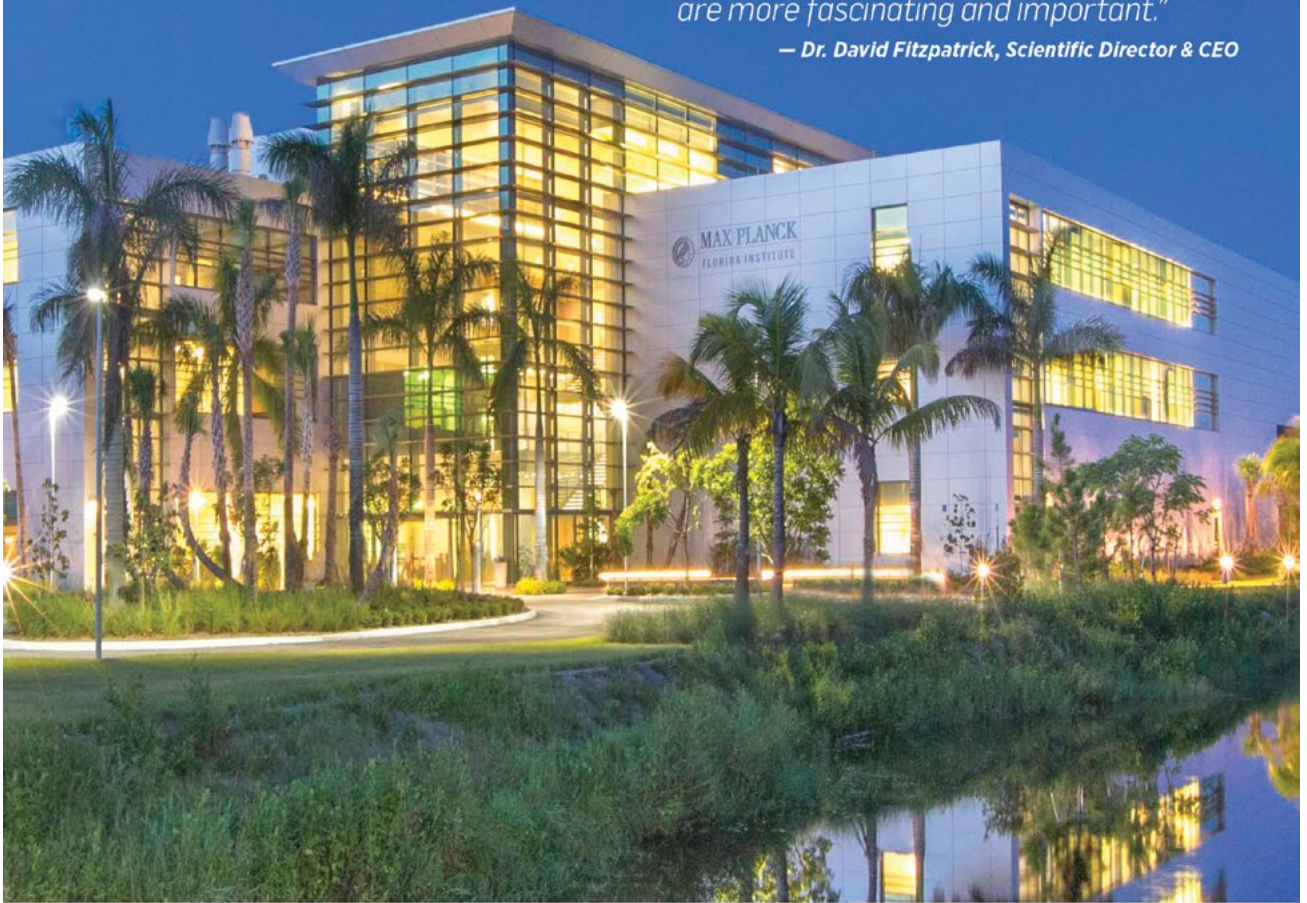
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Green

Preludes

NEUROSCIENCE

How Music Hijacks Our Perception of Time

Our brains march to the beat of their own drums

THE HUMAN BRAIN KEEPS its own time. It adjusts and recalibrates temporal perception. Our ability to encode and decode sequential information is fundamental to our survival. It allows us to find our place in, and navigate, our physical world. How can we tell our brains keep their own time? Music.

Music creates discrete temporal units, but ones that do not typically align with the discrete temporal units in which we typically measure time. Rather, music embodies a separate, quasi-independent concept of time, able to distort or negate “clock-time.” This other time creates a parallel temporal world in which we are prone to lose ourselves, or at least to lose all semblance of objective time.

Music hijacks our everyday relationship with time. More drinks are sold in bars with slow-tempo music, which seems to make the bar more enjoyable, and patrons want to linger—and order another round. Similarly, consumers spend 38 percent more time in the grocery store when the background music is slow.

Perhaps the clearest evidence of musical hijacking is this: In 2004, the Royal Automobile Club Foundation for Motoring deemed Wagner’s *Ride of the Valkyrie* the most dangerous music to listen to while driving. It is not so much the distraction, but the substitution of the frenzied tempo of the music that challenges drivers’ normal sense of speed—and the objective cue of the speedometer—and causes them to speed.

During periods of intense perceptual engagement, such as being enraptured by music, activity in the prefrontal cortex, which generally focuses on introspection, shuts down. The sensory cortex becomes the focal area of processing and the “self-related” cortex switches off.

These processes involve both memory and attention, which modulate the perception of time passing, depending upon how occupied or

stimulated we are. Hence time can “fly” when we are occupied, or seem to stand still when we are waiting for the water in the kettle to boil.

While the manipulation of time is a pervasive aspect of music and individual composers, it is Franz Schubert, more than any other composer, who succeeded in radically commandeering temporal perception. Nowhere is this more forceful than in his *String Quintet in C major*, composed in 1828, the last year of his life.

The slow second movement, in particular, puts me on the verge of a sense of temporal stasis. I feel submerged in a viscous medium—not at all struggling to move forward, but rather fully absorbed in an alternate temporal universe. Although immersed in the music, I am aware of time in the external world. I tend to breathe along with phrases, and find myself coming up short of breath. Like all music that feels both part of time and beyond it, the *String Quintet* seems to connect us to something bigger than ourselves—in the words of Schubert’s friend and collaborator, the poet Franz von Schober, “time’s infinite ocean.”

—Jonathan Berger



IMAGE OF FRANZ SCHUBERT: SHUTTERSTOCK

ARCHAEOLOGY

The Caveman's Home Was Not a Cave

Early man got around

THERE'S BEEN A PERSISTENT narrative of human evolution that describes a steady march from the primitive to the complex: Humans descended from the trees, stumbled about the land, made homes in caves, and finally found glory in high-rises.

By the 1980s, archaeologists understood that this picture was incomplete. But archaeologists continued focusing on caves, both because it was habitual and the techniques involved were well understood.

Then along came the American archaeologist, Margaret Conkey. We asked her what changed.

What tells an archaeologist that Paleolithic people spent less time in caves than we imagined in the past?

One big clue is seasonal occupation evidence, something archaeologists infer based on things like animal bones. Looking at found animal teeth can tell you in which season the animals were killed. Certain animals are only available at certain times—fish that spawn during certain seasons, for example. Almost all caves are described by archaeologists as seasonal, namely as autumn or winter occupations. It's clear that people were in caves for maybe a couple of months a year at the most.

How did you look for evidence on the landscape and what did you find?

We looked at 360 plowed fields, because when plows churn up dirt, they expose artifacts. Then we started excavating on a ridge that's never been plowed and found stone slabs, which we believe is a habitation structure in the open-air, probably from the Upper Paleolithic, about 17,000

In reality, our ancestors were people of the open landscape.

years ago. We found ochres that early humans used for art and body art. We also found pieces of flint that came from sometimes 200 kilometers away, suggesting that people carried flint from somewhere, used it for tools, and left it. That means people were on the move; making long treks, or passing these materials to each other as they met somewhere on the landscape.

Why have archaeologists held different views of home?

Archaeologists are influenced by their culture, not surprisingly. My colleagues and I are suggesting that we have certain biases about what constitutes a “home” and that mobile people didn't think of home as a stationary physical structure.

— Jude Isabella



BIOLOGY

The Curious Case of the Exploding Pig Farms

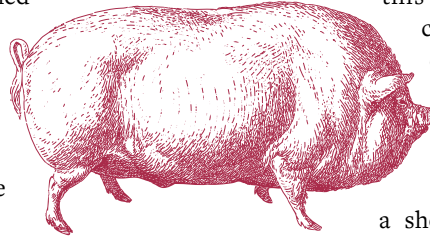
At first, the manure was just harmlessly foaming. Only later on did things get lethal.

HOG FARMS IN THE MIDWEST are great big barns sitting on top of great big pits filled with a great deal of manure. The pigs walk about on a slatted floor that lets their waste fall into the pit several feet below. Around 2007, farmers began noticing pig poop acting funny. The normally liquid mixture started producing foamy bubbles, rising up past the slats, right to the pigs' cloven hooves.

Then it got worse. Among the gases in the foam are methane and hydrogen sulfide—both highly flammable. In September 2011, a barn explosion killed 1,500 pigs and seriously injured one worker. It was the most serious in a string of explosions that have cost farmers millions of dollars. Scientists have focused attention on whether the manure contains some new surfactant, a chemical that, like soap, lowers the surface tension of liquids, allowing bubbles to form.

Around the same time the manure started foaming, farmers also started feeding their pigs more distiller's dried grains with solubles (DDGS), a cereal-like byproduct of ethanol production. DDGS is full of plant fibers and long-chain fatty acids—plausible surfactant candidates. Since the United States provides huge subsidies for making ethanol, DDGS was cheap and plentiful.

DDGS has been a suspected culprit of foaming manure from the beginning (the University of Minnesota's agriculture magazine called it "a pig bang theory"), but experiments have been inconclusive. It turns out to be quite hard to simulate the complicated chemistry that develops in a manure pit over a year.



It turns out to be quite hard to simulate the complicated chemistry that develops in a manure pit over a year.

The best short-term solution farmers have come up with is antibiotics. Rumensin 90, an antibiotic normally used to prevent bloat in cattle, has been repurposed to prevent gas in pig manure pits. No one has yet explained why it works.

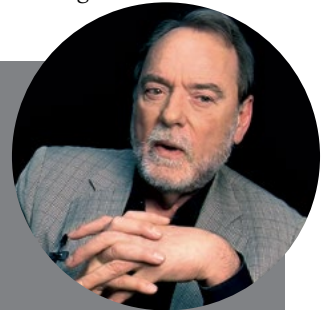
Farming accounts for 80 percent of all antibiotics sold in the U.S.—this widespread use contributes to the development of deadly antibiotic-resistant infections in people. Rumensin 90 is, at best, a short-term fix. If the foaming manure is indeed linked to DDGS, then the consequences of a poorly thought-through policy—incentives for producing ethanol—is quite literally blowing up in our faces.

—Sarah Zhang

PALEONTOLOGY

One Question for Ian Tattersall

What's the biggest misnomer about human origins?



THE NOTION THAT NATURAL SELECTION has somehow fine-tuned us to be a particular kind of creature, and we can blame evolution for all our shortcomings, and look upon ourselves as optimized and not have to change our behaviors. But if you look at the human fossil record, we see a pattern of revolutionary change. You see we are not the product of a process of perfectionizing. We are in many ways totally accidental, and that to me is the big lesson. If we're accidental, then we have the responsibility to exploit our own abilities in the most responsible way.

—IAN TATTERSALL is the curator emeritus at American Museum of Natural History

Ah, to Be a Croc

Reptiles rock out in old age, while humans waste away

BY AMY MAXMEN

ILLUSTRATION BY NORA KRUG

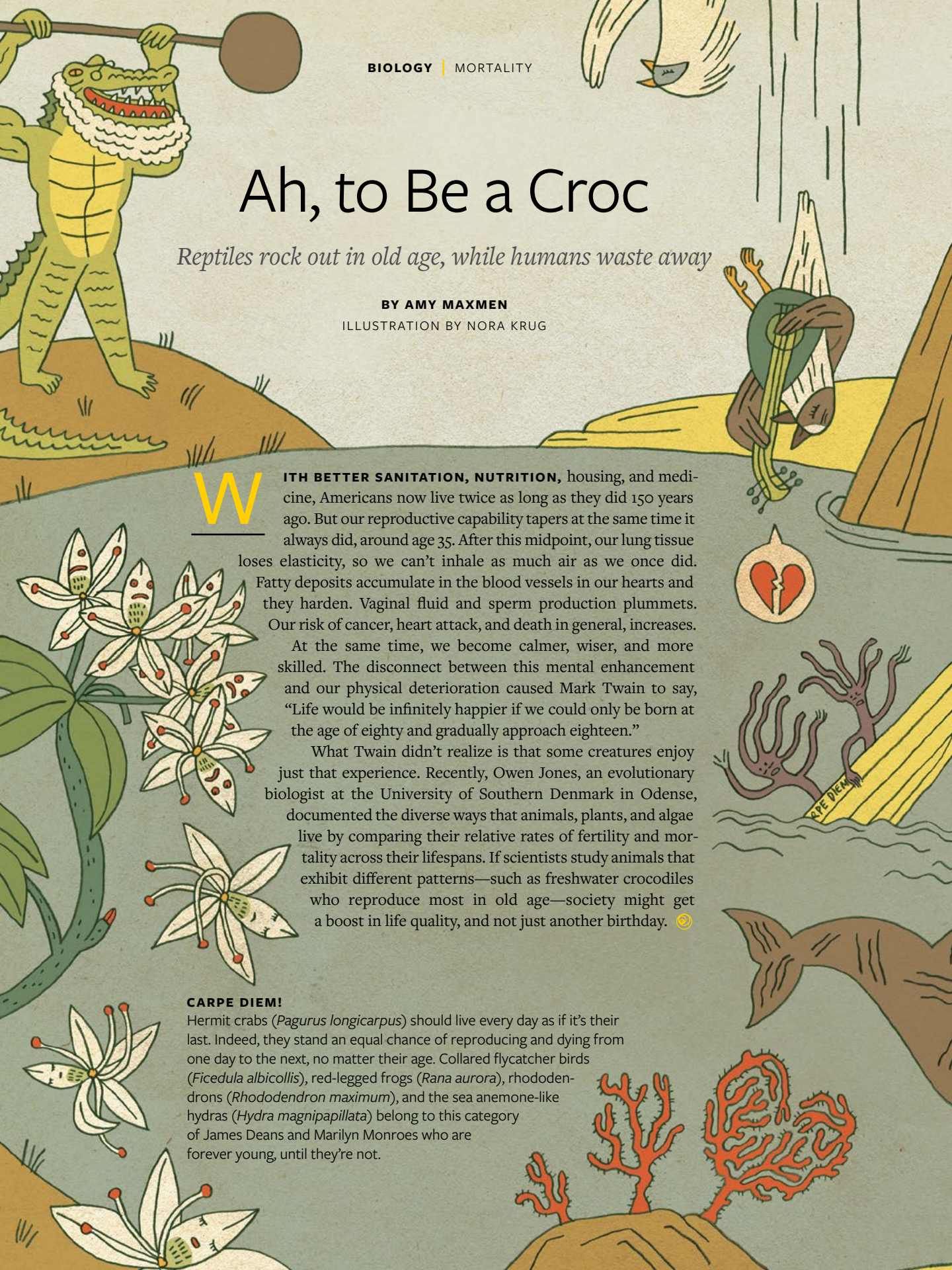
WITH BETTER SANITATION, NUTRITION, housing, and medicine, Americans now live twice as long as they did 150 years ago. But our reproductive capability tapers at the same time it always did, around age 35. After this midpoint, our lung tissue loses elasticity, so we can't inhale as much air as we once did. Fatty deposits accumulate in the blood vessels in our hearts and they harden. Vaginal fluid and sperm production plummets. Our risk of cancer, heart attack, and death in general, increases.

At the same time, we become calmer, wiser, and more skilled. The disconnect between this mental enhancement and our physical deterioration caused Mark Twain to say, "Life would be infinitely happier if we could only be born at the age of eighty and gradually approach eighteen."

What Twain didn't realize is that some creatures enjoy just that experience. Recently, Owen Jones, an evolutionary biologist at the University of Southern Denmark in Odense, documented the diverse ways that animals, plants, and algae live by comparing their relative rates of fertility and mortality across their lifespans. If scientists study animals that exhibit different patterns—such as freshwater crocodiles who reproduce most in old age—society might get a boost in life quality, and not just another birthday. 🐢

CARPE DIEM!

Hermit crabs (*Pagurus longicarpus*) should live every day as if it's their last. Indeed, they stand an equal chance of reproducing and dying from one day to the next, no matter their age. Collared flycatcher birds (*Ficedula albicollis*), red-legged frogs (*Rana aurora*), rhododendrons (*Rhododendron maximum*), and the sea anemone-like hydras (*Hydra magnipapillata*) belong to this category of James Deans and Marilyn Monroes who are forever young, until they're not.





In the twilight of their lives, desert tortoises (*Gopherus agassizii*), freshwater crocodiles (*Crocodylus johnsoni*), agave cacti (*Agave marmorata*), and the spindly sisters of jellyfish, red gorgonians (*Paramuricea clavata*), are at the peak of their reproductive potentials. The risk of death for tortoises and gorgonians drops over time as well, meaning that their seniors might have a lot in common with our teenagers, both groups falling into tumultuous love affairs and tossing caution into the wind.



By living far beyond their reproductive years, humans can nurture their offspring for decades. Extended parental care might also explain why killer whales (*Orcinus orca*) and chimpanzees (*Pan troglodytes*) have a similar pattern of decreasing reproduction and increasing mortality as they age. Nematode worms (*Caenorhabditis elegans*) and fruitflies (*Drosophila melanogaster*) do too, even though their babies are hatch-n-go. Whatever the reason, all of these animals spend almost half of their lifespan without (non-pharmacological) sex, and avoiding death, the risk of which rises every year.



Math's Beautiful Monsters

How a destructive idea paved the way for modern math

BY ADAM KUCHARSKI

MUCH LIKE ITS CREATOR, Karl Weierstrass' monster came from nowhere. After four years at university spent drinking and fencing, Weierstrass had left empty handed. He eventually took a teaching course and spent most of the 1850s as a schoolteacher in Braunsberg. He hated life in the small Prussian town, finding it a lonely existence. His only respites were the mathematical problems he worked on between classes. But he had nobody to talk to about mathematics, and no technical library to study in. Even his results failed to escape the confines of Braunsberg. Instead of publishing them in academic journals as a university researcher would, Weierstrass added them to articles in the school prospectus, baffling potential students with arcane equations.

Eventually Weierstrass submitted one of his papers to the respected *Crelle's Journal*. While his previous articles had made barely a ripple, this one created a flood of interest. Weierstrass had found a new way

to deal with a fiendish class of equations known as Abelian functions. The paper only contained an outline of his methods, but it was enough to convince mathematicians they were dealing with a unique talent. Within a year, the University of Königsberg had given Weierstrass an honorary doctorate, and soon afterward the University of Berlin offered him a professorship. Despite having gone through the intellectual equivalent of a rags to riches story, many of his old habits remained. He would rarely publish papers, preferring instead to share his work among students. It was not just the publication process he had little regard for: He was also not afraid to target mathematics' sacred cows.

Weierstrass soon took aim at the research of Augustin-Louis Cauchy, one the century's most eminent mathematicians. Much of Cauchy's work focused on calculus and rates of change (or "derivatives"). He had created what was in essence a calculus dictionary, specifying the subject's most important concepts.

But when Weierstrass read its definitions, he found them to be wordy and vague. There was too much hand waving, and not enough detail.

He decided to revise Cauchy's dictionary by replacing the prose with logical conditions. Chief among this early work was the redefinition of a derivative. To calculate the gradient of a curve at a certain point—and hence its rate of change—Isaac Newton had originally considered a line that passed through the point of interest and a nearby point on the curve. He then moved that nearby point closer and closer, until the slope of the line was equal to the gradient of the curve. But it was difficult to define the concept mathematically. What dictated whether two points were “close” to each other?

In Cauchy's verbose definition, the gradient would “approach indefinitely to a fixed value, in a manner so as to end by differing from it by as little as one wishes.” Weierstrass did not think this was clear enough. He wanted a more practical definition, so decided to convert the concept into a formula. Rather than manipulating abstract ideas, mathematicians would instead be able to rearrange equations. In doing so, he was laying the foundations for his monster.

AT THE TIME, MATHEMATICIANS drew much of their inspiration from nature. When Newton first developed calculus, he'd been inspired by the physical world: the trajectory of a planet, the swinging of a pendulum, the motion of falling fruit. This thinking led to a geometrical intuition about mathematical structures. They should make sense in the same way that a physical object would. As a result, many mathematicians concentrated on “continuous” functions. Conceptually, these are functions that can be drawn without taking pen from paper. Plot the speed of a falling apple over time and it will be a solid line; there will be no gaps or sudden jumps. A continuous function was, it was thought, a natural one.

Conventional wisdom held that for any continuous curve, it was possible to find the gradient at all but a finite number of points. This seemed to match intuition: A line might have a few jagged bits, but there would always be a few sections that were “smooth.” The French physicist and mathematician André-Marie Ampère had even published a proof of

If Newton
had
known
about
such
functions,
he would
have never
created
calculus.

this claim. His argument was built on the “intuitively evident” fact that a continuous curve must have sections that increase, decrease, or remain flat. Which meant that it must be possible to calculate the gradient in these regions. Ampère did not think about what happened when the sections became infinitely small, but he claimed that he didn’t need to. His approach was general enough to avoid having to consider things that were “*infinitement petits*.” Most mathematicians were happy with his reasoning: By the middle of the 19th century, almost every calculus textbook quoted Ampère’s proof.

But during the 1860s, rumors started circulating about a strange creature, a mathematical function that contradicted Ampère’s theorem. In Germany, the great Bernhard Riemann told his students that he knew of a continuous function that had no smooth sections, and for which it was impossible to calculate the derivative of the function at any point. Riemann did not publish a proof, and neither did Charles Cellérier at the University of Geneva, who—despite writing that he’d discovered something “very important and I think new”—stuffed the work into a folder that would only become public after his death decades later. Yet if the claims were to be believed, it meant a threat to the very foundations of calculus was forming. This creature threatened to tear apart the happy relationship between mathematical theory and the physical observation on which it was based. Calculus had always been the language of the planets and stars, but how could nature be a reliable inspiration if there were mathematical functions that contradicted the central ideas of the subject?

The monster was finally born in 1872, when Weierstrass announced that he had found a function that was continuous and yet not smooth at any point. He had constructed it by adding together an infinitely long sequence of cosine functions:

$$f(x) = \frac{\cos(3x\pi)}{2} + \frac{\cos(3^2x\pi)}{2^2} + \frac{\cos(3^3x\pi)}{2^3} + \dots$$

As a function, it was ugly and awkward. It was not even clear what it would look like when plotted on a graph. But that didn’t matter to Weierstrass. His proof consisted of equations rather than shapes, and this was

what made his announcement so powerful. Not only had he created a monster, he’d built it from concrete logic. He had taken his new, rigorous definition of a derivative and shown it was impossible to calculate one for this new function.

THE RESULT THREW THE mathematics community into a state of shock. The French mathematician Émile Picard pointed out that if Newton had known about such functions, he would have never created calculus. Rather than harnessing ideas about the physics of nature, he would have been stuck trying to clamber over rigid mathematical obstacles. The monster also began to trample over previous research. Results that had been “proven” started to buckle. Ampère had used the vague definitions favored by Cauchy to prove his smoothness theorem. Now, his arguments began to collapse. The vague notions of the past were hopeless against the monster. Worse, it was no longer clear what constituted a mathematical proof. The intuitive, geometry-based arguments of the previous two centuries seemed to be of little use. If mathematics tried to wave the monster away, it would stand firm. With one bizarre equation, Weierstrass had demonstrated that physical intuition was not a reliable foundation on which to build mathematical theories.

Established mathematicians tried to brush the result aside, arguing that it was awkward and unnecessary. They feared that pedants and troublemakers were hijacking their beloved subject. At the Sorbonne, Charles Hermite wrote, “I turn with terror and horror from this lamentable scourge of functions with no derivatives.” Henri Poincaré—who was the first to call such functions monsters—denounced Weierstrass’ work as “an outrage against common sense.” He claimed the functions were an arrogant distraction, and of little use to the subject. “They are invented on purpose to show our ancestors’ reasoning is at fault,” he said, “and we shall never get anything more out of them.”

Many of the old guard wanted to leave Weierstrass’ monster in the wilderness of mathematics. It didn’t help that nobody could visualize the shape of the animal they were dealing with—only with the advent of computers did it become possible to plot it. Its hidden form made it hard for the mathematics community

to grasp how such a function could exist. Weierstrass' style of proof was also unfamiliar to many mathematicians. His argument involved dozens of logical steps, and ran to several pages. The trail of ideas was subtle and technically demanding, with no real-life analogs to guide the way. The instinct was to avoid it.

But monsters have a habit of finding their way in from the cold, finding vindication in subsequent research. Indeed many concepts that now seem obvious, even essential, were once monsters. Negative numbers were shunned by mathematicians for centuries. The ancient Greeks, who dealt chiefly with geometry, saw no need for them. Nor did the medieval academics who adopted Greek ideas. The shadow of this monster will occasionally still appear today, such as when a child asks why multiplying two negative numbers together produces a positive one. But overall the beast has been tamed; nobody would dream of exiling it again.

In a similar fashion, Weierstrass' monster began to find acceptance. In 1904, Albert Einstein introduced physicists to the idea of "Brownian motion": Particles in a liquid, he said, follow a random path because fluid molecules are constantly knocking them around. The collisions are so frequent (more than 10^{21} per second) that no matter how good the microscope, or how detailed the observation, the trajectories are never smooth. At the practical level, it is not possible to find a derivative. If researchers wanted to work with such problems, they would need to confront Weierstrass' monster—and that is exactly what Einstein did. His theory for Brownian motion used functions that were infinitely jagged. It set a long-standing precedent: Physicists have used non-smooth functions as a proxy for Brownian motion ever since.

Once it became clear that the so-called "Weierstrass function" was actually quite useful, researchers began to develop ways to handle non-smooth functions gracefully. Rather than trying to analyze the path of a single particle in a liquid, they would look at the average behavior of many particles. How far were they likely to travel? When might they reach a given point? Outside of Brownian motion, mathematicians also started to rethink the basic tools of calculus. Rates of change had always been defined in terms of distances,



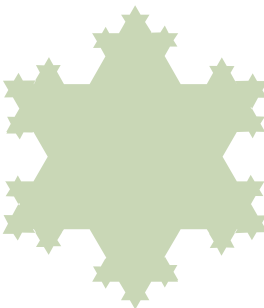
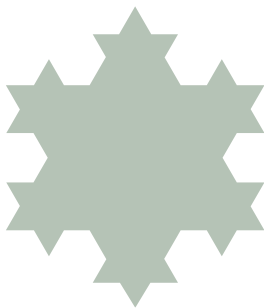
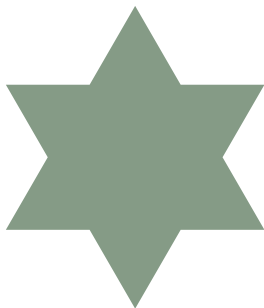
and areas under a curve measured geometrically. But when functions were not smooth, these ideas did not make sense.

At the University of Tokyo, Kiyoshi Itô found a way around the problem by thinking in terms of probabilities. It was an unorthodox, not to mention risky, tactic: During the 1940s, hardly anyone viewed probability theory as a rigorous subject. Yet Itô persevered. He treated functions like random processes, and translated Weierstrass' definitions into a new, probability-based language. Two random processes were "close" together, he said, if the expected outcomes were the same. He introduced a method for handling a mathematical function that depends on a non-smooth quantity—like Brownian motion—rather than a more traditional variable, like distance. Using his new methods, he derived "Itô's Lemma" to calculate how such a function changes over time.

By the 1970s, Itô's work had blossomed into a whole new area of mathematics, called stochastic calculus (mathematicians like calling things that are random "stochastic"). It came with a whole new set of tools and theorems, just as calculus had. Today, stochastic calculus is used to study all sorts of phenomena, from neurons firing in a brain to diseases spreading through a population. It is also at the heart of financial mathematics, where it helps banks estimate option prices. It can account for the bumpy behavior of a stock price, and hence reveal how the value of an option changes over time. The resulting equation, which is known as the Black-Scholes formula, is now used on trading floors around the world. Yet Itô was always puzzled when he won plaudits from bankers. As a pure mathematician, he hadn't expected his work to become famous for its applications.

Weierstrass' monster shook things up in geometry too. At the end of the 19th century, Swedish mathematician Helge von Koch had become interested in the idea of non-smooth functions, but he wanted to see their shape. He set out to build a shape (rather than a function) that was nowhere smooth, and hence show that the same monsters were lurking in both algebra and geometry. He might not be able to draw the Weierstrass function, but he would be able to picture its cousin. Working on the problem while hopping from one temporary job to another as a junior

The
\$1 million
prize
remains
unclaimed.
In many
ways it is
a ransom.



professor, von Koch found his creature in 1904.

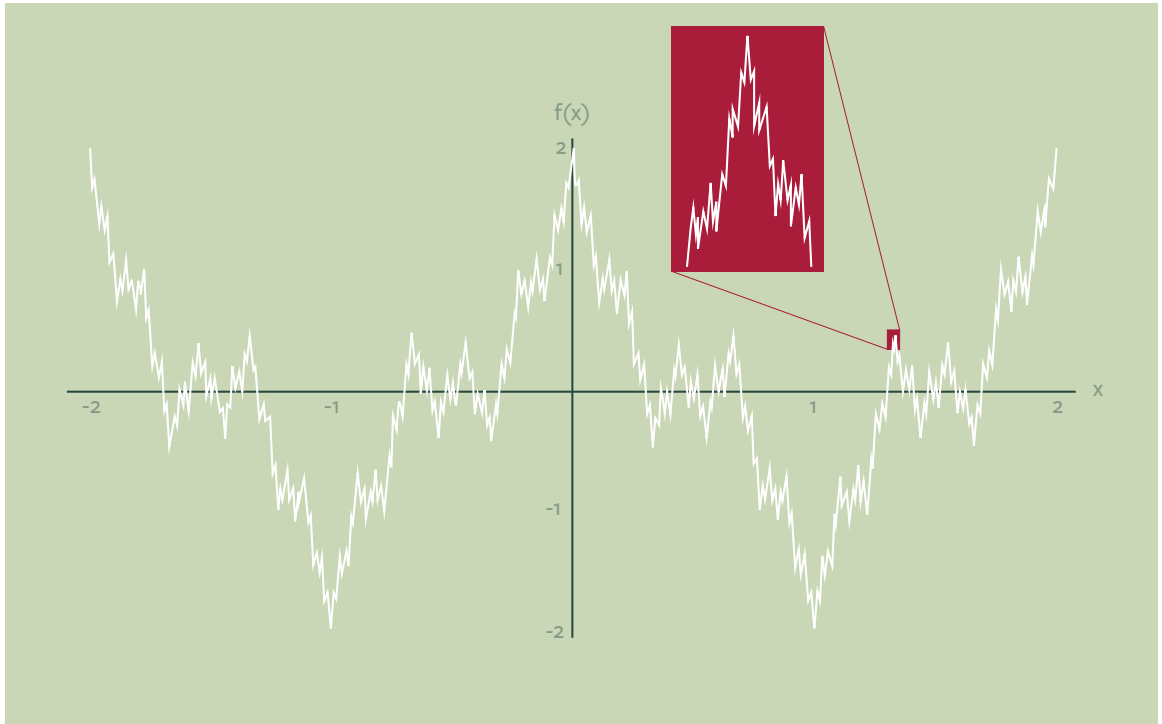
Constructed by taking an equilateral triangle, then adding three smaller triangles to each side, and continuing to do so indefinitely, it was a geometric shape that was continuous but had no derivatives. The shape's distinctive appearance meant it soon became known as the "Koch snowflake."

Koch had succeeded in extending Weierstrass' monster beyond the world of equations and functions. But there was something else noteworthy about his result. Upon closer inspection, it turned out that his snowflake had a curious self-similarity: Magnify one particular section of the snowflake and it would look similar to the zoomed-out shape. Many years later, it would become apparent that the Weierstrass function had the same property.

As time went on, this self-similarity began cropping up in all sorts of places. It would take Benoit Mandelbrot's seminal work during the 1980s to popularize the idea of "fractal" objects, which had shapes that were repeated at smaller and smaller length scales. From coastlines and clouds to plant and blood vessels, mathematicians discovered that fractals were ubiquitous in nature. Like Koch's snowflake, none were smooth. How could they be? If the shape had smooth sections, the pattern would disappear when magnified sufficiently. As Koch had found, the simplest way to obtain a non-smooth shape was to construct a fractal object. Perhaps it was inevitable that Weierstrass' work would guide mathematicians towards self-similar patterns, introducing researchers to a world of intricate, beautiful structures.

WEIERSTRASS' MONSTER CONTINUES ITS work in the present day. The Navier-Stokes equations describe the motion of a fluid and underpin modern fluid dynamics and aerodynamics, driving everything from aircraft design to weather prediction. However, although they were first developed in the 1840s, mathematicians still do not know if they can always be solved. In 2000, the Clay Mathematics Institute offered a \$1 million prize to anyone that could show that the

THE KOCH SNOWFLAKE Created by repeatedly adding small triangles to the sides of bigger ones, the Koch snowflake shows that it is possible for the edge of a geometric shape to have no smooth regions.



THE MONSTER Weierstrass' function is infinitely detailed, so even with a computer it is only possible to visualize its approximate shape. When magnified, new shapes emerge, which are similar in appearance to the overall curve.

equations always have smooth solutions—or find an example to the contrary. The problem is considered among the six most important outstanding problems in mathematics because, despite the widespread use of the Navier-Stokes equations, mathematicians do not know whether the equations always produce physically plausible results. The \$1 million prize remains unclaimed. In many ways it is a ransom, encouraging mathematicians to hunt for troublesome monsters.

From fluid dynamics to finance, creatures like the Weierstrass function have challenged our ideas about the relationship between mathematics and the natural world. Mathematicians around the time of Weierstrass used to believe that the most useful mathematics was inspired by nature, and that Weierstrass' work did not fit into that definition. But stochastic calculus and Mandelbrot's fractals have proven them wrong. It turns out that in the real world—the messy, complex

real world—monsters are everywhere. “Nature has played a joke on the mathematicians,” as Mandelbrot put it. Even Weierstrass himself fell victim to the trick. He created his function to argue that mathematics should not be based only on physical observations. His followers believed that Newton had been constrained by real-life intuition and that, once free of these limitations, there were vast, elegant new theories to be discovered. They thought that mathematics would no longer need nature. Yet Weierstrass' monster has revealed the opposite to be true. The relationship between nature and mathematics runs deeper than anyone ever imagined. ☺

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What the Deer Are Telling Us

A lesson in home improvement

BY CHRISTOPHER KETCHAM

IN 1909, A UNITED STATES Forest Service officer named Aldo Leopold shot a mother wolf from a perch of rimrock in the Apache National Forest in Arizona. It was a revelatory moment in the life of the young naturalist. “In those days we never heard of passing up a chance to kill a wolf,” Leopold wrote in an essay called “Thinking Like a Mountain,” later included in his *Sand County Almanac*, published posthumously after his death in 1948 and which went on to sell several million copies. “We reached the old wolf in time to watch a fierce green fire dying in her eyes. I realized then, and have known ever since, that there was something new to me in those eyes—something known only to her and to the mountain.”

Leopold, who today is revered among ecologists, was among the earliest observers of the impact of wolves on deer abundance, and of the impact of too many deer on plant life. In “Thinking Like a Mountain,” he outlined for the first time the basic theory of trophic cascades, which states that top-down predators

determine the health of an ecosystem. The theory as presented by Leopold held that the extirpation of wolves and cougars in Arizona, and elsewhere in the West, would result in a booming deer population that would browse unsustainably in the forests of the high country. “I now suspect that just as a deer herd lives in mortal fear of its wolves,” Leopold wrote, “so does a mountain live in mortal fear of its deer.”

One of the areas where Leopold studied deer irruptions was the Kaibab Plateau near the Grand Canyon. By 1924, the deer population on the Kaibab had peaked at 100,000. Then it crashed. During 1924-26, 60 percent of the deer perished due to starvation. Leopold believed this pattern of deer exceeding the carrying capacity of the land would repeat across the U.S. wherever predators had been eliminated as a trophic force. By 1920, wolves and cougars were gone from the ecosystems east of the Mississippi—shot, trapped, poisoned, as human settlement fragmented their habitat—and they were headed toward extirpation in most parts

ILLUSTRATION BY CHRIS BUZELLI

of the American West. Within two generations, the hunting of deer had been heavily regulated, the calls from conservationists had been heeded for deer reintroduction throughout the eastern U.S., and swaths of state and federally managed forest had been protected from any kind of hunting.

Freed both of human and animal predation, however, deer did not follow the pattern predicted by Leopold. Instead of eating themselves out of house and home, they survived—they thrived—by altering their home range to their benefit. As recent studies have shown, certain kinds of grasses and sedges preferred by deer react to over-browsing the way the bluegrass on a suburban lawn reacts to a lawnmower. The grasses grow back faster and healthier, and provide more sustenance for more deer. In short, there has been enough food in our forests, mountains, and grasslands for white-tailed deer in the U.S. to reach unprecedented numbers, about 32 million, more than at any time since record-keeping began.

In 1968, Stanford biology professor Paul Ehrlich predicted that another widespread species would die out as a result of overpopulation. But he was spectacularly wrong. Like the deer, the steadily ingenious *Homo sapiens* altered its home range—most notably the arable land—to maximize its potential for survival. As *Homo sapiens* continues to thrive across the planet today, the species might take a moment to find its reflection in the rampant deer.

Conservation biologists who have followed the deer tend to make an unhappy assessment of its progress. They mutter dark thoughts about killing deer, and killing a lot of them. In fact, they already are. In 2011, in the name of conservation, the National Park Service and U.S. Department of Agriculture teamed up with hunters to “harvest” 3 million antlerless deer. I asked Thomas Rooney, one of the nation’s top deer irruption researchers, about the losses in forest ecosystems overrun by deer. “I’d say the word is ‘apocalypse,’” Rooney said.

On a warm fall day last year, I went to see Rooney, a professor of biology at Wright State University, in Dayton, Ohio. In his office, I noticed a well-thumbed copy of Ehrlich’s *The Population Bomb*, and I asked him if he thought a comparison might be drawn between human overpopulation and deer overpopulation. He looked at

“He looked at me as if the point was obvious. “Deer, like humans,” he said, “can come in and eliminate biodiversity, though not to their immediate detriment.”

me as if the point was obvious. “Deer, like humans,” he said, “can come in and eliminate biodiversity, though not to their immediate detriment.”

We took a walk through the university’s 200-acre “biology preserve,” its tall hardwoods bounded on all sides by the city’s bucolic suburbia. The afternoon sun stippled the understory, the autumn leaves were just turning, the colors yet to peak, and the sight, it seemed to me, was splendid. Rooney said the reserve was doomed. Saplings of almost all the native trees—shingle oaks, walnut, white ash, elm—were stunted or dying from the over-browsing of too many deer. The forest, he said, would never regenerate if deer went uncontrolled.

Rooney bent to his knees and held the leaves of a white ash sapling three feet in height. Most of the leaves had been chewed away, reduced to nubs. “Deer ruins,” said Rooney. “It might have three, four years left. It can’t eat enough sunlight without leaves.” We stopped at a ragged elm sapling that stood perhaps



OH DEER White-tailed deer, like these feeding in a Virginia meadow, now total 32 million in the U.S. They've literally made a new ecological home on the range.

a foot tall. Maybe it would grow to three feet, said Rooney. A few paces away we found wild ginger, which deer in the preserve had only begun browsing. The deer were working down to plants they had hitherto avoided. "They'll successively work down to everything they can eat," said Rooney.

He told me about a study published last year in *Conservation Biology* that bemoaned "pandemic deer overabundance," language suggesting the creature was a disease on the land. Ecosystem damage becomes apparent at roughly 15 deer per square mile, and the damage grows with density. Some areas of the northeast host as many as 100 deer per square mile. (The Wright State University reserve has a density of around 40 deer per square mile.) He noted a 2013 article co-authored by a group of Nature Conservancy scientists who warned that "no other threat to forested habitats is greater at this point in time—not lack of fire, not habitat conversion, not climate change."

Researchers at Cornell University last year concluded that one-third of the forests in New York State had been "so heavily compromised as a result of excessive herbivory" that the hardwoods failed to recruit new saplings for the replacement of older generations. These over-browsed forests consisted only of the middle-aged, the old, and the dying. There were no young folk among the trees. A 2005 report from British Columbia's Haida Gwaii archipelago found that the predator-free islands, where deer have had the run of the place for more than 50 years, contained 85 percent fewer shrubs and herbaceous plants than deer-free islands. On Anticosti Island, in Quebec, deer feasted so remorselessly on currants, gooseberries, and wild fruits that the native bear population, dependent on the fruits for survival, died out within 50 years of deer introduction. This was astonishing. A prey species, by stealing away plant resources, had extirpated its predator. In Pennsylvania, researchers in 1994 and again

The optimist, surveying our advances of the last century, has only to smile and conclude that we have happily launched ourselves beyond the constraints of carrying capacity.

in 2012 found that song-bird populations crashed as a result of deer destroying the understory where the birds nested.

I asked Rooney about the remarkable ability of deer to thrive in their home range—most of the U.S.—while producing ecosystem simplification and a biodiversity crash. In his own studies of deer habitats in Wisconsin, Rooney found that only a few types of grass thrive under a deer-dominant regime. The rest, amounting to around 80 percent of native Wisconsin plant species, had been eradicated. “The 80 percent represent the disappearance of 300 million years of evolutionary history,” he said. He looked deflated.

A turkey vulture pounded its wings through the canopy, and in the darkening sky a military cargo plane howled in descent toward nearby Wright-Paterson Air Force Base. Rooney and I emerged from the forest onto a campus parking lot where *Homo sapiens* held sway. The self-assured mammals crossed fields of exotic bluegrass under pruned hardwoods surrounded by a sea of concrete, tarmac, glass, and metal. There were no flowers except those managed in beds. There were no other animals to be seen except the occasional squirrel, and these were rat-like, worried, scurrying. The *Homo sapiens* got into cars that looked the same, on streets that looked the same, and they were headed to domiciles that looked more or less the same. This is home for us.

A FEW DAYS LATER, I called up a former U.S. Fish and Wildlife Service biologist named Leon Kolankiewicz, who has written extensively about human overpopulation and biodiversity, to ask about the effect of 7 billion human beings on wild flora and fauna. Habitat for these wild creatures, he said, is being destroyed, fragmented, or degraded. Animals and fish are poached, overhunted, overharvested. Ecosystems are contaminated with toxic pollutants, and invasive species are deliberately or unwittingly introduced. Earth, as biologist E.O. Wilson has noted, is in the midst of a sixth mass extinction. (There are five others in the geologic record, stretching back 500 million years.) “Extinction is now proceeding thousands of times faster than the production of new species,” Wilson writes.

Kolankiewicz offered a perverse angle of hope for the human race in the midst of this carnage. Loss of biodiversity may not threaten the survival of our species. “Hypothetically, we could survive for quite some time on a simplified planet,” said Kolankiewicz. “Deer are a good analogy. Throughout human history, populations have invaded and colonized new ecosystems, hunted and displaced other species, have caused massive losses of biodiversity, and went on to survive in these depauperate settings.”

Take the human invasion of North America circa 13,000 years ago, when the wise ape, adept with deadly technology and savvy in methods of cooperative

hunting, succeeded in wiping out in a few hundred years the megafauna that had ranged across the continent for hundreds of millennia. North American man went on to stake his home ground and thrive on a continent shorn of its most majestic predators and herbivores. Take the examples of the rise and remarkable success of every large-scale agricultural civilization in pre-modern history, from the Mayans in the Americas to Egypt and Sumer and China. These civilizations, with high population densities, commandeered vast raw resources—land, space, soil, water, nutrients—for the intensive cultivation of grain crops, and biodiversity was clobbered in the march of progress. They thrived for hundreds of years—until collapse was precipitated by the usual factor: their own too-muchness, the breaching of the limits of carrying capacity, their home overwhelmed.

The optimist, surveying our advances of the last century, has only to smile and conclude that we have happily launched ourselves beyond the constraints of carrying capacity. If human population doubled between 1804 and 1927, and doubled again between 1927 and 1974, and almost doubled again to 6.9 billion today, with the latest forecasts projecting more than 10 billion people by 2100, we can look to nanotechnology, genetically modified crops, antibiotic feed supplements for livestock, more efficient transportation networks, unconventional oil deposits, safe nuclear energy, wind and solar arrays, smart grids, and much else in the techno-arsenal to keep the human species from crashing. In the perennial face of collapse, “innovation resets the clock,” said Geoffrey West, a physicist, and expert in social systems, at the Santa Fe Institute. How long can the clock of innovation tick? Who can say? Again and again, time has proven the Malthusian pessimists wrong. Like the deer without its predators, *Homo sapiens* has remade its home range to its benefit.

A FEW WEEKS AFTER I met with Rooney, I went into the Catskill Mountains of New York State to visit my family’s vacation home. The place, hanging for dear life on three mountainous acres, is a drafty board-and-batten cabin, about 10 by 15 in size, with no running water, no toilet except the forest, no electricity. Home might be a generous description. As a young man I had installed a wood stove, and had gotten in the habit of

escaping from New York City to spend weekends there, writing by candlelight, stoking the fire to keep warm during the freezing nights, bushwhacking in the spring green-up. At the time I thought that I was privileged to watch the workings of a healthy ecosystem.

My mother had told me that when she bought the property in 1971 it held swamp maple, oak, hemlock, birch, yellow poplar, beech, hickory nut, ash. Our five hemlocks have died. The birch are tall and middle-aged or old and dying, as are the hickory nut and the ash and the poplar and the beech. The grandfather of the trees on the property, a fat gnarled oak personality like something out of Tolkien, fell over last summer in what must have been a terminal act of colossal noise. The dense forest that I remembered as a kid to be impassible, the understory full of walls of green and few paths, was now open and easy-going. I found only a few saplings, and those were chewed away, pitiful, bent. Rooney had told me in the Ohio woods that “home for the deer is now a lot less interesting place.” And for us too. ☺

CHRISTOPHER KETCHAM is a contributing editor at *Harper's Magazine*.

The Men Who Planted Trees

In West Africa, a model for worldwide conservation takes root

BY ANNA BADKHEN

ILLUSTRATIONS BY SAM GREEN



AN HOUR BEFORE SUNUP the Bani River uncoils through the dark Sahel in bright silver curves, a reflection of a day not yet dawned, hardships not yet known, hopes not yet broken. Onto such a magical surface the Bozo fishermen of Sindaga shove off with bamboo poles and float downstream in redwood pirogues, one silent man per boat. The fishermen work standing up: solitary Paleolithic silhouettes keeping perfect balance against the river's luminescence, each man one with his boat like some pelagic centaur, performing one of mankind's oldest rites. They cast their diaphanous seines into the night. Handmade sinkers kiss the surface, pucker it lightly, drag the nets under.

By the time daybreak trims burgundy the sparse savannah, the fishermen row their day's first catch back to the village. In squat banco houses that crowd the river, the men take breakfast of rice and fish sauce. They patch up the nets while their wives and mothers sort the morning haul into giant wicker baskets and lug it to the nearest market town. After midday prayer, the men cast off again.

Such has been their fishing schedule for centuries, aligned with the orderly procession across the West African sky of 26 sequential constellations. Each new star signifies the advent of a windy season, of weeks of life-giving drizzle or days of downpour, of merciless heat or relentless malarial mosquitoes dancing in humid nights. Each star announces the arrival of the blue-tinged Nile perch, of the short-striped daggers of clown killi, of the lunar disks of the Niger stingray, of the toothless garras that like to nibble the bare ankles of laundresses, and that, in the West, are used for pedicures in foot spas.

Or so it used to be. Mali has been growing drier and hotter since the 1960s. For the past three decades, the weather has been chaotic, out of whack with the stars. The rainy season has been starting early or late or not arriving at all. Droughts throttle the land and wring dry the river. Flash floods wash away harvests and entire homesteads hand-slapped of rice straw and clay. Acres of deforested riverbank dry out and blow away, or collapse into the water. The fish run off schedule. "The river is becoming broken," said Lasina Kayantau, a Sindaga elder.



TREE OF LIFE At the feet of village elder Lasina Kayantau, an acacia sapling springs to life. "I want the people in the village to remember me. To say, 'Lasina kept the river alive for our children.'"

(Photos by Anna Badkhen)



Kayantau received me on a late afternoon last November. I was researching a book and spent much of the year herding cattle with a family of Fulani cowboys, nomads forever chasing rain in the oceanic spaces of Africa's margin lands. For a time, my hosts pastured their cows near Sindaga. Kayantau and I sat on a blue and yellow plastic mat under a mango tree outside his low adobe house. He was a heavyset

man in his 60s, and he wore a soiled maroon boubou with yellow polka dots and, around his neck, a cell phone on a lanyard. One of his four wives, Kadija, sat on a low bamboo stool, propping up a toddler with her feet. Fishnets dangled from tree limbs and eaves. Ducks sidestepped discarded tackle. Kayantau turned to blink at the Bani. The river rippled in the slanted sun, blinked back.





“The trees that kept mud from sliding into the river are gone,” Kayantau explained. “Now when it rains, mud slides into the river. The mud adds up, and one year, one day, there will be no river. But we are fishermen. This river is our life. It’s what we will leave our sons and grandsons. If the river is gone, how will they live? We had to do something.”

So one morning last summer, Kayantau asked the hard, sunjerked men of Sindaga to leave their pirogues moored and stay ashore. He gathered the children and womenfolk. For five days, armed with hoes, sandaled, their soiled boubous flapping like giant wings in the thirsty wind, the 4,800 villagers—any man, woman, and child strong enough to work in the humid summer sun—bedded out 13,560 slim, two-foot-tall saplings of *Acacia nilotica* along the east bank of the Bani, downstream from the village. The idea, Kayantau told them, was simple: As the saplings grew into twisted, fissured trunks under dense thorny crowns, their roots would cinch the abrading topsoil of the desiccated seasonal swamplands and keep alluvial cut-banks from slumping into the river, preserving the watercourse for their descendants.

The villagers worked for free. They became volunteer conservationists, planting back the bush.

After a year of walking in the Sahel and speaking to ecologists in Africa and the West, I have come to see the villagers’ effort to persevere and preserve their ecosystem as a future model for conservation worldwide. People did not “arrive” in Africa the way we did on other continents: We were born here, and we evolved together with its ecosystems. Today, 70 percent of Malians live rurally. The Sindagans’ approach to saving their environment stems from necessity, from immemorial African traditions of husbanding nature, and from the limbic understanding that they are an indivisible part of it.

IF YOU WERE TO look at the Bani River from space, you would see that it sashays through a meandering band of a continental scale: a 1.1 million square-mile belt of pointillist ochre-green savannah that stretches

MORNING ON THE BANI RIVER Mali’s Bozo fishermen trace their ancestry to capricious man-eating water spirits and amphibians and may have been fishing the Bani River since the Neolithic.

The political unraveling echoes the steady and inexorable deterioration of the land itself, as if under Mali's pustulating skin her very skeleton is creaking apart.

from the Atlantic Ocean to the Red Sea, dividing the Sahara from the African tropics roughly along the 13th parallel. The Sahel.

The most common tree in the Sahel is the acacia. First classified in 1773 by Carl Linnaeus, the father of modern taxonomy and ecology, *Acacia nilotica*—known as thorn mimosa, scented thorn, *Vachellia nilotica*, or prickly acacia—splotches across the semiarid land. The lives of the tree and the people who are born, rest, plant, and die in its shade are deeply intertwined.

Prickly acacia is a super plant. It can grow up to 65 feet tall, with a crown as wide. It thrives in poor, dry, and saline soils, adding three-quarters of an inch in diameter each year. It needs little rain. It is resistant to fire. By its fifth year it can produce up to 175,000 seeds annually, and although most of its seeds do not sprout when the pods drop, they still can germinate 15 years later. The seeds are rich in protein. Of all the acacias, the *nilotica* has one of the deepest rooting systems, up to nine feet, which means it can tap into relatively deep ground water. The horizontal spread of its lateral roots is 1.6 times greater than the umbrella span of its crown. Prickly acacias may stand two dozen feet apart but underground they clasp the soil together in a tight, resilient web. Along a river they create an indigenous natural revetment.

Africans use prickly acacia's seeds as food flavoring and dye, its glabrous bark for tea, its leaves as fodder and antibiotic, its sap to bind pigment to colored fabric, its twigs as toothbrushes, its thorns as awls, its inner bark and pods to tan leather. It is a nitrogen fixer, so grain yields are richer in its shade.

But Sahel's very texture is changing. Acacia scrublands are turning to infertile dustbowl. Red dunes grow where the 14th-century traveler Ibn Battuta described lush orchards and fecund fields. Winter *harmattan* winds fill Bamako, the capital of Mali, with dust from the Sahara hundreds of miles away. Most people in Mali have never heard about climate change, but they can describe with scientific precision its symptoms: the hotter, stronger wind; the fickle rainfall; the disappearing forests. Last summer the rainy season arrived six weeks late. Around Sindaga, the fens that usually become rice paddies in June still lay bone-dry in early August. My Fulani hosts herded skeletal Zebu cattle through grassless pastures. The Bani at Sindaga was a tepid slow stream you could wade across, and there were no fish. In fact, in the last 40 years Mali has become 12 percent drier and about 1.6 degrees Fahrenheit warmer.

A perfect storm of global and local factors is responsible for Mali's environmental crisis: changing weather patterns; disastrous land management by French colonists; post-colonial explosion in population growth; overgrazing by expanding cattle herds; commercial farming and fishing. The people's supreme dependency on the land does not mean that the 58 million people in the Sahel live in complete harmony with the environment. Like most men, they want the land to work for them, not vice versa. The deforestation speaks for itself.

Between 1990 and 2005, droughts and human misuse killed 10 percent of Mali's forests. Some trees were eaten during the famines, when crops failed and people

survived on leaves and bark. Some quit on the waterless soil. Most were chopped down: Malians rely primarily on firewood for cooking, and a 2010 report from Mali's agriculture ministry said that more than 500,000 hectares of forest are cleared for firewood and charcoal each year—and we are talking grown trees, not two-foot saplings. Today, only one-tenth of the country—about 12 million hectares—is forest.

The fallout of this altered landscape extends beyond droughts and famines. In 2012, Mali weathered three successive coups and counter-coups and a simultaneous Tuareg uprising in the northern desert.

Last year, it became the newest front-line of the global war on terror after Islamist fundamentalists linked to al Qaeda hijacked that rebellion; now they are fighting against French-led United Nations troops backed by the United States. Many analysts, including Caitlin E. Werrell at The Center for Climate and Security, and the University of Michigan Islamic Studies historian Juan Cole, consider the turmoil a facet of desertification

and link the jihad to the depletion of natural resources in one of the poorest countries on the world's poorest continent. The political unraveling echoes the steady and inexorable deterioration of the land itself, as if under Mali's pustulating skin her very skeleton is creaking apart.

Yet even after two centuries of centralized urban control of rural resources abraded the people's relationship with the Earth, and even after the introduction of modern tools, weapons, and livestock vaccinations have enabled a voracious draining of the land,

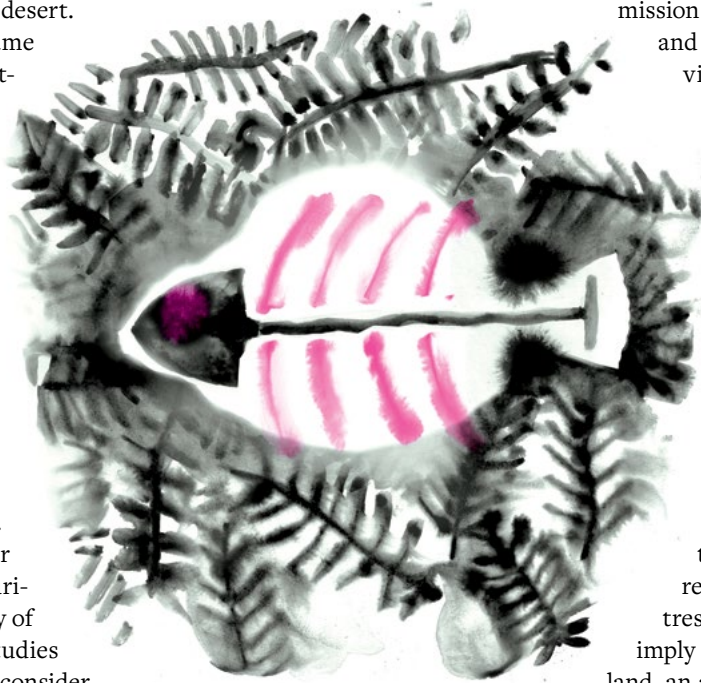
there still exists in Mali a level of conservation ethic that for millennia had prevented the people from destroying their environment. The central premise of that ethic stems from a myth.

Most Malian traditions, explains Dr. Doulaye Konaté, president of the Association of African Historians, hold that natural resources are on lease to humans from gods, and that humans use the land according to their contract with the gods. Long after most Malians converted to Islam in the 19th century, spiritual leaders here continued to serve as interlocutors with the

old divinities and doled out the permission to use the resources and the punishment for violating the restrictions, determining who could cut down a specific tree, hunt a particular animal, fish during a certain season. Many remain such guardians of the land to this day. And most Malians still populate waterways, the bush, the desert with powerful jinns that control these resources and penalize trespassers. Such beliefs imply an intimacy with the land, an attitude toward it not of ownership but of companionship.

Over months of ambulations with the nomads, I camped alongside the Bani River, laundered my clothes in it, broke Ramadan fast with its tepid water, forded it, swam its anastomosing currents. I'd thought I knew it well. The Bozo at Sindaga wear it like skin. They have no school, no electricity, no sanitation, no source of income but what the river yields. They have an innate memory of their connectedness. They cannot afford to unweave what we call nature from their identities.

Last summer, when Kayantau approached environmentalists in Djenné, the nearest big town about 10



He saw my raised eyebrows and smiled. “Do not look at an old question with eyes of today.”

miles upstream from Sindaga, he did not ask them to step in and save the river. He asked them to help the villagers remember, relearn, how to keep the river safe.

The elder spoke to Hamma Ba, who oversees the directorate of fisheries at the district branch of Mali’s ministry of the environment. Ba also heads a tiny environmental nonprofit he founded a year ago with a \$440,000 grant from the Global Climate Change Alliance, an agency the European Union established in 2007 to assist developing countries most affected by climate change. Ba’s nonprofit, which has a staff of five and goes by the French acronym AVDR, focuses on reforestation and education about climate change. Ba offered to donate to Sindaga some tree saplings to secure the crumbling shore if Kayantau rallied the villagers to do the planting. Thoughtful reintroduction of native species is being used to restore riparian ecology worldwide. Scientists credit the planting of sea-buckthorns along the banks of the Onggi River, which was dredged and diverted during the Mongolian gold rush of the 1990s, with that river’s improved flow through the Gobi Desert into Lake Ulaan. And in the U.S., the ongoing reforestation of the Lower Mississippi Alluvial Valley by the Wetlands Reserve Program is creating a buffer around the wetlands that helps prevent soil degradation, provide habitat for wildlife, and reduce agricultural runoff into the Gulf of Mexico.

Malian conservationists obsess about reforestation. It is the cornerstone of Mali’s national climate change policy: “We have a five-year program to reforest, starting in 2014. Millions of trees! All this made by people!” Ousmane Ag Rhissa, the minister of environment, told me.

Planting trees, counting trees, and agroforestry are the focus of dozens of Malian non-governmental

organizations, big and small, most of them funded by the European Union. Then there is the Great Green Wall, an 11-nation African project to erect a barrier of trees that, when or if completed, would measure more than 25 million acres from Dakar to Djibouti and prevent degradation of the soil, halt desertification. (An acre of trees may absorb between two and three tons of carbon dioxide per year—so the Great Green Wall may reduce global emissions by between 50 and 80 million tons.)

Pan out from the flat adobes of Sindaga. Imagine: the fishermen and their families, contributors to the largest horticultural endeavor in human history.

Ba acknowledges that a handful of villagers planting 13,560 acacias on 370 Sahelian acres cannot undo deforestation. His goals are much humbler—though, in a way, also much loftier: He hopes that conservation projects such as the one in Sindaga will remind rural Malians to be more responsible toward the erratic landscape of a changing planet.

“You cannot protect nature if there is a separation between you and it,” says Ba. Something as simple as planting trees along a riverbank, he says, encourages the planters to thoughtfully reconnect with their environment. It allows them to re-imagine the potential of the Sahel, to see the possibility for a different, healthier landscape and a different relationship with it, and to see that they have the power to create both.

WHEN I VISITED THE historian Konaté in Bamako, he told me, “There are many ways of protecting the environment, spiritual ways,” He saw my raised eyebrows, smiled, and added, “Do not look at an old question with eyes of today.”

I remembered then a similar notion the writer Barry Lopez expressed in *The Rediscovery of North America*. To bridge the chasm between the ransacked landscape of the New World and the descendants of the Europeans who for centuries have exploited it, Lopez proposes inquiring of the land and its original inhabitants how best to coexist with it. “We are curious,” he writes in his short, forceful manifesto, “about indigenous systems of natural philosophy, how our own Western proposals might be answered by some bit of this local wisdom, an insight into how to conduct our life here so that it might be richer.”

It is such gentle relearning, I think, that makes the men of Sindaga role models for modern Western environmentalists. Their effort to protect their ancestral fishing grounds comes at a time when scholars in the West are reassessing their own approach to conservation. The classic, divested strategy—most eloquently manifested in vast, unpopulated national parks—has outlived itself because it further demolishes the bonds that once existed between humans and the rest of the natural world. The Canadian writer J.B. MacKinnon writes that conservation’s “most fatal flaw, perhaps, has been to encourage the separation of people from nature: parks here, humans there, and there, and there.”

What is necessary today, some conservationists propose, is a type of ecological restoration in which humans are everyday participants, immediately invested in nature because they understand themselves to be a part of it. We all should be planting back the bush—in our homes, communities, cities, parks. To do so, we can set our bearings by the fishers of Sindaga, who are remembering, faithfully and without fanfare, the ancient practice of nurturing their home ground. Our livelihood, too, depends on a intimate relationship with our environment.

In November, scores of Fulani nomads en route from wet-season grazing grounds to the lush dry-season pastures around Djenné passed through Sindaga driving thousands of lyre-horned Zebus, sheep, and goats. My hosts and I were among them. The Fulani stayed on the Bani River for about a week, but that was all it took for their animals to strip the spindly twigs of prickly acacia of most of their sensitive bipinnate leaves. But after we moved on, the saplings—some with chewed-off tips, some with only one or two flecks of glaucous green surviving on the reddish stems—were still there, marking a sheer, hopeful grid along the Bani’s eastern bank just north of the village. Every few days Lasina Kayantau rode his scooter to check on the trees. One afternoon, I left the campground where my Fulani companions had stopped in a copse of thorn trees, and tagged along.

It was odd to watch Kayantau’s sandaled, thick frame move through this imaginary future forest. His hands were flat, massive, shingly with callus, dry-cracked into grooves. Miniature maps of the Sahel. I tried to take pictures but couldn’t: Kayantau was

simply too large, the shoots too small—too small for his figure; too small, it seemed, for that unforgiving, cauterized land.

Kayantau showed me two of the five saplings he had planted himself. Scraggy, anemic twigs stuck out of trampled alluvium a few steps away from a dry gulch that, when it rains, dumps clayey mud into the river. Several other saplings were there, too. I don’t know how he could tell them apart.

Kayantau stood over the seedlings, but when he spoke, he turned to the Bani, choppy and blindingly white in the 5 o’clock autumn sun.

“I want to leave a mark,” he told the river. “After I die, I want the people in the village who elected me their elder to remember me. To say, Lasina, he did something. Lasina kept the river alive for our children.” ☺

ANNA BADKHEN writes about people *in extremis*. Her latest nonfiction book is set in Afghanistan. She is working on *Walking with Abel*, a book about transience.

07

IN THE 1997 MOVIE *Fifth Element*, Gary Oldman pushes a glass off his desk to prove a point. As a handful of robots stream out of a wall hatch to clean up its shattered pieces, he explains to Ian Holm that the flurry of activity shows how destruction—waste—is at the center of the circle of life. “What a lovely ballet ensues, so full of form and color,” he opines. Oldman, the movie’s antagonist, is both repulsive and intriguing—the latter, not least because of statements like this one.

After all, we intuitively know his claim to have some inkling of truth. Witness the many aphorisms in the English language that use waste to interpret and define our world, from “waste not, want not” to “one man’s trash is another man’s treasure.” They suggest a meaning that extends beyond the literal—beyond the empty candy wrapper—to something moral and organizational.

In this theme we turn to the science of waste. We follow it as it leads us from the complications and trials of physical refuse, through to the new technology and art that we create in response to waste, and finally to waste’s role at the center of some of nature’s broadest narratives. In thinking about waste, we find ourselves thinking about beginnings and endings, in all the corners of our world—a kind of “lovely ballet,” indeed.

Welcome to “Waste.”

—MS

“When you smile, the gleam of your teeth obscures a slight glow from radioactive waste.”

CURT STAGER

“You Are Made of Waste” p.44

Waste

ENDINGS AND BEGINNINGS

You Are Made of Waste

Searching for the ultimate example of recycling? Look in the mirror

BY CURT STAGER

YOU MAY THINK OF YOURSELF as a highly refined and sophisticated creature—and you are. But you are also full of discarded, rejected, and recycled atomic elements. Don't worry, though—so is almost everyone and everything else.

Carbon: Your inky nails

Look at one of your fingernails. Carbon makes up half of its mass, and roughly 1 in 8 of those carbon atoms recently emerged from a chimney or a tailpipe. Coal-fired power plants, petroleum-guzzling cars, and kitchen gas stoves release carbon dioxide into the atmosphere. Each of those waste molecules is a carbon atom borne on two atomic wings of oxygen. Fossil-based carbon dioxide molecules that are not soaked up by the oceans or stranded in the upper atmosphere are eventually captured by plants, shorn of their oxygen wings, and woven into botanical sugars and starches. Eventually, some of them end up in bread, sweets, and vegetables, while others help form

carbon-rich animal tissues, finding their way into meat and dairy products. Historically, atmospheric carbon dioxide was mainly replenished by volcanoes, forest fires, and biotic respiration. Today, one quarter of atmospheric CO₂ is the result of fossil fuel combustion, whether it rose from smokestacks or was displaced from the oceans. (When fossil-fuel CO₂ dissolves into ocean water, it displaces already-dissolved carbon dioxide derived from natural sources.) And because all of the carbon in your body derives from ingested organic matter, which in turn obtains it from the atmosphere, your fingernails and the rest of the organic matter in your body are built, in part, from emissions.

ILLUSTRATIONS BY YUKO SHIMIZU





Radioactive Carbon-14: Your pearly whites

When you smile, the gleam of your teeth obscures a slight glow from radioactive waste. During the late 1950s and early 1960s, atmospheric testing of thermonuclear weapons scattered so much radioactive carbon-14 into the atmosphere that it contaminated virtually every ecosystem and human. Several thousand unstable radiocarbon atoms explode within and among your cells every second as their unstable nuclei undergo spontaneous radioactive decay. Some are the natural products of cosmic rays that can turn atmospheric nitrogen into carbon-14, while others result from the decay of unstable mineral elements that are found in soil. But many of them represent the echoes of thermonuclear airbursts from the Cold War, finding their

way into our water supply and meals. If they happen to disintegrate within your DNA, they can damage your genes. And many of them are bound up in your teeth. Unlike most of the atoms in your body, those embedded in your strong, stable tooth enamel have been with you ever since you ingested them through your umbilical cord and your infant feeding. If you were born during the early 1960s, you have more nuclear waste in your teeth than if you were born later, when soils and oceans had had time to bury radioactive atoms. In fact, forensic scientists use the proportion of bomb carbon in tooth enamel to determine the age of unidentified human remains.

Oxygen: Your leafy breath

The oxygen in your lungs and bloodstream is a highly reactive waste product generated by vegetation and microbes. Trees, herbs, algae, and blue-green bacteria split oxygen atoms out of water molecules during photosynthesis. They use most of the resultant gas for their own purposes, but thankfully some leaks out to sustain you. In fact it makes up about a fifth of the air you breathe. Your cells harness oxygen to release energy from chemical bonds in the food you consume.

Oxygen absorbs electrons released by broken food molecules, which attract hydrogen ions, resulting in a molecular waste of your own making: metabolic water, which comprises one tenth of your body fluids. An average adult carries between 8 and 10 pounds of homemade wastewater within them, and 1 in 10 of your tears are the metabolic by-products of your breathing and eating.

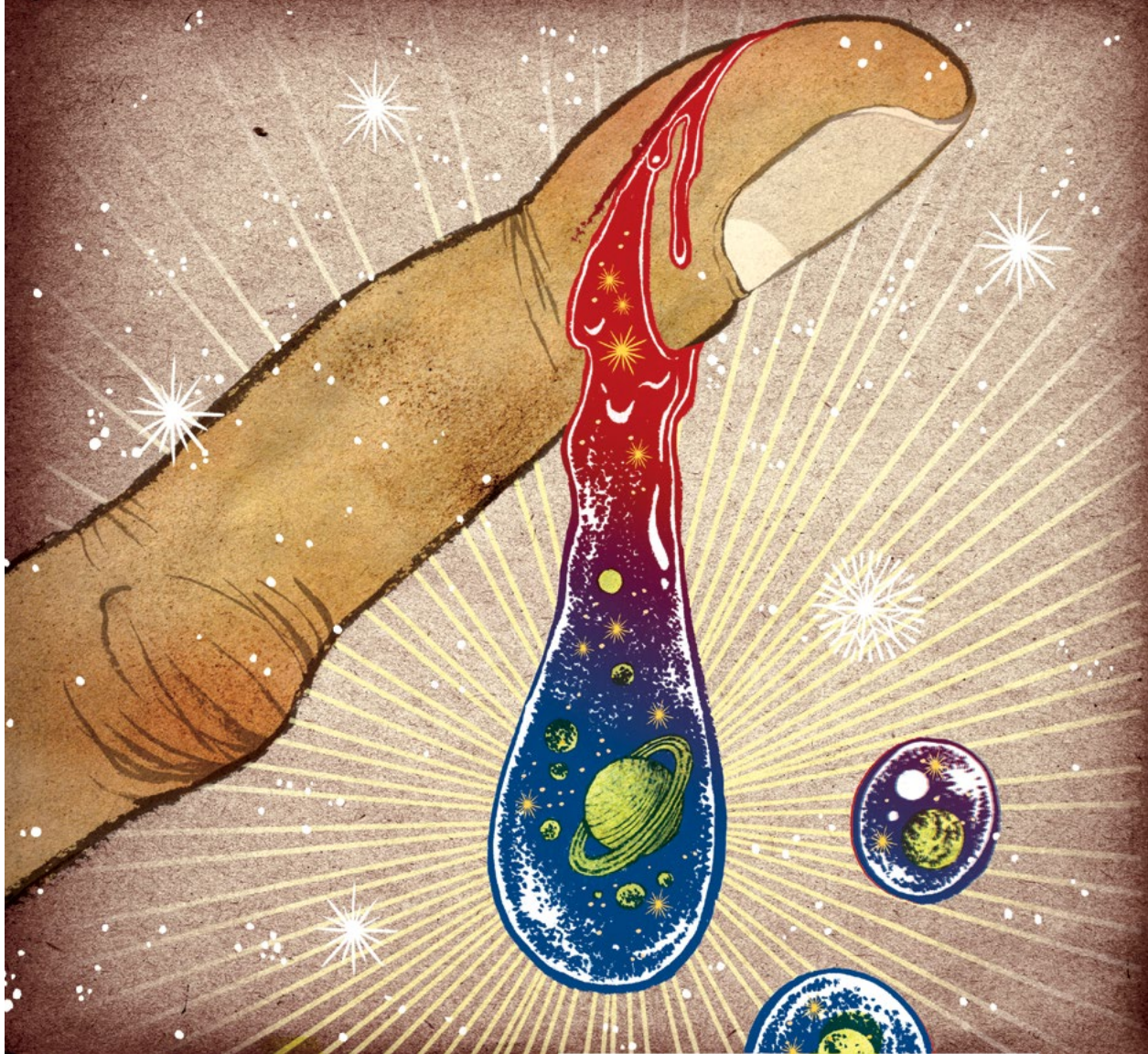


Nitrogen: Your natural curls

The next time you brush your hair, think of the nitrogenous waste that helped create it. All of your proteins, including hair keratin, contain formerly airborne nitrogen atoms. But the nitrogen in air is biologically inert. For nitrogen to become a component of your hair, it has to be converted into a more accessible form. Nitrogen-fixing bacteria is one way that can happen. They live among the roots of beans, peas, and other legumes, consuming atmospheric nitrogen and releasing it as ammonia, a kind of microbial manure that fertilizes soil in which plants grow. When you eat a plant, you consume formerly atmospheric nitrogen.

Every flash of lightning and every automotive spark plug emits a puff of nitrogen oxide, which can dissolve into raindrops and fall to earth as a form of fertilizer, again finding its way into food webs through plants. But most of the nitrogen in modern foods comes from urea and ammonium nitrate fertilizers artificially fixed by industrial processes. In ages past, the nitrogen in human hair came mainly from bacterial waste and lightning. But today, unless you eat a strictly organic diet, you run your hairbrush through nitrogenous frameworks that are mostly of human origin.





Iron: Your ancient blood

When you cut yourself, the wreckage of stars spills out. Every atom of iron in your blood, which helps your heart shuttle oxygen from your lungs to your cells, once helped destroy a massive star. The fierce nuclear fusion reactions that set stars ablaze create the atomic elements of life. As the star ages, it fuses progressively larger elements, such as silicon, sulfur, and calcium. Eventually, iron atoms are fused. The problem is that iron fusion consumes as much energy as it produces, so it weakens the star. If the star is big enough, it will collapse in on itself, its outer layers rebounding against the dense inner core, and a supernova explosion will result. The blast sprays out

iron at supersonic speeds, filling great swathes of space with debris that can form new solar systems. The iron in your frying pan, house keys, and blood is essentially cosmic shrapnel from the tremendous explosions that ripped through our galaxy billions of years ago. The same blasts also released carbon, nitrogen, oxygen, and other elements of life, which later produced the sun, the Earth, and eventually—you. ☺

CURT STAGER is an ecologist and climate scientist at Paul Smith's College. He is the author of *Deep Future: The Next 100,000 Years of Life On Earth*, and also co-hosts a weekly science program on North Country Public Radio.



Blissed-Out Fish on Prozac

Why we can't get our water supply free of drugs

BY ADAM PIORE

ILLUSTRATIONS BY YUKO SHIMIZU





JEFFREY HAWKINS WRITER LIKES to say that the average drop of water entering the Mississippi River headwaters north of Minnesota will be used 11 times before it reaches the Gulf of Mexico. That drop might irrigate crops, flow through wastewater treatment plants, pour out of residential taps, move through digestive systems, arc into toilet bowls, swirl down into sewers, and then do it over again. Whatever its fate along its 2,300-mile journey South, this water will mix with all kinds of chemicals, human metabolites, and unnatural compounds. Writer can attest to that. When he floated down the big river in the early 1990s on a government research boat measuring contaminants, he detected everything from heavy metals to pesticides to caffeine.

But the waters of Colorado, Writer's current base of employment, should be an entirely different matter. On a late September morning, Writer and I are driving along the outskirts of Boulder. The road is lined with picturesque stands of cottonwoods and willows; sheep graze lazily in sun-dappled fields. The seasoned environmental engineer points to craggy, snow-capped mountain peaks looming over the hills above us, a source of virgin water feeding into the Boulder Reservoir, the town's primary source of drinking water, and eventually its main tributary, Boulder Creek.

We are on our way to the heart of town, where Writer, a hydrologist at the United States Geological Survey (USGS), wants to show me a favorite local haunt near the University of Colorado, Boulder. It's a bucolic spot on Boulder Creek where families swim, dogs frolic, and children go tubing in the summer. Upstream of Boulder's central wastewater facilities, the crystal clear water is fed mainly by the runoff from the Arapaho Glacier and scores of streams like it, migrating down from the Rockies through waterways notched into the hills.

So when we pull up and step out of the car, it comes

as somewhat of a surprise when Writer tells me what's in the water. Recently, he picked up significant traces of a drug called lamotrigine, a compound prescribed to treat epilepsy and manic depression. The metabolites, he speculated, came from the one source of treated wastewater upstream of the reservoir, located in a tiny 1,445-person mountain town called Nederland.

"Even here in this pristine stream, there's no running away from it," Writer says. "What we're seeing is how medicated our society is. These compounds are extremely persistent and show up wherever you look for them."

In recent years, watershed studies across the United States have turned up eye-opening levels of antidepressants, butalbital (a barbiturate), sulfamethoxazole (an anti-bacterial), carbamazepine (an anti-seizure medication often used to treat bipolar disorder), as well as metabolites of caffeine, cigarettes, steroids, and lipid regulators. According to the USGS, pharmaceutical traces can be found in 80 percent of U.S. streams.

Despite the ominous findings, the impact of all these metabolites on human health is not yet fully understood. A 2011 U.S. Government Accountability Office report "confirmed the presence of pharmaceuticals in drinking water throughout the nation," though added "the human health effects of exposure to these pharmaceuticals is largely unknown."

THE DRUG TRACES IN the nation's water supply cast into sharp focus an issue seldom discussed in environmental science, but bound to become prominent in the future: the increasingly outmoded state of wastewater treatment plants.

For many years, wastewater treatment was a relatively simple proposition. Back in the old days, biologists assumed most pollution was tied up in solids or contained in bacteria and pathogens. So most wastewater treatment plants removed debris, separated

solids from liquids, usually by using gravity or other physical means, and then disinfected the liquid that remained, before releasing it back into the watershed. Many plants exposed the water to chlorine gas, a cheap, highly reactive element that quickly oxidizes and kills microorganisms and bacteria carrying scourges like cholera, pneumonia, or typhus.

Now, however, with improvements in the ability to detect tiny yet potent trace elements in the water, along with an explosion of highly medicated urban populations, biologists are finding plenty of things to worry about. (A 2005 to 2008 survey revealed that 1 in every 10 Americans over age 12 is taking antidepressants, a 400 percent increase on the previous survey, conducted between 1988 and 1994.)

One fear is “nutrient pollution,” a phenomenon caused by the release of too much nitrogen and phosphorus by wastewater plants and agricultural runoff back into the environment. Phosphorus is a common ingredient in most synthetic dish and hand soaps, laundry detergents, and disinfectants, while nitrogen is a key component of the metabolic byproducts produced by humans and livestock. Aquatic vegetation has reacted to the surge in nutrient-rich wastewater like a weightlifter on steroids, blooming into gargantuan oxygen-sucking fields of pond scum that blot out sunlight. Today, algae blooms are threatening a wide array of iconic watersheds, including the Gulf of Mexico and the Chesapeake Bay.

More dramatic are hermaphrodite fish. In the past decade, numerous studies have shown that “endocrine disruptors,” or hormonal metabolites like birth control pills, tamoxifen, and steroids, are creating intersex fish. In studies done all over the world, normally male fish downstream of wastewater plants appear to be growing ovary tissue in their testes, while female fish have been found with sperm-producing nests in their ovaries instead of eggs. The chemicals also affect sexual differentiation in the womb, tilting the balance of male to female fish dramatically. In one study conducted downstream of Boulder’s wastewater treatment plant, researchers found a 10 to 90 ratio of male to female fish.

Biologists are alarmed to learn that feel-good drugs like Prozac are making little fish recklessly apathetic to the dangers of the bigger fish who like to eat them. Blissing out on Prozac, after all, is a quality of life boon

U.S. waterways are a pharmaceutical soup, and that soup is becoming more difficult to identify and filter everyday.



if you’re a neurotic New Yorker dealing with the stress of preschool tuition payments, angry cabbies, and demanding bosses. But it can prove fatal in the ruthless arena of nature, where hesitation can mean you’re someone else’s lunch. “If you want to draw the parallel to humans, it is like an impaired driver who is slow to pick up a threat and respond to it,” says Heiko Schoenfuss, a professor of toxicology at Minnesota’s St. Cloud State University, who exposed larval fathead minnows to Prozac at different doses.

Vance Trudeau, a biologist at the University of Ottawa, who has found evidence of “sexual side effects” in goldfish exposed to traces of Prozac in his lab, says “Prozac is the tip of the iceberg.” He adds that U.S. waterways are becoming a “pharmaceutical soup,” and he, along with Writer and other biologists, says that soup is becoming more difficult to identify and filter everyday. “Most sewage treatment plants have not been built with the removal of pharmaceuticals in mind because it wasn’t something people were thinking about,” Trudeau says. “To upgrade is prohibitively expensive. So pretty much anything we take ends up in the water.”

MANY PHARMACEUTICALS ARE explicitly designed to break down slowly in the human body. But that has a downside. The active ingredients in delayed-release

Morphine, cocaine,
methamphetamine,
and ecstasy are
present as complex
mixtures in surface
waters.



drugs are often tied up in a matrix of insoluble compounds that are expelled before they have released their load.

In Colorado, it takes about two hours for raw sewage to travel from the toilet bowls of central Boulder to the North 75th Street Wastewater Treatment Facility on the outskirts of town. The sprawling plant sits on rolling green pastures, fronted by rows of solar panels, a half a football field up from the banks of the surging waters of Boulder Creek.

On a clear morning, I follow Leigh Rickert, an affable, grey-haired maintenance manager, into a boxy, concrete building on the edge of the compound. Rickert informs me that we have entered the gateway for the 13 million gallons of raw sewage expected to arrive that day. Already the stench is worse than a row of Porta-Potties at the end of a weeklong rock festival.

Rickert motions to two oversized metal grates that rise up from depths of the bubbling mess flooding out of two massive intake pipes. The grates are the first step in the crude sorting process that transforms the refuse-choked, chocolate-brown incoming waters into treated outflow, as clear as a mountain spring.

Stepping past an impressive array of detritus trapped by the grates, we head outside and into a complex of humongous basins. We walk over a vast web of metal catwalks and gaze down on three sets of massive, brackish, bubbling, stinky vats of water known as “aeration pools.” The pools, Rickert explains, are filled with billions of microorganisms that love nothing better than to feast on the nitrogen and carbon compounds in human waste.

“That is called a floating mixer,” Rickert says, pointing to the top of an oversized, rotating metal disc poking out of the muck like an iceberg. “Basically it keeps the food coming to the bugs. The bugs eat shit and die, and when they die, their body is a more stable entity than what they ate.”

Five years ago, Boulder became one of a growing number of towns to install an “activated sludge” process, a cutting edge, \$28.5 million upgrade, that takes nitrogen-rich human waste, feeds it to microorganisms, and transforms what would otherwise escape in water runoff to biosolids that can be carted away and used as fertilizer or released as a harmless nitrogen gas—the kind that constitutes 78 percent of

the Earth’s atmosphere.

Every day, plant operators feed hundreds of thousands of gallons of human waste into the three basins. The water resides in the basins for 24 hours, during which the microorganisms cleanse it of from 50 to 55 percent of its nitrogen, at which point it is allowed to migrate to the next stage in the process. Although the microorganisms prefer to snack on the simple nitrogen and carbon compounds excreted in human waste, once they are done, they will move on to more complex compounds.

“Most of the microorganisms are common soil bacteria and are pretty good at adapting to whatever food is there,” explains Chris Douville, the plant’s wastewater treatment manager. “They’re like kids at the cafeteria. They’re going to hit the donuts and Pringles first, then move on to burgers and rice, and maybe have a salad at the end.”

Douville says the process is removing some of the estrogens and other hormones present in the water, chemicals that for years were allowed to pass back into the Boulder watershed. Even so, many of the neurotropic substances are so exotic that the snacking microorganisms ignore them. Other substances take so long to break down in the vats that while microbes are munching on other compounds, they are flushed out of the system.

“Antidepressants are atypical of most organic compounds that organisms typically encounter, and organisms may not have the requisite biochemical tools or enzymes to metabolize these compounds,” Writer told me. “More research is needed to evaluate why, but many of the antidepressants seem to be quite environmentally persistent.”

Cleansing those lingering drug compounds from the wastewater is an arduous and expensive process. “The only other options we know of at this time use advanced techniques, such as chemical techniques to oxidize and destroy them, or filtering out completely pure H₂O,” Douville says. “But at this scale that would cost several hundreds of millions of dollars.”

NEARLY ALL THE SCIENTISTS I interviewed lamented the multiplication of drug compounds. “As soon as we find a compound in the water, pharmaceutical companies are saying we found a better one,” says

Mission not-impossible

In 1966, The Standells embraced the foul state of Boston's Charles River. They sang: "I love that dirty water; Oh, Boston you're my home!" A few years earlier, signs posted on its banks banned swimmers from a dip. Sailors who fell in were advised to go to the hospital for tetanus shots.

The swimming ban followed a century of runoff from nearby textile factories, a gun production facility, coal-burning power plants, and two enormous slaughterhouses. In 1955, the historian Bernard DeVoto wrote that the Charles was "scummy with oil, unlikely to be mistaken for water."

Yet in 1995, a federal effort to clean the Charles began. Eighteen years and \$500 million later, the "dirty water" loved by the Standells is no more. For the first time last year, the river was open for public swim. Perhaps one day, waterways will be drug-free, too.



Mike Thurman, a UC Boulder chemist who has been analyzing water samples for psychoactive pharmaceuticals since 2008. "It's hard to keep up; they're already changing compounds."

The detection of pharmaceuticals in treated wastewater has led some researchers to take the next logical step—they have begun to search for evidence of illegal drugs in the water. And they have not been disappointed. In the U.S., about 22.5 million Americans aged 12 and older—or 8.7 percent of the population—used illegal drugs in 2011, according to a survey conducted by the Substance Abuse and Mental Health Survey Administration. That effectively means that while 11 percent of the population is flooding sewer systems with antidepressants and their metabolites, almost 10 percent are excreting metabolites from drugs such as marijuana, cocaine, heroin, or methamphetamine into the nation's water supplies.

"Residues of illicit drugs can reach sewage treatment plants in substantial amounts, escaping degradation, and be released into surface waters," wrote Ettore Zucato and Sara Castiglioni, of the Department of Environmental Health Sciences, Mario Negri Institute for Pharmacological Research, in a 2009 survey. The Italian researchers identified drug traces in waterways in Italy, England, and Switzerland. "Environmental concentrations are low, but risks for human health and the environment cannot be excluded," they wrote. "Morphine, cocaine, methamphetamine, and ecstasy all have potent pharmacological activities, and their presence as complex mixtures in surface waters may be toxic to aquatic organisms."

In 2007, a team led by Oregon State chemist Jennifer Field garnered nationwide headlines announcing they had tested the sewage of 10 major cities for drugs and discovered, among other things, that concentrations of methamphetamine in Las Vegas were 500 percent of those in Omaha, and twice that of Oklahoma City.

Some of these substances almost certainly make it into the drinking water. In 2009, a team led by Maria Huerta-Fontela of the Spanish company AGBAR-Aigües de Barcelona, examined the drinking water from a Spanish drinking water treatment plant. Most amphetamine-type stimulants and nicotine were completely removed by the processes. But 10 percent of caffeine and about 26 percent of Benzoylcgonine, the

main metabolite of cocaine, survived and was still present in the filtered water.

A number of experts agree that, for now, there is little evidence that trace elements of either legal or illegal drugs in the water are dangerous to human health.

Daniel R. Dietrich, head of the Environmental Toxicology Research Group at the University of Konstanz, Germany, who has studied drug compounds in waterways, likes to tell a joke about aspirin—which routinely makes its way into sewage discharge—to drive the point home. Dietrich notes that he lives and works in a community on the border of Lake Konstanz, where Swabians are famed for being cheap. Some researchers have found small amounts of a popular non-steroidal anti-inflammatory known as diclofenac in the water. “We always make the joke that in order for one Swabian with a headache to avoid paying for a single pill, he would have to drink a million liters of water a day,” Dietrich says. “There’s no data that would suggest people could have adverse effects at those concentrations.” Similarly, Oregon State’s Field told one reporter in 2008 that you’d have to drink 1,000 liters of raw sewage to get a typical dose of cocaine.

Some researchers remain wary of dangers. Thurman, the UC Boulder chemist, notes that comparable concentrations of pesticides are considered contamination and usually prompt government intervention. “We’re seeing these things in the water in parts per billion. When we get parts per billion on pesticides it’s a big deal. Society has to ask the question—why are we finding such a variety of antidepressants at these levels? We’re using pesticides, at least we know why we are using them.”

It’s an issue that will only grow more pronounced, notes Bryan W. Brooks, Ph.D., director of the Baylor University Environmental Health Science Program, and one of the first scientists to identify Prozac in the water. While in the past great cities were built on great waterways, that is no longer the case for megacities emerging in the 21st century. Increasingly, populations are expanding into areas veined with seasonal water streams and rivers. In Texas, the population is expected to double in the next 40 to 50 years.

With more people comes more wastewater, and that, Brooks says, is turning natural stream-flow patterns, often intermittent trickles, into steady flowing

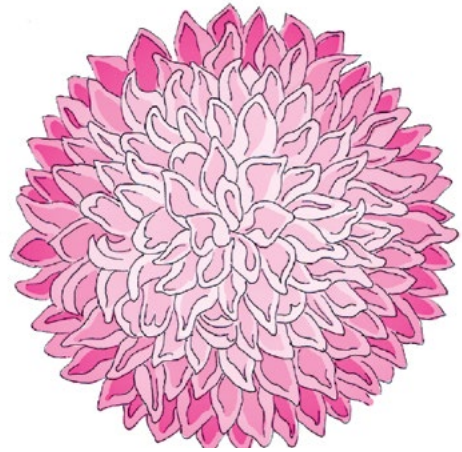
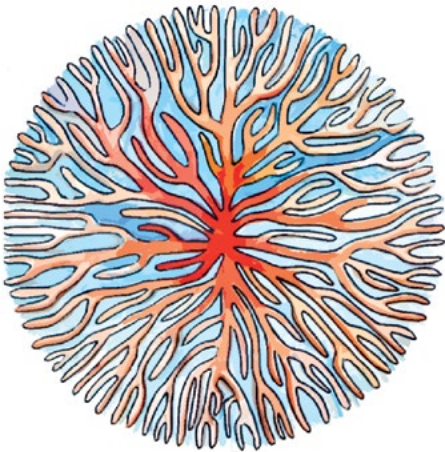
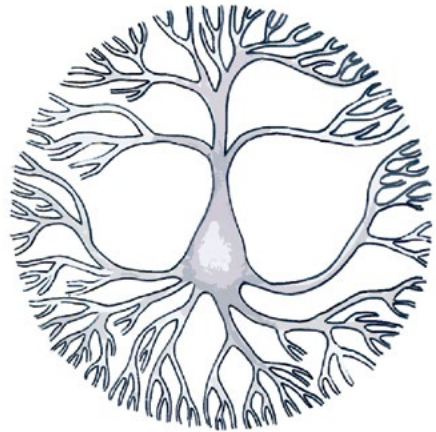
waterways deluged with millions of gallons of treated human wastewater. More people also means that wastewater, with its pharmaceutical traces, is being channeled into uses across society. “We depend on what was once wastewater for potable, for industry, for agriculture, and also to base flows to maintain coastal fisheries,” Brooks says.

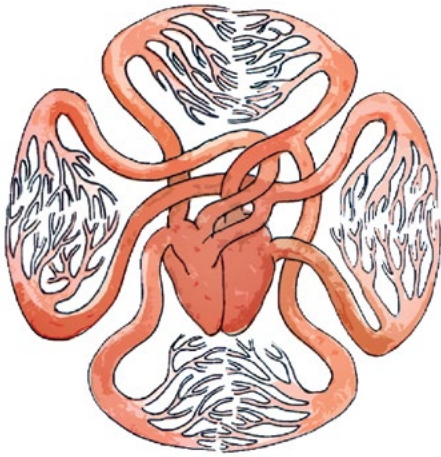
AS THE SUN GOES down in the Rockies, Writer and I stand on the banks of the Boulder Creek, watching a flood of wastewater gush out of a huge pipe from the treatment plant, merging with the alpine waters surging by. The water is headed to the St. Vrain River, where it will join a flow carrying wastewater from the town of Lyons. Just down from that confluence, the city of Longmont will siphon off the water for drinking, only to be expelled by residents into toilet bowls, sending it toward another sewage treatment plant, before it is dumped back into the river again. There it will join the Big Thompson River, carrying pure streams and discharges from Rocky Mountain National Park, continue south, and merge into the mighty Mississippi.

Writer draws my attention to our beautiful surroundings. The nearby cottonwoods are home to several bald eagle nests. “The eagles nest in the cottonwoods and prey on the fish,” Writer says. He points to several humongous carp in the foaming creek below us. “See those carps there? They’re swimming in 100 percent effluent.” I have to wonder if the carp seem so docile because they found the conditions so pleasant. Or because their apathetic daze is induced by imbibing too much Prozac. ☺

ADAM PIORE, a contributing editor at *Discover* and freelance writer, is based in New York.







Nature, the IT Wizard

Nature manages information, the currency of life, with exquisite efficiency

BY KELLY CLANCY



ILLUSTRATIONS BY THE AUTHOR



AS SPACE EXPLORATION GEARED up in the 1960s, scientists were faced with a new dilemma. How could they recognize life on other planets, where it may have evolved very differently—and therefore have a different chemical signature—than it has on Earth? James Lovelock, father of the Gaia theory, gave this advice: Look for order. Every organism is a brief upwelling of structure from chaos, a self-assembled wonder that must jealously defend its order until the day it dies. Sophisticated information processing is necessary to preserve and pass down the rules for maintaining this order, yet life is built out of the messiest materials: tumbling chemicals, soft cells, and tangled polymers. Shouldn't, therefore, information in biological systems be handled messily, and wasted? In fact, many biological computations are so perfect that they bump up against the mathematical limits of efficiency; genius is our inheritance.

DNA

Not only does DNA store information at a density per unit volume exceeding any other known medium, it can achieve one quarter of the maximum information density allowed by the laws of physics (set by the entropy of a black hole). It's so dense that all the

world's digital data could be stored in a dot of DNA the weight of eight paper clips. This remarkable storage density is paired with an equally remarkable reading mechanism. A developing embryo must self-direct the rapid division, migration, and specialization of its constituent cells based on the information stored in DNA. Cells diverge from one another to grow in different ways, depending on their position in the embryo. This means that precise control of gene expression is necessary both in space and in time. Even minor errors could spell death or deformity for the organism.

The question is, how quickly and effectively can spatial information be communicated in order for development to unfold properly? Alan Turing, the father of modern computing, was fascinated by the idea that life might be reducible to mathematical laws, and tackled this question in the early 1950s. He predicted that the spatial patterning of tissues during embryonic development could be controlled through the concentration of chemical signalers, called morphogens. He derived equations showing that interactions between morphogens that activate and inhibit one another's gene expression could set up standing waves of morphogen concentration, and control embryonic patterning. With just four variables—production and degradation

A rule of thumb common in the halls of Intel was programmed into our bodies eons ago.

rates, diffusion rate, and interaction strength—Turing could reproduce biologically plausible, self-directed pattern formation.

His prediction of a chemical system of information management was proven true decades later with the first discovery of a morphogen in fruit flies, called bicoid (though his equations proved to be too simple). Cells in a fruit fly embryo with high bicoid concentration become the fly's head, and those with lower concentration become its body. What is remarkable, however, is how quickly and accurately these cells differentiate. In 2007, a team led by Princeton biophysicist Thomas Gregor measured the concentration gradient and diffusion rate of bicoid in fruit fly embryos. They estimated that it would take around two hours for embryonic cells to measure the morphogen concentration with enough precision for adjacent cells to mature differently (measurement precision increases with measurement time). But this is nearly the entirety of the fruit fly's developmental period, from fertilization to cellularization. The embryo was developing faster and more precisely than should have been possible.

Gregor proposed that multiple cells could be sharing information with each other using a second signaling chemical: One candidate is a morphogen called

hunchback. This would allow them to compute a spatial average of bicoid concentrations, rather than relying entirely on individual readings. The averaging process would be less susceptible to variation and noise, and would allow the required pattern accuracy to be achieved in about three minutes, rather than two hours.

The process is not just ingenious, but efficient. To find out how efficient, physicist William Bialek used nucleus-by-nucleus measurements of morphogens in fruit-fly embryos to study how closely hunchback concentrations followed changes in bicoid concentrations. He found that the fidelity of this information transfer was 90 percent of the theoretical maximum.

Fractal Network

When an embryo develops into an adult, it confronts a new information processing challenge. Its body must learn how to sample and integrate both external and internal information. Odorant molecules signal a predator, prompting a rodent to flee. The setting sun triggers melatonin release, causing a cascade of effects throughout the body, inducing sleep. Internal chemoreceptors measure high carbon dioxide levels, causing an athlete to breathe faster. Information from microscopic measurements, sampled by disparate sensors,



must be integrated and used to make macroscopic decisions that are efficiently communicated back out to relevant body parts.

Here, too, nature has discovered an optimal solution, whose details can be read in the shapes of our anatomical structures. One of the earliest observations of a mathematical relation in biology was that almost every living creature in every ecosystem on the planet, spanning more than 20 orders of magnitude in size from uni- to multi-cellular, has features that scale with the mass of the organism, including heart rate, life span, aorta size, tree trunk size, and metabolic rate. This is called allometric scaling.

Strangely, the relationship between these features and an organism's mass usually follows a power law. That means, for example, that metabolic rate depends on the organism's mass, raised to some constant power. Even stranger, the constant for the majority of these features is some multiple of one fourth. Physicist Geoffrey West has argued that this scaling results from the ubiquity of fractal-like networks within organisms. Fractals are structures that have similar structure at very different spatial scales—one familiar example is the vasculature of a leaf, whose branching geometry is replicated in miniature across the leaf's surface. They can be found in a dizzying variety of systems,

Slow oscillations in the brain are coherent over large anatomical distances, in the same way you can hear the bass from your neighbor's sound system better than the treble.



including our nervous system, blood vessels, capillaries in plant leaves, lung bronchioles, the calyxes of kidneys, neurons, root systems, and mitochondrial cristae.

Why would nature use fractal geometry so regularly? Mathematically, fractals are interpreted as having a fractional dimension higher than the space they reside in: A fractal drawn on a two-dimensional sheet of paper, for example, has a higher dimension—say, 2.1. This is a useful feature, allowing nature to pack some part of a fourth dimension into three-dimensional space.

To see why it might be useful, we can turn to a well-known result in the semiconductor industry, called Pollack's Rule. It states that the speedup achievable by adding computing elements to a processor is proportional to the number of added elements, raised to the power of $(1-1/D)$, where D is the dimension in which the processors are arranged. A three-dimensional arrangement of, say, 100 processors will give a greater boost than a two-dimensional arrangement of those same processors, due to reduced signal latency. The same kind of speedup can be achieved in our nervous and circulatory systems with a D of greater than three. A rule of thumb common in the halls of Intel was programmed into our bodies eons ago; the fractal arrangement of our biological sensors and the nerves that connect them are designed for speed.

The Brain

The brain represents the height of biological information processing and transmission. But for years, it's been considered a noisy instrument. Neurons code information with binary electrical events called spikes, shocking one another like tiny batteries. Once a neuron receives enough input that its voltage passes a certain threshold, it will spike in turn, sending its signal to downstream neurons. Fluctuations in the summed output of the brain's 100 billion neurons, as measured by an electroencephalogram, or EEG, are much smaller than the amplitude of individual spikes, and were long thought to be epiphenomenal: pointers to various brain states, but not an information-carrying signal in itself. In other words, noise.

Yet, as we saw with genetic expression, interactions among many discrete elements can be incredibly useful. It's becoming clear that the so-called noise seen in an EEG is actually an important signal, and one that is crucial to neural computation. The fluctuation of the summed output of the brain's neurons feeds back to affect the resting potential of those neurons, bringing them closer to or farther from spike threshold. Slow oscillations (as found in drowsy or sleeping animals) are coherent over large anatomical distances, in the same way you can hear the bass from your neighbor's

sound system better than the treble. This is how the brain may be facilitating communication between disparate brain areas: If an individual spike is timed with the crest of the slow amplitude fluctuation, it will have a bigger effect downstream than if it is timed with a trough. Neurons are somehow coordinating themselves to generate self-directed, global feedback that serves to adaptively boost even sub-detectable signals: No informational signal is wasted.

In fact, it is an open question whether the idea of “waste” can even be properly defined in the context of the brain. Theoretical neuroscientist Tony Bell argues that the hallmark of biological computation is that information flows across multiple hierarchies of complexity, bubbling up from microscopic to macroscopic levels and back down again.

Simpler structures (like neurons) communicate with more complex structures (like areas of the brain), and vice versa. Computations are occurring on and between every level, from molecules to cells to organisms as a whole. There is a good deal of evidence that even the subcellular compartments within neurons are doing their own computations. Most recently, a study¹ published in *Nature* in October 2013 showed that activity within dendrites (a compartment representing a neuron’s “input”) shapes the information processed by that neuron. Given this multi-level information flow, Bell argues that noise simply cannot be defined: Deviations from expectation should be interpreted as meaningful communication at another level of the complexity hierarchy.

This information flow is not restricted to the brain, and can also be observed, for example, in epigenetics. Bell says this kind of dynamic multidirectional information flow is what defines life. Artificial intelligence, when it arrives, may not be built from silicon, but repurposed biology. Before we get there, though, we will need a vastly different approach to science in order to understand the higher-order, emergent capabilities of nature’s self-organizing structures. While biomimicry holds incredible promise, perhaps in so assiduously copying the physical design of systems we are missing the point: Form is transient in Nature, cast to meet shifting needs in a given niche. Determining the rules by which biology struck upon these ingenious solutions in the first place will spark the true revolution. ☯

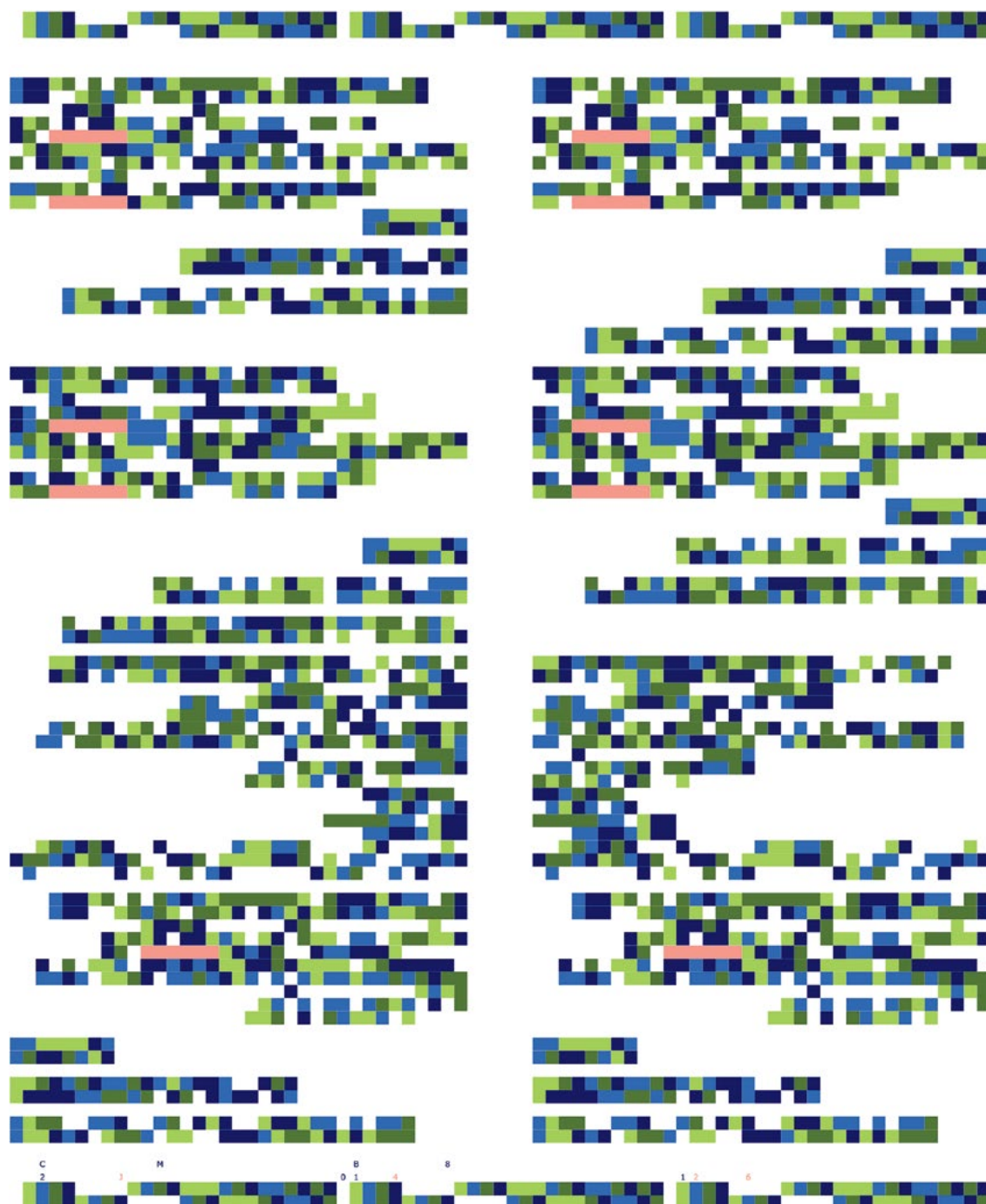
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LOU BEACH



The Cost of Cryptography

Computer security is trying to avoid wasting your time

BY YEVGENIY DODIS

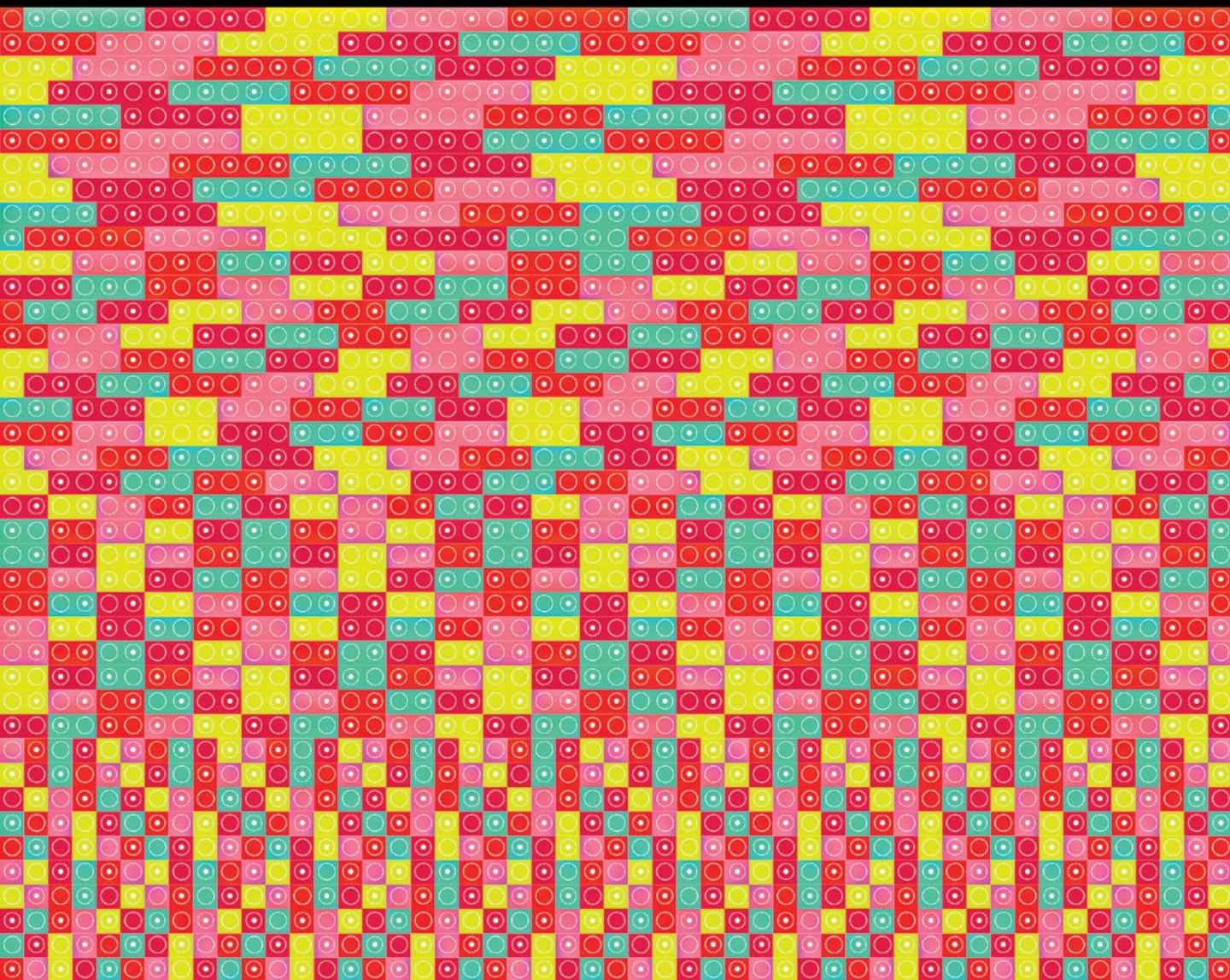
THE VENONA PROJECT REPRESENTS one of the most successful counter-intelligence attacks of the Cold War. It revolved around an encryption system, called the “one-time pad scheme,” that was completely unbreakable, but required generating a new, random encryption key for every message. This was hugely inconvenient, and prone to human error. And error is exactly what happened. Someone on the Soviet side (it is still not known who) began to reuse keys, allowing the decryption of about 3,000 top-secret messages by the West.

The story teaches us that security needs not just strong codes, but an easy-to-use and secure implementation. To this day, attacks rarely break the encryption algorithm (cryptographers have done their job very well!), but usually find ways to avoid it entirely instead, by discovering some unexpected weaknesses in the implementation. The modern computer security age has therefore relied on a reduction of the “cryptographic overhead”—cutting fat from

the system and eliminating avenues for unexpected attacks—as much as it has been about codes per se. This has meant inventing new systems, as well as improving existing ones.

IN A SEMINAL 1949 paper, Claude Shannon defined the notion of perfect encryption: It is achieved when an encrypted message, or cipher, becomes entirely independent of the original message. He also defined its cost: The encryption key needs to be at least as long as the message. Encrypting a streaming movie in real-time would require a movie-length key. This suggested that cryptography had a limited future, at least outside of espionage.

Fortunately, cryptographers eventually realized that overhead requirements could be drastically reduced, in exchange for what was, in effect, only a theoretical reduction in security. These reductions came in the form of two reasonable assumptions: An attacker cannot carry out an arbitrarily large number of computations



CRYPTO ART Artist Christopher Blakely pulled himself out of a 10-year creative block by producing art through mathematical principles. He encoded poems, lyrics, and phrases with colors and patterns. In his piece, “CP01,” shown on pg. 66, Blakely generated patterns according to lyrics by The Smiths. Meanwhile, the pattern in “Taijitu,” above, reflects a Fibonacci sequence, and is laced with symbols related to the Greek philosopher, Anaximander.

in a given time, and that attacker has a tiny, but non-zero, chance of actually breaking encryption.

Subtle as these assumptions are, they set the stage for a cryptography revolution. The amount of key material demanded by the one-time pad scheme turned out to be a waste of resources—encryption that was almost as strong could be achieved with short, reusable keys. Today, a set of encryption schemes standardized in 2001 (built around the Advanced Encryption Standard, or AES) allows movies to be encrypted and streamed in real time, even on relatively small devices, such as tablets and smartphones, at almost no computing cost.

With the easing of one type of overhead, however, came another. The AES are all symmetric encryption schemes, meaning that the key for encoding the message is the same as the one for decoding it. The difficulty is that the sender and receiver need to agree on the key ahead of time, which is feasible if there are only a few people involved. However, modern-day communication happens among parties that are large and dispersed. If each sender needed to arrange a unique key with each receiver, nothing like the quantity of information now exchanged on the Internet would be possible.

The solution to the problem lies in so-called public-key or asymmetric-key cryptography, first suggested in the seminal work of Whitfield Diffie and Martin Hellman in 1976. Metaphorically, in an asymmetric scheme, Alice sends Bob an encrypted message by first asking him to send her an open padlock. This padlock can be intercepted and even “copied” by an attacker, Eve. Alice then puts her message into a box, closes it with Bob’s padlock, and sends it back to him. Eve can observe the locked box, but can’t open it because she doesn’t have Bob’s key. Bob then opens it with his private key, and reads the message. Alice and Bob did not have to secretly exchange keys, or even know who they were communicating with in advance. In addition, since Bob’s padlock is not specific to Alice, it can be reused by other parties wishing to communicate with Bob. The process effectively requires two keys: The *decryption* key is known only by Bob, but the *encryption* key (represented by the padlock) is public.

This solves the problem of distributing keys between many dispersed parties. But it introduces another problem: For short messages, public-key cryptosystems are as much as 100 times slower than

Subtle as these assumptions are, they set the stage for a cryptography revolution.

symmetric schemes. That’s because it is easier to communicate in private when Alice and Bob have some common secret from Eve, than it is when Eve knows everything that Alice knows, but only Bob knows the secret. But here, too, researchers have found an answer. For longer messages, we can first encrypt a short new key with the public-key approach, and then use that key to encrypt the message under a much faster private-key scheme. Similarly, for many consecutive short messages, the same encrypted key can be used for the entire duration of the communication, and then erased when the communication is over. This is called the “ephemeral key” approach.

So public-key systems solve a lot of problems. Nevertheless, their use is limited by yet another key distribution problem: making sure that the right public keys are used. If an attacker can convince someone to use a rogue public key, it is possible for him gain access to privileged information. Currently, the authentication of public keys is performed by Certificate Authorities (CAs), which verify the identity of the public-key owner and issue a certificate saying so. These authorities need to ensure that they do not issue certificates to the wrong users, or compromise the secrecy of their own signing keys.

Unfortunately, this doesn’t always happen. The major browsers (Firefox, Chrome, Internet Explorer, and Safari) include a “hardwired” list of trusted CAs, called “root CAs.” Root CAs are allowed to certify smaller CAs. According to the SSL Observatory project run by the Electronic Frontier Foundation, in early 2013, Mozilla, Microsoft, and Google had certified about 150 root CAs, which in turn certified about 1,500 other CAs as entities whom average users should *unconditionally trust*. Needless to say, most of

these entities are completely unknown to average users, and the odds that all of them will avoid security compromises appear alarmingly low.

In fact, in the last few years several high-profile scandals have surfaced around various CAs. In 2011, a fraudulent Google certificate was signed under the key of a Dutch CA called DigiNotar, which was used (by still unknown entities) for serious “man-in-the-middle” attacks on Google users in Iran. Around the same time, the Turkish CA TURKTRUST discovered it had “accidentally certified” (according to them) two intermediate CAs in August 2011. One of these was used to sign fake Google certificates.

In principle, public key systems with proper CAs provide extremely strong protection. But the architecture *around* that protection is itself vulnerable. The Edward Snowden leaks drove this point home. They showed us that the most successful large-scale attacks against cryptography, including the bulk of the mass surveillance program allegedly run by the NSA against American citizens, access privileged information *in the cleartext form*: either before encryption, or after decryption, or simply sitting in unencrypted form in places which were assumed to be secure. Other attacks have exploited imperfectly random key generation.

A physical parallel to these software attacks are so-called “side channel” attacks, in which the intruder gets access to some (seemingly benign) physical information surrounding a normal run of a given cryptographic system, such as timing information, power consumption, acoustic data, or cache misses. Quite remarkably, by carefully comparing this information with the specifications of the cryptographic algorithm being used, the attacker can often completely recover the secret key. These attacks were pioneered by Paul Kocher in 1996. He exploited the fact that the running time of the popular public-key cryptosystem, RSA, is highly correlated with the contents of its secret key (specifically, the number of 1s in the bit decomposition). By manipulating public inputs to the RSA algorithm, he used repeated executions with the same key to perform a statistical correlation analysis, and recovered the key completely.

The cryptographic research community, in recognition that security relies on more than code strength alone, is broadening modern-day systems to protect

against non-cryptographic attacks. New “leakage-resilient” cryptosystems are able to resist large classes of side channel attacks. Cryptographers have also developed tools to meaningfully compute on *encrypted* data, without requiring any decryption steps at all (until the very last step, when the final result is decrypted). In a scheme called “fully homomorphic encryption,” it is possible for a user to send an encrypted query to Google and receive an encrypted reply, without Google having any idea about the actual search that was carried out (these algorithms are too slow to be feasible at the moment, but are being worked on). Researchers are also studying how to secure, control, and compute on data stored in the cloud, and starting entirely new initiatives, like anonymous credentials and privacy-preserving data mining.

These challenges represent a significant broadening and expansion of the mission of cryptography research—often with the goal of extending capabilities well beyond traditional encryption and authentication, and reducing the overhead involved in implementation. We have come a long way since the VENONA project and single-use keys, and continue to live the lesson that security should not just be strong, but also seamless. ☺

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YUKO SHIMIZU

How to Waste Time Properly

The right distractions can boost creativity

BY GREG BEATO



ILLUSTRATION BY FRANCESCO IZZO

EVER SINCE FREDERICK WINSLOW TAYLOR timed the exact number of seconds that Bethlehem Steel workers took to push shovels into a load of iron ore and then draw them out, maximizing time efficiency has been a holy grail of the American workplace. But psychologists and neuroscientists are showing us the limits of this attitude: Wasting time, they say, can make you more creative. Even seemingly meaningless activities such as watching cat videos on YouTube may help you solve math problems.

Brent Coker, who studies online behavior at the University of Melbourne in Australia, found that people who engage in “workplace Internet leisure browsing” are about 9 percent more productive than those who don’t. Last year, Jonathan Schooler, a psychology professor at the University of California, Santa Barbara, published with his doctoral student Benjamin Baird a study called “Inspired by Distraction.” It concluded that “engaging in simple external tasks that allow the mind to wander may facilitate creative problem solving.”

Schooler gave participants a series of “unusual uses tasks” (UUTs), which asked them to invent as many different uses as they could for a mundane object. The more original the responses, the more creativity they were demonstrating. After performing a baseline test, participants were divided into groups and given different 12-minute “incubation” periods. These consisted of either a demanding memory task, an undemanding memory task that allowed for mind-wandering, or total rest. A fourth group had no incubation interval at all. Then all four groups were presented with more UUTs, which involved at least one object from the first round. The group that had been given a non-demanding incubation task showed the most-improved UUT scores.

“The most surprising result of the study was that the non-demanding task was actually better than doing nothing,” Schooler says. Why this is so, however, is less clear. “My best guess is that if you’re engaged in a non-demanding task, it kind of prevents you from having long trains of thought,” Schooler posits. “It’s sort of churning things up, stirring the pot, so you’re not maintaining one thought for a particularly long time. There are a lot of different ideas going in and out, and that sort of associative process leads to creative incubation.”

Schooler isn’t alone in his conclusion. In 2006, psychologist Ap Dijksterhuis at Radboud University in the Netherlands also found that people tasked with making a complex decision do better when they are allowed a brief period of distraction before deciding. He presented his study participants with a list of cars and their attributes, both positive and negative. Then he asked participants to assess the cars’ quality. One group had to think about the information they had learned for four minutes before making their assessments. The other group was asked to perform a “distractor task” during that four-minute interlude. The group that performed a “distractor task” demonstrated the best judgment.

People who engage in “workplace internet leisure browsing” are about 9 percent more productive than those who don’t.

A few years later, Carnegie Mellon student James Bursley, Carnegie Mellon psychology professor David Cresswell, and Northeastern University research scientist Ajay Satpute replicated Dijksterhuis’s study. But they went a step further—they used functional magnetic resonance imaging (fMRI) to track the brain activity of their subjects. Their research confirmed that decision-related neural processes were occurring during moments of “unconscious thought.” Bursley says it happened because unconscious thought and conscious thought recruited “distinct non-overlapping neural regions.” The neural regions responsible for unconscious thought continue to process previously recorded information, which results in unconscious decision-making that can be “called up to consciousness” when needed. In layman’s terms, it means that we’re capable of paying explicit attention to one thing (cat videos) while resolving another (complex math problems). “Brief periods of unconscious thought can improve decision-making,” the authors

If you want to get the most out of your time-wasting, stare at random YouTube babies, not the babies of your Facebook friends.

concluded in the January 2013 issue of *Social Cognitive and Affective Neuroscience Advance Access*.

So what kinds of distractions, exactly, are best? “You want a distractor that’s pretty far away from what you want to process unconsciously,” Bursley says. If you want your brain to unconsciously process a math problem, it would be better to have the distractor be something totally different, like playing tennis, he says, rather than something similar, like a spatial puzzle.

Which is all great advice for your few-minute work break. But entrepreneur Jacques Habra is taking these findings further—he wants to build an ideal distraction, and make money off of it. Habra’s start-up, SelfEcho, is developing an app called UpJoy, which is a recommendation engine for positive and motivational video imagery. Tell it what type of content interests you—sports, animals, nature, humor, or compassion, for example—and it will unleash a stream of clips and images that have been previously viewed by large numbers of viewers and dubbed sufficiently positive by a majority of them. Over time, UpJoy will learn what you respond to best, and will filter its stream to your tastes. “It’s exactly the kind of intervention that our research suggests would benefit creativity for two reasons,” says Schooler, who is helping SelfEcho develop the software. “One is that it enhances mood, and it’s a very well-established fact that things that are mood uplifting lead to enhanced creativity. And two, it provides a non-demanding break.”

Habra says that images which encourage you to think about the future or inspire a sense of exploration are also good distractors. So do images that are

“ego-less”—that do not involve the specifics of your life. “When people take a break at work and get on Facebook, it becomes an ego-driven experience,” says Habra. “They see someone’s pictures from vacation, and they think, ‘Why isn’t that me? I wish I was on vacation too.’” If you want to get the most out of your time-wasting, stare at random YouTube babies, not the babies of your Facebook friends.

SelfEcho is working to determine the ideal duration and number of breaks a day to prevent a phenomenon known as hedonic adaptation. “As we adjust to things, both positive or negative, their emotional intensity is reduced and we become largely immune to their effect,” Habra says. The daily amount of time people can spend on UpJoy will have limits, at least in settings where it’s being deployed with the goal of productivity enhancement.

The ghost of Frederick Winslow Taylor must be nodding in approval: Finally, break time—the last unmanaged part of the workday—will no longer be a waste of time. ☺

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YUKO SHIMIZU

Ruin Porn

Berlin's layers of history beckon with imperfect memories

BY LUISA ZIELINSKI

PHOTOS BY MATTHIAS LOCHMANN,
J.D. & ROTTEN RUINS BERLIN URBEN



T'S 6:45 ON A TUESDAY morning as Ulrike, a feisty Berliner in her early 50s whose dyed strawberry blonde hair whispers hints of gray, climbs out of her car, clutching a camera. The September fog is just lifting. Ulrike says she'd be grateful for its cover. We are about to break into an abandoned military hospital built in the 19th century on the outskirts of Berlin. As we approach the sprawling brick sanatorium, Ulrike tells me that our excursion is about more than adventurism and seductive photo opportunities. It's about being a witness to history, to memory, to ourselves. It's about the very visceral experience of being in a "lost place."

We leave the car on a side street and scale a chain-link fence, alighting in a muddy field of grass, out of breath. We climb through a broken, arched window and emerge into the sanatorium's grandiose atrium. In the empty, silent hall, I feel what Ulrike means. What was once a working hospital, swarming with nurses and doctors tending to wounded soldiers, has lain abandoned for more than 50 years—declared waste, left to wither and rot away. We are witness not just to the passing of time and gradual decay, but to the discarded dreams of a different era, represented in what remains of its opulent architecture. It is a link to the past that feels both distant and immediate.

Ulrike, who grew up in the former East Germany, shoots photos inside and outside the dilapidated sanatorium. She plans to load the images onto social media sites, where they will be viewed by countless fans who have become enraptured with "ruin porn." Although photographing abandoned buildings is a rarified hobby, urban explorers, who number about 20,000 globally, have created online forums devoted to the sights of history's waste and the stories we construct around them. Sigmund Freud said the psychoanalyst acts as an archaeologist, unearthing buried memories. When they surface, the new facts might conflict with the old ones, but they form a new narrative we have to face.

BALLHAUS GRÜNAU For more than a century it served as an opulent event hall, hosting the grand balls of Imperial Germany, the roaring 20s of the Weimar era, and the Nazi period. Today its crumbling interior stands as reminder of the upheavals of the 20th century.









Ruin porn resonates with us today because it is an unmediated experience in a mediated culture. We experience the past directly, not through a book, museum, TV, or newspaper. The old and decayed buildings are not cleaned up or packaged, as they would be in a time capsule. They poke through the patina of tourism; there are no postcards here. History is present in our minds, stirring our memories. We are alive in the ruins.

Urban exploring is in no way exclusive to Berlin. Yet Berlin exerts a particular draw. It's a city vibrant with history, one on which war, dictatorship, and division have left their marks. Many of the ruins attracting urban explorers around Berlin are imbued with significance. Old ministries, garrisons, and derelict air raid shelters speak of the historical context under which they came into existence, and under which they were abandoned. Berlin's ruins open a doorway to a past that stretches beyond the objectified framework of textbook history. Ruins are not just objects of history—they're palaces of memory. They're haunted places, full of traces and vague intimations of personal stories that may or may not have happened within their confines. They offer us a subjective point of access to things past, beckoning us to enter and explore.

Vogelsang: History and Memory

Hidden in a dense forest north of Berlin lies the ghost town of Vogelsang, a relic from the Cold War. Like most ruins, Vogelsang comes with a few health warnings—its grounds and meadows remain riddled with unexploded mines and grenades. Built in 1951, the military base housed thousands of Soviet troops stationed in Germany. Unknown to the surrounding population—and, in fact, many of the soldiers—its bunkers contained nuclear missiles aimed at London and Paris well into the 1980s. The garrison was abandoned in 1993, a few years after the fall of the Soviet Union. In contrast to many of the ruins around town, Vogelsang has remained relatively unscathed by vandalism. From the Lenin statue at the entrance, the many fading Socialist Realist murals and the odd pair of army

VOGELSANG A former Soviet garrison where nuclear warheads pointing at London and Paris were stored into the 1980s. The grounds are still specked with mines and grenades.





TEUFELSBERG Located on Berlin's highest point, this is the wall of a tower that was used during the Cold War by Americans to spy on East Germans. Today, it's a popular tourist spot. (Left) another view of the Ballhaus Grünau.

boots left by its former inhabitants, it appears to have conserved one particular historical moment. An idea, perhaps. An idea, which from our vantage point looks as pale and dated as the buildings that still enunciate its peculiar aesthetic.

In its present state as a ruin, the garrison reveals the intersection, and perhaps the opposition, of history and memory. Its historical details are clear; the history of the Cold War has been written and rewritten countless times, and with all of that in mind, the curious visitor is perfectly placed to understand the garrison's historical significance. History, however, is only one mode of grasping what happened. As French 20th-century philosopher Pierre Nora writes, while history looks at the concrete changes wrought by the past, memory lives in the present, for the act of remembering always takes place in the here and now. The work of memory is always continuous, never finished. It consists of smoothing over gaps, of retelling a story—made up of fragmented, disjointed pieces—at any given moment in which we remember.

A walk around the former military base resembles the work of our own memory. The buildings are full of disparate traces of a lost reality; old jackets, boots,

and pictures of sweethearts long aged, dead, or forgotten. There are no history books to help us account for those artifacts. Much like the events that form the substance of our own memories, we're confronted with fragments through which we attempt to form coherent stories and harmonize conflicting pieces of information. Whose wife is that? And what happened to her? Why did he leave his boots and jacket in the gym? Or did another visitor place them there? Where the purpose of history is to create certainty, however illusory, memory is about the stories we tell ourselves—to give meaning to events that, as artifacts of our own lived experience, offer very little in the way of certainty.

Teufelsberg: Voids and Lapses

Many urban explorers scoff at Teufelsberg, a former listening station for the National Security Agency (NSA) of the United States that sits on Berlin's highest point of elevation, translated as the "devil's mountain." It is a public place that is a popular tourist destination. Everybody and their mother has been there; director David Lynch even made a pitch some years ago to buy what remains of the concrete skeleton holding oversized, golf-ball-like radar domes whose torn fabric covers



ABANDONED HOUSE Private residences, like the one in which these personal items were found, are urban explorers' biggest catch. Residents fled to the west after the Berlin Wall came down, worried that repression would resume.

rattle deafeningly in the wind. Teufelsberg was built out of the rubble of bombed out buildings and outfitted with listening devices to pick up on signals from east of the Iron Curtain. The first Allied spying activities on the site date back to the late 1950s, though it wasn't until later that the NSA erected the permanent structure with which the hill has become eponymous. Despite its name, there is nothing particularly hellish about the place. Except, perhaps, that it epitomizes the history of the Cold War, born out of the destruction of the war that went before it. In the early 1990s, the NSA gutted the building, removing all electronics and antennas, leaving only the vast and empty structure that remains on the site and a ghostly presence. In its current state as a ruin—derelict and full of graffiti—the former listening station has much to say about how we remember.

Memory scholar Aleida Assmann distinguishes between two kinds of memory. First, there is memory as *ars*. That's the art of remembering, of committing to mind entire books or intricate maps. It's an art that needs practice to be mastered. As an art, it's artificial. It's not the way the mind works when we try to call up

the experience of, say, our first kiss or how we felt on 9/11. That is memory as *vis*, the organic, fragile process of remembrance. Much like a ruin refers to a historical moment, our memories, too, may well reference actual, material events. But they're by no means an accurate representation of those events. Like these buildings, memories are ruinous—full of holes and lapses. Like the countless and ever-changing graffiti appearing on the walls of the former listening station at Teufelsberg, our memories are subject to constant change, to effacement, to being overwritten every time we call them up.

Ballhaus Grünau: The Palimpsest

Just on the outskirts of Berlin lies the once-scenic suburb of Grünau, home to a lush art nouveau ball house that has fallen into disrepair. Ballhaus Grünau—or Ballhaus Riviera, as it was also known—was in use for more than 100 years. From the days of Imperial Germany to the roaring 20s of the Weimar Era, as part of the Nazis' state-controlled leisure organization "Strength Through Joy" (KdF) and throughout the German Democratic Republic, the ball house stood as

a silent witness to the upheavals of the 20th century.

A visit to the ball house reveals little about what it may or may not have seen of grand-scale history; what remains in the space is mostly the chaos of disrepair, the odd faded ornament or mural, as well as the very recent swastika graffiti left by Neo-Nazis. The fenced-off ruins attract them because reproducing the symbol is illegal in present-day Germany and the unregulated spaces can accommodate versions of history—such as a glorified view of the Nazi past—that do not square with the current version of collective memory. Their marks add another layer to the disparate elements that make up the dilapidated ball house. There are many such stories, both personal and historical, that must have unfolded and become layered here in the past century. Perhaps, then, the Ballhaus Grünau aspires to the condition of a palimpsest, the ancient parchment scroll continuously inscribed and re-inscribed. It bears no more than fragments of its past inscriptions, which we might be able to discern, though perhaps not decipher. And those fragments may even hint at narratives that sit uncomfortably with us.

Urban explorers sometimes act as archaeologists of the not-too-distant past. Some spend hours of research preparing for their trips. And no less often do they spend hours trying to piece together bits of information. Countless online forums are devoted to making sense of a place, to unearthing its story—or its many stories—from the rubble, from the layer of debris that obscures it. This work of contemporary archaeology also applies to ruins as representations of how our memory works. They unearth memories buried deep in the realm of forgetting and repression.

Abandoned House: Haunted Memory

The view into someone else's bedroom is the most sought after type of photograph. All I know about the abandoned house in these pictures is that it is located somewhere in East Germany, no more than an hour's drive from Berlin. I'm not supposed to know anything else. These places are the best-kept secrets and the most coveted treasures of the urban explorer community; to make their details public amounts to treason. The idea, I'm told, is that flocks of ruin-tourists would descend on them, and disturb their peace. People tend to be more respectful of personal ruins than public ones. They

don't project a historical context as forcefully, and we don't view them through that lens, in contrast to, say, the garrison or the Teufelsberg listening station. Rather, our access point is entirely through memory—memory that is immediate, personal, and usually oblique. After all, we enter into a private, domestic space. One not too dissimilar to the one we ourselves inhabit and inscribe with our own lived experience.

If undisturbed, abandoned houses seem to halt the passing of time. And this is what constitutes their particular aesthetic: We find ourselves in the moment of rupture—the house in the state the owners left it in when they last closed the door behind them. It is a moment that lasts, suspended forever in the timeless space of the house. The urban explorers I've spoken to about visiting such places told me that the feeling is one of "being haunted"; haunted by the former owners' lasting presence in the space, and the usually inaccessible reasons that made them leave. I think this image of haunting is, incidentally, the most fitting in relating the ruin and memory. Ruins are haunted by the stories, histories, and memories they contain as much as they are haunted by the memories we project into them. So, too, are our own memories haunted. Much of the wealth of our lived experience lies dormant in the depth of our subconscious, waiting to erupt and resurface.

IF RUINS ARE WASTE suspended in time, it seems that time is catching up with them. Berlin's urban explorers are often racing to get to these places before they are claimed by real estate developers, eager to turn them into condos or luxury hotels. What has made the city so special for the past 20 years—its dense condensation of history and memory, with a wealth of places in which this becomes accessible—will soon be glossed over by the ubiquitous glass facades, leaving it indistinguishable from any other modern city. ☺

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Reading the Book of Life in Prehistoric Dung

“Paleoscatologist” Karen Chin has uncovered the humble origin of life after dinosaurs

BY ELIZA STRICKLAND

KAREN CHIN DOESN'T HAVE all the answers, but she is willing to make those awkward phone calls that will give her the information she needs. There was the time back in 1998 when she needed to know what size animal could produce a fecal mass of 2.4 liters in one go. So she called a physician who studied bowel movements. “I said, ‘This is going to be a funny question, but I’m a paleontologist, and I’m interested in finding out what is the largest fecal mass that a human can produce. I wonder if I can talk to the doctor about this.’” She pauses in her anecdote, remembering the silence on the other end of the phone line. “It was a weird question.”

It took a while to convince the receptionist that Chin wasn’t making a prank call, but eventually the message was passed on to the doctor. The physician, driven by who-knows-what mixture of courtesy and curiosity, called her later that day. He explained that in his line of work he typically focused on the health

of his patients, as revealed through their bowel movements, not on the volume of matter they produced. He couldn’t give Chin a precise figure. However, he told Chin, it just didn’t make sense for a man, or a man-sized animal, to produce 2.4 liters of excrement. That answer was enough to make Chin’s heart sing. Because she was pretty sure she’d identified the first fossil of a *Tyrannosaurus rex* turd.

Chin isn’t the world’s only paleoscatologist—a handful of other researchers around the world study the fossilized excrement of ancient peoples to learn about their diet, health, and lifestyles, and a few others study the fossilized droppings of extinct animals. But Chin is an undisputed leader in the field, and her work has brought new insights to scientists’ understanding of the Mesozoic Era, when towering reptiles walked the earth. “I think it’s fair to say I’ve studied more dinosaur feces than most,” she says modestly.

The fossilized droppings that Chin studies are

called coprolites. The basic process of fossilization is not much different from the way bone fossils form: Sediment layers over the dung, protecting it from air and water and consuming critters, while mineral-laden water seeps through it. Gradually the minerals replace the original material, leaving a stone facsimile.

A warm and cheerful woman, Chin is immune to jokes about her line of work—she’s heard them all. “I like working with dinosaurs because I can more easily constrain what I like to call the poopetrator!” she says. That 2.4-liter specimen from Saskatchewan, Canada, was not only large enough to suggest a king-sized beast, it also contained bone splinters indicative of a carnivorous diet. That evidence, in conjunction with the turd’s discovery in a sediment layer near *T. rex* bone fossils, gave Chin confidence in her groundbreaking identification.

Chin, now an associate professor of geological science at the University of Colorado, Boulder, has specialized in fossilized feces for more than 20 years, driven by their unique potential to reveal extinct ecosystems and to show animals’ places in those webs of life. She studies the leavings to imagine her way back to the beginnings.

Chin’s most recent investigation has yielded clues regarding one of the most cataclysmic events to occur on this planet: the global extinction event at the end of the Cretaceous period. When an asteroid or comet slammed into the Earth about 65 million years ago, it doomed not only the non-avian dinosaurs, but also approximately 75 percent of all species in the world: plants, insects, mammals, and so many more. Chin has immersed herself in the destruction and the

geological evidence of how the world recovered. In those landscapes of death, life found a way to return, and new species emerged and flourished. Chin and her colleagues think they may have found the humble origin of that resurrection.

CHIN’S RECENT DISCOVERY is rooted in her early training, which opened her eyes to the role of a lowly creature in the web of life. Like most budding paleontologists, she had read about William Buckland, a 19th-century Oxford University professor of geology, who coined the term coprolite from the Greek words for dung and stone. Buckland became the father of the field after studying remains in Great Britain’s Kirkdale Cave, thought to be prime evidence of Noah’s flood. In fact, Buckland discovered, the cave was a hyena den, where the scavengers dragged their meals for consumption, leaving behind deposits of their own. Buckland’s study of the hyenas’ fossilized feces had large import: It was perhaps the first paleontological study to sketch the contours of an ecological system. That ancient web of life, with its ravenous carnivores and their unlucky meals, could be traced to the droppings left behind by those repasts.

In the 1980s, Chin was getting a master’s degree in biology at Montana State University when she took a job with the legendary dinosaur hunter Jack Horner, the inspiration for the paleontologist protagonist in *Jurassic Park*. At first, Chin’s job was simply to slice fossilized bones into thin sections that Horner could examine under the microscope. They were working with fossils found in Montana’s Two Medicine Formation, a sandstone outcropping that Horner was exploring. The rock layers were rich with bones of a new-found duck-billed dinosaur named *Maiasaura*, and not just the bones—also nests and eggs, and strange blobby deposits a bit removed from the nests. Horner believed these chunky rocks, embedded with shreds of fossilized plant material, were dinosaur patties.

Chin volunteered to work on these fossils, and set to work trying to confirm that they were indeed coprolites. “The context was appropriate,” she says, in that the material hadn’t been found as a uniform layer, but rather as discrete deposits. They didn’t have particularly turd-like shapes, but then, she figured, they would have fallen some distance from the big duck-billed

“That was the coolest implication of this research. Here we had evidence of interaction between the dinosaurs and the beetles.”



SHE CAN DIG IT Paleontologist Karen Chin, who studies dinosaurs through their dung, examines a coprolite on a Utah hillside.

dinosaurs and impacted on the ground. But she found her smoking gun, she says, when she began slicing up the fossils and found what looked like small burrows inside. Could they be dung beetle burrows?

She called a leading dung beetle expert in Canada and explained her research question, and they agreed to meet when Chin was in Toronto for a conference. The meeting took place over a coffee table in a generic Toronto hotel room. “He had brought some dung beetle balls from Africa, and I had brought the coprolites,” Chin remembers. The expert compared the burrows in each of the materials, and showed Chin the obvious similarities. In the middle of this scene, the housekeeper came in to make up the room, but the two scientists barely looked up. “He was showing me why the burrows in the coprolite were characteristic—and he got really excited and I got really excited,” says Chin. The two scientists started waving their arms around, exclaiming enthusiastically that it must be dung, it just must be! All the while, the housekeeper dutifully tidied.

While most paleontologists dream of reconstructing bones into the skeletons of whole animals, Chin was realizing that modest coprolites could tell a more interesting story. “Body fossils are vital because they tell us the types of organisms that lived in an ancient

environment and what they looked like,” she says. “That can tell us that they moved in a certain way and had particular teeth that could take advantage of a particular diet. But they don’t tell us about interactions between specific organisms.”

Since a world full of dinosaurs would naturally involve a lot of dung, scientists had presumed there were organisms that recycled that material back into the ecosystem. But no direct evidence had been found of how that process occurred. Chin’s discovery was the first evidence of dung beetle activity before the Cretaceous–Paleogene (K–Pg) extinction event. “To me, that was the coolest implication of this research,” says Chin. “Here we had evidence of interaction between the dinosaurs and the beetles.”

Horner was also delighted with Chin’s identification of the coprolites, and her subsequent analysis that showed that the plant material in the dinosaur patties came from conifers. “The coprolites have the only plant material preserved at the site, and they did help us to put together the ecosystem,” Horner says. “We would always like to reconstruct the ecosystem, but usually it’s really hard to do.” It’s uncommon to find fossilized plants alongside fossilized bones, Horner explains, because plant material preserves better in

Earthworms may have aided and abetted the survival of animals, leading to that glorious process of evolution that resulted in you.



THE WORM OF LIFE Fossilized burrows in North Dakota suggest worms survived the dinosaur-killing asteroid and restarted the food chain.

an acidic environment, while bones do better in an alkaline environment. The coprolites at the Two Medicine Formation offered a way around that conundrum, and yielded surprising information. “Determining the bite-sized pieces that the dinosaurs had chewed off, that told us a lot about how the dinosaurs fed,” Horner says.

In the course of working with Horner, Chin decided to get a Ph.D. in geological science, and wrote her dissertation on herbivorous dinosaur coprolites. Still, she didn’t think that coprolites would define her career; she expected to move on to other subjects in paleontology. “No one wants to be associated with feces,” she says slowly. But she couldn’t turn away from the intriguing coprolites that paleontologists kept sending to her. “I’m not trying to reframe my research anymore, because there’s so much we can learn from fossil feces,” Chin says. “I think the questions are some of the most fascinating I’ve ever encountered.”

THE LATEST QUESTION THAT Chin couldn’t resist was stored in a back room of a museum, in a specimen box stashed high up in a drawer.

She was in North Dakota visiting Dean Pearson, a paleontologist at the Pioneer Trails Regional Museum, who has done a great deal of work on the K-Pg. Pearson tries to create reconstructions of what the environment looked like prior to and after the big event by studying a geologically rich outcropping that contains evidence of the impact. The K-Pg boundary is marked by a thin layer of sediment containing high levels of iridium, an element that is scarce on earth but abundant in asteroids and comets, as well as two types of rock created by powerful impacts: shocked quartz and glass spherules.

By studying the fossils below and above this geological boundary, Pearson can piece together the ancient ecosystems of North Dakota. “Before the impact it was a warm, wet environment,” he says. “You can visualize southwest North Dakota as being similar to the Florida everglades.” The scene thrummed with life: Dinosaurs, smaller reptiles, and mouse-sized mammals meandered through the grasslands, while fish filled the streams and insects buzzed in the air. The impact ended that vibrant world, and brought on an era of blazing fires and dark skies. Researchers

believe the collision sent vast clouds of dust and ash into the atmosphere, enough to block the sun and prevent photosynthesis in green plants. The die-off of flora led to the destruction of the fauna that fed on it, and Pearson's sunny grasslands became a bleak landscape of rotting vegetation and corpses.

As part of his quest to understand how life bounced back after that calamity, Pearson has been carefully investigating the sediment above the K-Pg boundary layer to determine which plants and animals made a comeback. Just six centimeters above the boundary layer, a blink of an eye in geologic time, he found something interesting: the fossilized remains of burrows. When Chin came to visit him in 2010, Pearson got her up on a ladder to peer into the high drawer that contained that specimen, and showed her the network of tunnels in the rock. Chin told him she already had too many projects, she couldn't possibly take on another one, but—oh, these were cool.

Reluctance gave way to curiosity. Chin began slicing the perforated rock and studying the sections under the microscope, calling on her colleague Allan A. Ekdale for expert insights on burrows. Together they determined that the burrows, which were horizontal and of uniform shape and width, were strikingly similar to the tunnels created by modern-day earthworms. When Chin found minuscule pellets of clay within the burrows, the case was closed. The dirt that passes through earthworms' digestive tracts comes out as clay-rich feces. Chin realized she was staring at coprolites from worms that had writhed through the wreckage in the aftermath of a holocaust.

"I think worms rebounded immediately after the impact," says Chin. She believes they were largely protected from the initial blast in their underground burrows, and more importantly, they were able to find sources of food in the long hungry time that followed. "People have surmised that the organisms that survived were in the detritus food web," she says.

Geologist Peter Sheehan of the Milwaukee Public Museum is one of the main proponents of this theory: His work has suggested that animals that were part of a food chain that involved green plants were in trouble. But detritivores, which fed on rotting organic matter, and the larger animals that ate those detritivores would have had a much better chance of survival.

Chin's earthworms fit well with that theory, since they would have found plenty of decomposing plant matter to eat in that rotting world. "I can just imagine them emerging from the burrows into this scene of devastation and saying, 'This is fine for me!'" she says with a laugh.

Not all vertebrates perished in the extinction event: Some types of birds, reptiles, and small mammals did make it through, and went on to repopulate the planet. Aquatic turtles seem to have breezed through the apocalypse, for example, and a group of burrowing, rodent-like mammals called multituberculates weren't particularly fazed. But how did they make it through? Paleontologists have documented not just the die-off of green plants, but also of insects that fed on those plants. "Those animals that ate insects would have needed some other source of protein," Chin says, "and worms may have been key."

Researchers who have spent their lives in the few inches of rock that tell the story of life's near-extinction say that Chin's worm-burrow paper adds a nice piece of evidence to the emerging picture of how vertebrate animals survived and repopulated the planet.

"It's a very nice story—everything seems to agree," says David Fastovsky, a paleontologist at the University of Rhode Island who has worked with Sheehan on studies of the extinction event survivors. "The organisms that got through are animals that can find places to hide, and that could feed on the available food—and detritus would be about the only types of things that would be available," he says. "Chin's paper reinforces this detritivore signal very strongly," he says.

In other words, these ancient earthworms may have aided and abetted the survival of vertebrate animals, leading to that glorious process of evolution that resulted in, among other things, you.

It's an elegant theory: In the wastage of the world, one creature found sustenance, and provided nourishment in turn to the animals that were starting a new legacy of life. And it was the earthworm's own refuse that told the story to the inquisitive Chin. The book of life is written in scat. ☺

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08

AT FIRST GLANCE, HOME may seem to be a human construct, an intersection of time, place, and emotion that is unique to our mental sphere, and disjointed from science.

But animals also have homes, whether it is a beaver dam or a termite mound. So homes clearly extend beyond the human. And bacteria have homes too, of a kind: Self-constructed masses of dead cells and symbiotic communities without which they cannot function, and which researchers are only starting to reproduce in the laboratory. They show that home does not require even a resident consciousness.

Turning skyward, we find that our sun has not only an ancestral birth cluster, but likely also sibling stars of similar dimensions and composition, which may give us clues about the origins and nature of the Earth. The idea of home then becomes independent of life. In fact, it can be independent of any material object whatsoever—researchers working on artificially intelligent computer programs must understand what a “home” for the mind looks like, and whether it even exists.

The intersection between home and science, then, is broad and varied. But the message we are left with is familiar, and even intuitive: Home is ephemeral, complex, and universally important.

Welcome to “Home.”

—MS

“The more we try to draw inspiration from natural architecture, the more we understand that even the simplest structure is deeply entangled with the character and identity of its builder.”

LEE BILLINGS

“The Termite and the Architect” p.136

Home

THE PLACES THAT MATTER



The Madness of the Planets

Our home in the universe continues to rock out of control

BY COREY S. POWELL

I AM A STAUNCH BELIEVER in leading with the bad news, so let me get straight to the point. Earth, our anchor and our solitary haven in a hostile universe, is in a precarious situation. The solar system around us is rife with instability.

Residents of Chelyabinsk, Russia, experienced this firsthand at 9:20 a.m. local time on Feb. 15, 2013, when a 50-foot-wide asteroid slammed into Earth's atmosphere and exploded above the town, shattering windows, collapsing the roof of a local zinc factory, and sending more than a thousand people to the hospital with glass cuts and other injuries. Millions of people saw the videos of Comet ISON meeting a different but related cataclysmic fate as it took a swan dive past the sun on Thanksgiving Day that year. In the space of a few hours, the 4.5-billion-year-old comet was reduced to a cloud of sputtering rubble.

But these incidents are mere pixels in the sweeping picture emerging from the latest theories of how our solar system formed and evolved. Collisions and

dislocations are not occasional anomalies; they are a fundamental cosmic condition.

"Things are not as simple as they were supposed to be, with the planets staying quiet forever," says Alessandro Morbidelli, a planetary dynamics expert at the Nice Observatory in France. "When the planets form they don't know they have to form on good orbits to be stable for billions of years! So they are stable temporarily, but are not stable for the lifetime of the star."

Translation: Earth was forged in chaos, lives in chaos, and may well end in chaos.

While Morbidelli is explaining all this to me in a cheery Italian accent, I cannot help fixating on the grim connotations of his last name. He and his scientific compatriots are amplifying a recent realization about our celestial home: Instability is our natural state. For centuries, Isaac Newton and his followers envisioned a solar system that runs like divine clockwork. Only in the past decade have high-precision mathematical simulations shown just how wrong he was. Carl Sagan

famously declared that “we’re made of star stuff.” Morbidelli has an equally profound message: We are made of cosmic chaos.

“You might take a trip around the galaxy, come back in five billion years, and say, hey, there is no Mercury anymore and Earth is now on an eccentric orbit that is catastrophic for life,” Morbidelli continues in his musical voice. It’s easy to be cheery when talking about events that nobody alive will ever experience, I suppose, but his tone doesn’t change a bit as he starts ticking off the parts of the solar system in flux.

“There are unstable populations in the asteroid belt, Kuiper belt, and Oort Cloud,” Morbidelli says. These instabilities are relics of the chaos in which Earth and the other planets formed. The Chelyabinsk meteor emerged from the asteroid belt, perhaps from a smash-up that took place about 30,000 years ago. The Kuiper Belt, just beyond Neptune, and the Oort Cloud, a vast hive of dormant comets extending halfway out to the next star, can also send objects careening our way. That is where Comet ISON came from.

After the Chelyabinsk disaster, Morbidelli and a group of colleagues huddled to figure out the implications of all that instability. Meteor impacts seemed to be happening a lot more often than their models predicted. When they presented their updated results in November, 2013, they concluded that the true rate of Chelyabinsk-scale events is probably 10 times as high as they had previously estimated. There is no clean separation between the unsettled past and the present.

Morbidelli’s view replaces Newtonian clockwork with something more akin to quantum uncertainty, with everything defined by probabilities of survival. Over time, every object in the solar system that can be destroyed, scattered, or ejected *will* eventually be destroyed, scattered, or ejected. That is how Earth came to be. That is how it exists today.

The belief that Earth and the rest of the solar system were born in largely their present form—the arrangement and characteristics of the planets almost preordained—has deep, clinging roots in the history of science. It extends further than Newton, back to the influential writings of the 13th-century monk Johannes de Sacrobosco, who described the universe in terms of clean, geometric patterns. You could plausibly draw a line all the way to the perfect heavenly spheres of

Aristotle. Amazingly, the same basic philosophy (built atop a very different scientific foundation) persisted well into the Space Age.

In retrospect, that simple and comforting view had begun to unravel long before most scientists recognized what was happening. As far back as the 1970s, theoretical models trying to simulate the formation of the solar system kept coming up with an unwanted result: The planets migrated wildly, toward and away from the sun, making a royal mess of things in the process. “It would come out of pen and paper theory work, but it was immediately ignored,” says Kevin Walsh, a leading researcher in solar system dynamics at Southwest Research Institute in Boulder, Colo. “It showed up as like throwaway comments in some papers, but no one seriously proposed that planetary migration was an important process.”

The idea languished for a couple decades until a series of scene-shifting discoveries forced the theorists to reconsider. In 1995, two Swiss astronomers detected 51 Pegasi b, a planet orbiting a dim yellow star located 50 light years away in the constellation Pegasus. It was the first world found orbiting another star similar to the sun. The planet is a gassy, Jupiter-size giant, the kind of world that theoretically can form only in the cool regions far from its parent star.

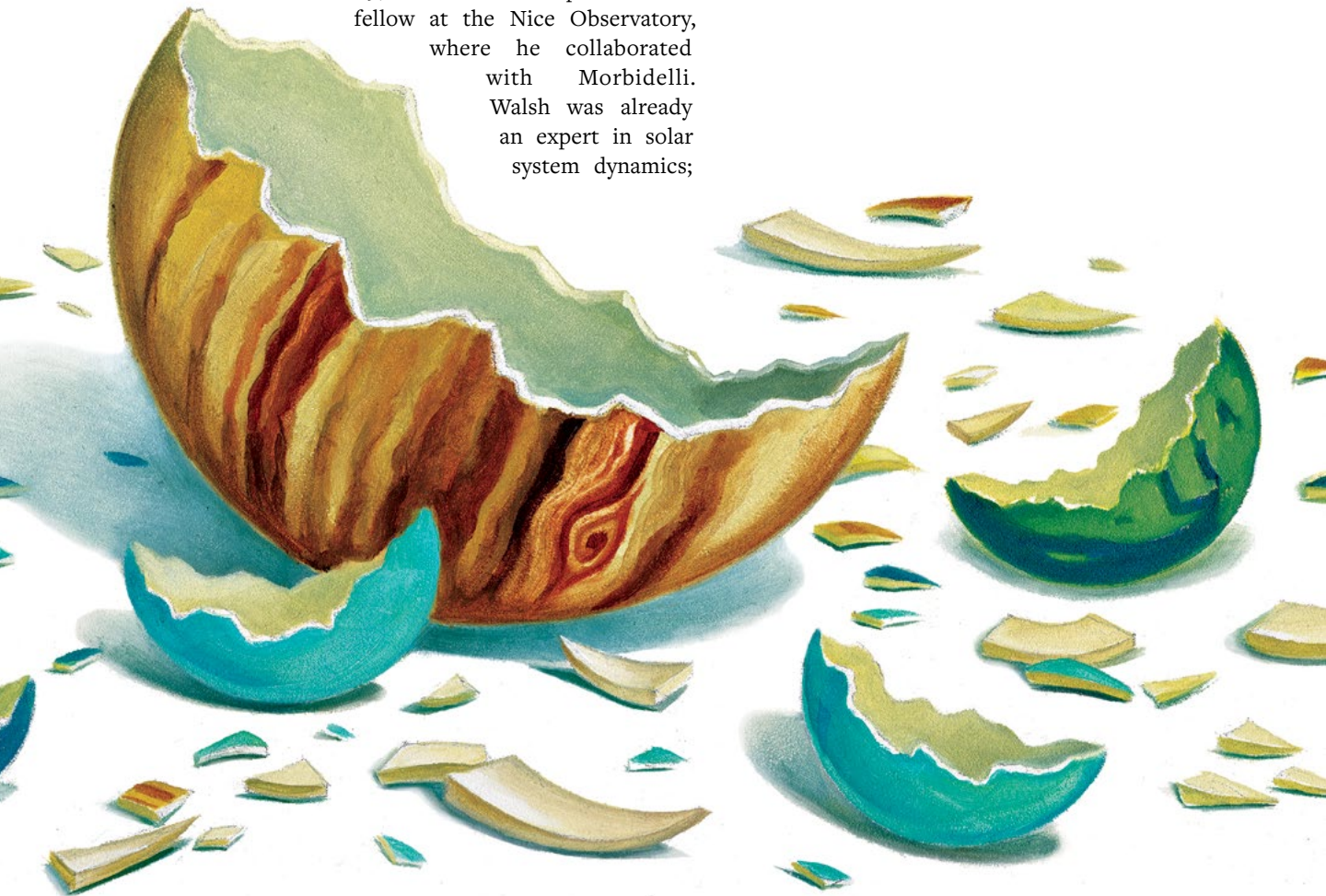


But there was 51 Pegasi b, hugging close in a searing-hot orbit. The only sensible explanation astronomers could come up with was that the planet had formed far out and then somehow shifted sharply inward. They dubbed this puzzling world a “hot Jupiter” and waited to see if it was a fluke.

It was not. Within a year, a competing American team discovered two more hot Jupiters; several dozen similar worlds are now catalogued. As astronomers got better at searching, they started to find a number of other improbable planets. Some were in highly oval orbits; some revolved around their stars at a steep angle, or even backward. Such arrangements did not seem physically possible unless the planets had migrated dramatically at some point. If that process happened around other stars, it could have happened here as well. “And that’s when it really started to kick off,” Walsh says.

In 2009, Walsh was a postdoctoral fellow at the Nice Observatory, where he collaborated with Morbidelli. Walsh was already an expert in solar system dynamics;

Collisions and dislocations are not occasional anomalies; they are a fundamental cosmic condition.



now he became fascinated by the concept of migrating planets and buried himself in the details of how the process would work. He focused on the earliest stages of solar system formation while Morbidelli tackled a later, secondary instability.

Getting planets to move is extremely easy in mathematical models of a newborn solar system. The challenge—as those pen-and-paper theorists of the 1970s had discovered—was finding ways for planets not to move. Data from the Hubble Space Telescope and other great observatories show that, in the big picture, infant planets emerge from a swirling disk of gas and dust around a just-formed star, known as a protoplanetary nebula. For the first few million years, planets are little more than debris bobbing on the waves in the disk.

“That nebula outweighs the planets about a thousand to one, so the gas can push the planets around really dramatically,” Walsh says. As a result, he realized, the early solar system must have been more like bumper cars than clockwork. He also saw that if he fully embraced the idea of instability and took it to its logical conclusions, he could account for many aspects of the solar system that had previously defied easy explanation: Why is Mars so small? How did the asteroid belt form? And above all, why is Earth’s chemical makeup so different than was predicted by the original formation models?

Walsh knit his ideas into a theory he calls the Grand Tack, which creates a startlingly new narrative of how the Earth and other planets formed. At present, Jupiter’s orbit is 5.2 times wider than Earth’s. It is also sticking to its 11.8-year orbit like a metronome. But according to Walsh, Jupiter actually formed quite a bit farther out and then, during the solar system’s initial 5 million years, executed a series of dramatic swoops. First it spiraled inward to the place where Mars is now (about 1.5 times the Earth-sun distance), as the dense gas in the nebula dragged it toward the sun. Then it migrated out past its current location, yanked by the gravitational influence of the newly formed planet Saturn. The whole process took about 500,000 years—an eternity in human terms, but blazingly fast for the solar system, which is 4.6 billion years old.

So what happens, I ask, when a planet that size goes on the prowl? “Oh, it raises hell!” Walsh replies. “That’s a really big planet and it’s moving all over the

place. It acts like a giant snowplow and essentially wipes out everything in its way.”

Fortunately for us, Earth had not yet formed when Jupiter was on the move; if it had, our planet might have plunged into the sun or spun off into dark oblivion. The giant planet’s influence on the inner solar system, where we live, was more indirect. Most of the action happened on the outbound track, when Jupiter rammed through thick swarms of icy comets and asteroids. That snowplow effect sent those water-rich objects raining down on Earth just as it was beginning to grow. “The bulk of the water that we see on Earth is a result of the scattering from Jupiter’s outward migration,” Walsh says. Whenever you take a swim, or just take a drink, you are benefiting from the solar system’s foundational instability.

The migration of Jupiter reshaped the solar system in many other ways. It cleared out the original asteroid belt on the way in and filled it with new objects on the way out. It reorganized the distribution of comets. It stunted the growth of Mars, making it into the cold and nearly airless world it is today—bad luck for prospective Martians. At the same time, Jupiter deposited enough material closer to the Earth that our planet ended up colliding with one of the leftover planetary cores. The moon is thought to have formed from the wreckage of that cataclysm.

After Jupiter finished its wanderings the solar system looked stable, but the appearance was superficial. Instead, it had set the stage for a second great upheaval, one that has been baffling scientists for half a century.

NASA’S APOLLO MISSIONS ACHIEVED many notable things, but for the purposes of this story their greatest legacy was bringing back 842 pounds of moon rocks. On Earth, almost all evidence of the solar system’s unruly early history has been worn away by erosion, biological activity, and the slow dancing of the continents. On the moon, there is no erasure. The moon never forgets.

During the 1970s, even as NASA was retreating from the majestic Apollo missions to a rickety Skylab, several groups of researchers set out to decode the lunar samples brought back by the astronauts. The moon’s surface contains an intact chemical record of all the asteroids that have pummeled it over the eons.



Planetary scientists expected to find a steady progression from disorder to order: lots of impacts right after the formation of the solar system, then a rapid tapering off as the moon (like the Earth and other planets) mopped up the last bits of debris. That is not at all the story written in the rocks.

When three geochemists—Fouad Tera, Dimitri Pap-anastassiou, and Gerald Wasserburg—sifted thoroughly through the lunar material, they saw instead that most of the material created by impacts had an age of about 3.9 billion years. The moon apparently experienced another intense barrage of asteroids at that time, a full 700 million years after the formation of the solar system. The researchers called it the “terminal lunar cataclysm”; now it’s known as the Late Heavy Bombardment. Either way, it stayed on the books for decades as one of the solar system’s biggest mysteries.

Around 2005, Morbidelli decided to take a crack at solving it. In conjunction with three other researchers, including Harold Levison, Walsh’s neighbor and collaborator at the Southwest Research Institute, he wrote up a series of papers in which he connected the Late Heavy Bombardment to a previously unknown, belated instability in the formation of the solar system. The resulting “Nice model” (that’s Nice as in the French town where Morbidelli works) is now the most widely accepted explanation for the solar system’s second wave of devastating impacts.

According to this model, the solar system never quite found its steady groove after Jupiter migrated back out and the sun blew out its birth nebula. An enormous cloud of comets orbiting the sun beyond Neptune—the region that now marks the Kuiper Belt—was slowly but inexorably working gravitational mischief.

At first, Neptune’s orbit was synchronized with Jupiter’s, a pattern called a resonance. Jupiter circled the sun three times, perhaps, for each one orbit of Neptune. Resonances tend to keep things stable. Over hundreds of millions of years, however, that cometary cloud dragged Neptune into a new orbit. “When Neptune gets off resonance with Jupiter the system goes ‘boom,’ completely unstable. Then the violent evolution starts,” Morbidelli says. Neptune migrated out, flinging comets inward; those comets reached Jupiter, which batted them even farther out; Jupiter, in response, migrated inward.

Whenever you take a swim, or just take a drink, you are benefitting from the solar system’s foundational instability.

In the end, Saturn and Uranus, as well as Neptune, moved into more distant orbits. Jupiter settled into its present, closer one. In one version of the theory, developed by Morbidelli’s colleague David Nesvorný at the Southwest Research Institute, our solar system originally had a fifth giant planet that got ejected entirely during this commotion; if so, it is currently wandering alone among the stars. Most comets got exiled to the Oort Cloud, far beyond the planets. Many other comets and asteroids went careening closer to the sun, where great numbers of them smacked into moon, Earth, and other inner planets.

Although almost all traces of this hellish era have vanished from Earth, some fleeting bits remain. Bruce Simonson of Oberlin College is tracking down extremely ancient impacts from the most distinctive evidence they leave behind: glass spherules the size of BBs (created from rock melted by the asteroid or comet) and elevated concentrations of the element iridium (much more common in meteorites than in Earth’s surface). Earth’s two oldest rock beds, one in western Australia and the other in South Africa, preserve records going back at least 3.4 billion years. For the past two decades, Simonson has been prospecting there for signs of what the Late Heavy Bombardment did to our planet.

One of his most intriguing results is that the rain of asteroids may have continued for a staggeringly long time, until 2.5 billion years ago or even more recently. “There’s evidence it was a more gradual ramp down, and we think it’s convincing evidence, but of course



it's ours," Simonson says. If he's right, regular asteroid blows were occurring well into the era of life on Earth, which began around 3.5 billion years ago. He also sees signs of what he technically calls "big-ass impacts," many times bigger than the impact that helped kill off the dinosaurs.

Surprisingly, Simonson thinks life soldiered on just fine amid all the falling rocks. "I'm not a big fan of impacts and extinction," he confides. "The only one where we have clear coincidence between impact and a change is the end Cretaceous [when the dinosaurs went extinct]." He thinks that, overall, extinctions are more likely to have been caused by enormous volcanic eruptions and by the changing configuration of the continents and oceans. That's a little comfort, at least, considering that everywhere on Earth where he looks, he finds evidence of ancient asteroid blasts.

AT THE TIME OF the Late Heavy Bombardment, asteroids were hitting Earth at least a thousand times as often as they do now. Could something like that happen again? No, both Morbidelli and Walsh answer without hesitation. The first two planetary rearrangements cleared out 99.9 percent of the asteroid belt and Kuiper Belt; there is just not enough left to recreate the kind of chaos that ruled 3.9 billion years ago.

So are we home free? No again. "The terrestrial planets, they are not totally stable," Morbidelli says. That instantly captures my attention: Earth is one of the four terrestrial planets. "Mercury is on the edge of the instability, and it could go nuts, start to encounter Venus, then the orbits of Venus and the Earth could become unstable themselves." From there, Venus could collide with Earth, or Earth could go careening off on a totally new orbit, sterilizing the planet. The odds are not great, but they're not all that small either—about 1 percent over the next few billion years.

I question Morbidelli to make sure I'm understating him correctly. A 1 percent chance of disaster is surprisingly high odds in the cosmic-doomsday business. He sets down the phone for a moment and I hear him in the distance, double-checking with someone else in his office ("Do you know the probability that Mercury gets crazy?"). Then he's back on the line: "Yes, 1 percent." And he warns that the subtle divergences that would set the whole cataclysm in motion are like the weather:

chaotic and impossible to forecast far in advance. They could be building up right now.

We are back to a probabilistic view of the solar system, in which nature builds some inherent uncertainty into the system. "It may be that instabilities are just a natural part of life for planetary systems as complicated as ours, and chaos keeps us from really understanding it," Walsh says.

There are definitely other, less catastrophic, and more comprehensible forms of instability at work right now. Comets still leak out of the region around the Kuiper Belt, a lingering hangover from the Late Heavy Bombardment. Comets in the Oort Cloud get sent flying by passing stars. In addition to gravitational mischief by the planets, a slight pressure created by sunlight, known as the Yarkovsky Effect, keeps shifting the paths of the asteroids, guaranteeing that the risk of impact will never go away. A year ago, the standard line was that events like Chelyabinsk happen once every 200 or 300 years. The updated estimate is a couple times a century, maybe more often.

But Morbidelli is not at all gloomy or apocalyptic about his work. The more I speak to him, the more I absorb his perspective. Instability is a mechanism that transforms things from generic and boring into particular and interesting—whether those things are people or planetary systems. "If you want to describe the global evolution of a person, well, he's born and then he dies. That's it," Morbidelli says. "If you want to describe a specific person in detail, I cannot do it in a general scheme. There is a general scheme, but there are plenty of specific ramifications that drive you to be the person that you are. For a planetary system it is the same thing. That's chaos: extreme sensitivity to tiny changes."

To Morbidelli, we're not at war with a hostile universe, we're part of it. The astronomer has clearly spent a lot of time contemplating the personal implications of his work. "Planetary systems evolve by instable steps until they find their final peace; it is almost a Buddhist view of the universe," he concludes, lyrical as ever. "Everything evolves to wisdom and peace—and stability—through big revolutionary events." ☯

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ELLEN WEINSTEIN



A.I. Has Grown Up and Left Home

It matters only that we think, not how we think

BY DAVID AUERBACH

THE HISTORY OF ARTIFICIAL Intelligence, said my computer science professor on the first day of class, “is a history of failure.” This harsh judgment summed up 50 years of trying to get computers to think. Sure, they could crunch numbers a billion times faster in 2000 than they could in 1950, but computer science pioneer and genius Alan Turing had predicted in 1950 that machines would be *thinking* by 2000: Capable of human levels of creativity, problem solving, personality, and adaptive behavior. Maybe they wouldn’t be *conscious* (that question is for the philosophers), but they would have personalities and motivations, like Robbie the Robot or HAL 9000. Not only did we miss the deadline, but we don’t even seem to be close. And this is a double failure, because it also means that we don’t understand what thinking really is.

Our approach to thinking, from the early days of the computer era, focused on the question of how to represent the knowledge about which thoughts are

thought, and the rules that operate on that knowledge. So when advances in technology made artificial intelligence a viable field in the 1940s and 1950s, researchers turned to formal symbolic processes. After all, it seemed easy to represent “There’s a cat on the mat” in terms of symbols and logic:

$$\exists x \exists y (x = \text{cat} \wedge y = \text{mat} \wedge \text{sitting}(x, y))$$

Literally translated, this reads as “there exists variable x and variable y such that x is a cat, y is a mat, and x is sitting on y .” Which is no doubt part of the puzzle. But does this get us close to understanding what it is to *think* that there is a cat sitting on the mat? The answer has turned out to be “no,” in part because of those constants in the equation. “Cat,” “mat,” and “sitting” aren’t as simple as they seem. Stripping them of their relationship to real-world objects, and all of the complexity that entails, dooms the project of making anything resembling a human thought.

This lack of context was also the Achilles heel of the final attempted moonshot of symbolic artificial intelligence. The Cyc Project was a decades-long effort, begun in 1984, that attempted to create a general-purpose “expert system” that understood everything about the world. A team of researchers under the direction of Douglas Lenat set about manually coding a comprehensive store of general knowledge. What it boiled down to was the formal representation of millions of rules, such as “Cats have four legs” and “Richard Nixon was the 37th President of the United States.” Using formal logic, the Cyc (from “encyclopedia”) knowledge base could then draw inferences. For example, it could conclude that the author of *Ulysses* was less than 8 feet tall:

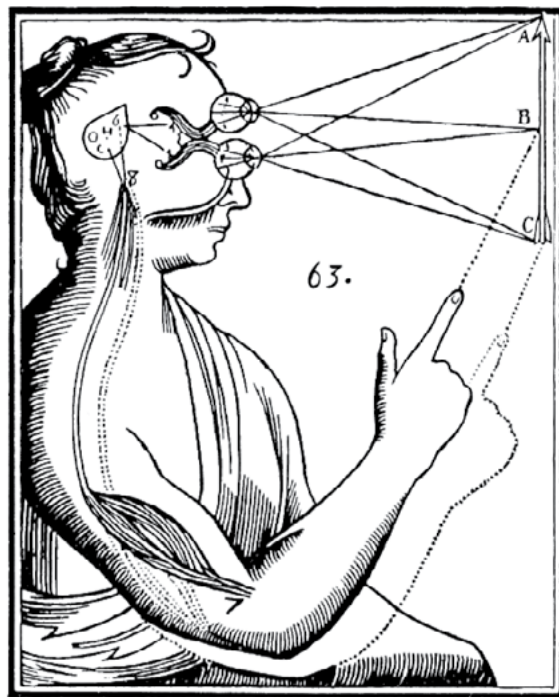
```
(implies
  (writtenBy Ulysses-Book ? SPEAKER)
  (equals ?SPEAKER JamesJoyce))
(isa JamesJoyce IrishCitizen)
(isa JamesJoyce Human)
(implies
  (isa ?SOMEONE Human)
  (maximumHeightInFeet ?SOMEONE 8))
```

Unfortunately, not all facts are so clear-cut. Take the statement “Cats have four legs.” Some cats have three legs, and perhaps there is some mutant cat with five legs out there. (And Cat Stevens only has two legs.) So Cyc needed a more complicated rule, like “Most cats have four legs, but some cats can have fewer due to injuries, and it’s not out of the realm of possibility that a cat could have more than four legs.” Specifying both rules and their exceptions led to a snowballing programming burden.

After more than 25 years, Cyc now contains 5 million assertions. Lenat has said that 100 million would be required before Cyc would be able to reason like a human does. No significant applications of its knowledge base currently exist, but in a sign of the times, the project in recent years has begun developing a “Terrorist Knowledge Base.” Lenat announced in 2003 that Cyc had “predicted” the anthrax mail attacks six months before they had occurred. This feat is less impressive when you consider the other predictions Cyc had made, including the possibility that Al Qaeda

might bomb the Hoover Dam using trained dolphins.

Cyc, and the formal symbolic logic on which it rested, implicitly make a crucial and troublesome assumption about thinking. By gathering together in a single virtual “space” all of the information and relationships relevant to a particular thought, the symbolic approach pursues what Daniel Dennett has called a “Cartesian theater”—a kind of home for consciousness and thinking. It is in this theater that the various strands necessary for a thought are gathered, combined, and transformed in the right kinds of ways, whatever those may be. In Dennett’s words, the theater is necessary to the “view that there is a crucial finish line or boundary somewhere in the brain, marking a place where the order of arrival equals the order of ‘presentation’ in experience because what happens there is what you are conscious of.” The theater, he goes on to say, is a remnant of a mind-body dualism which most modern philosophers have sworn off, but which subtly persists in our thinking about consciousness.



MIND AND BODY Dualists believe that mental phenomena are not entirely physical.

This is a double failure, because it also means that we don't understand what thinking really is.

The impetus to believe in something like the Cartesian theater is clear. We humans, more or less, *behave* like unified rational agents, with a linear style of thinking. And so, since we think of ourselves as unified, we tend to reduce ourselves not to a single body but to a single *thinker*, some “ghost in the machine” that animates and controls our biological body. It doesn’t have to be in the head—the Greeks put the spirit (thymos) in the chest and the breath—but it remains a single, indivisible entity, our soul living in the house of the senses and memory. Therefore, if we can be boiled down to an indivisible entity, surely that entity must be contained or located somewhere.

This has prompted much research looking for “the area” where thought happens. Descartes hypothesized that our immortal soul interacted with our animal brain through the pineal gland. Today, studies of brain-damaged patients (as Oliver Sacks has chronicled in his books) have shown how functioning is corrupted by damage to different parts of the brain. We

know facts like, language processing occurs in Broca’s area in the frontal lobe of the left hemisphere. But some patients with their Broca’s area destroyed can still understand language, due to the immense neuroplasticity of the brain. And language, in turn, is just a part of what we call “thinking.” If we can’t even pin down where the brain processes language, we are a far way from locating that mysterious entity, “consciousness.” That may be because it doesn’t exist in a spot you can point at.

Symbolic artificial intelligence, the Cartesian theater, and the shadows of mind-body dualism plagued the early decades of research into consciousness and thinking. But eventually researchers began to throw the yoke off. Around 1960, linguistics pioneer Noam Chomsky made a bold argument: Forget about meaning, forget about thinking, just focus on syntax. He claimed that linguistic syntax could be represented formally, was a computational problem, and was universal to all humans and hard-coded into every baby’s

head. The process of exposure to language caused certain switches to be flipped on or off to determine what particular form the grammar would take (English, Chinese, Inuit, and so on). But the process was one of selection, not acquisition. The rules of grammar, however they were implemented, became the target of research programs around the world, supplanting a search for “the home of thought.”

Chomsky made progress by abandoning the attempt to directly explain meaning and thought. But he remained firmly inside the Cartesian camp. His theories were symbolic in nature, postulating relationships among a variety of potential vocabularies rooted in native rational faculties, and never making any predictions that proved true without exception. Modern artificial intelligence programs have gone one step further, by giving up on the idea of any form of knowledge representation. These so-called subsymbolic approaches, which also go under such names as connectionism, neural networks, and parallel distributed processing take a unique approach. Rather than going from the inside out—injecting symbolic “thoughts” into computer code and praying that the program will exhibit sufficiently human-like thinking—subsymbolic approaches proceed from the outside in: Trying to get computers to *behave* intelligently without worrying about whether the code actually “represents” thinking at all.

SUBSYMBOLIC APPROACHES WERE PIONEERED

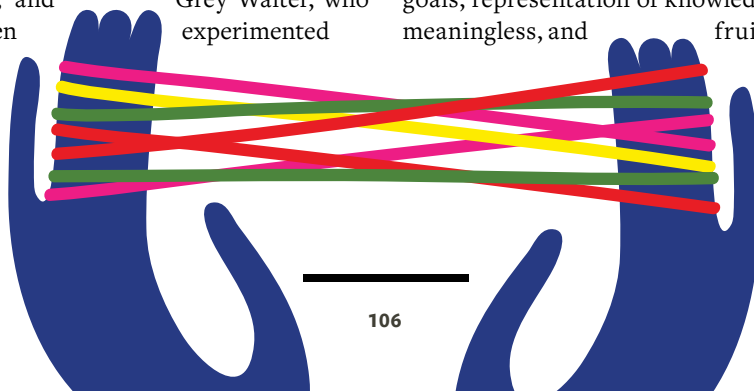
in the late 1950s and 1960s, but lay fallow for years because they initially seemed to generate worse results than symbolic approaches. In 1957, Frank Rosenblatt pioneered what he called the “perceptron,” which used a re-entrant feedback algorithm in order to “train” itself to compute various logical functions correctly, and thereby “learn” in the loosest sense of the term. This approach was also called “connectionism” and gave rise to the term “neural networks,” though a perceptron is vastly simpler than an actual neuron. Rosenblatt was drawing on oddball cybernetic pioneers like Norbert Wiener, Warren McCulloch, Ross Ashby, and Grey Walter, who theorized and even experimented with homeostatic machines that

sought equilibrium with their environment, such as Grey Walter’s light-seeking robotic “turtles” and Claude Shannon’s maze-running “rats.”

In 1969, Rosenblatt was met with a scathing attack by symbolic artificial intelligence advocate Marvin Minsky. The attack was so successful that subsymbolic approaches were more or less abandoned during the 1970s, a time which has been called the A.I. Winter. As symbolic approaches continued to flail in the 1970s and 1980s, people like Terrence Sejnowski and David Rumelhart returned to subsymbolic artificial intelligence, modeling it after learning in biological systems. They studied how simple organisms relate to their environment, and how the evolution of these organisms gradually built up increasingly complex behavior. Biology, genetics, and neuropsychology are what figured here, rather than logic and ontology.

This approach more or less abandons *knowledge* as a starting point. In contrast to Chomsky, a subsymbolic approach to grammar would say that grammar is determined and conditioned by environmental and organismic constraints (what psychologist Joshua Hartshorne calls “design constraints”), not by a set of hardcoded computational rules in the brain. These constraints aren’t expressed in strictly formal terms. Rather, they are looser *contextual* demands such as, “There must be a way for an organism to refer to itself” and “There must be a way to express a change in the environment.”

By abandoning the search for a Cartesian theater, containing a library of symbols and rules, researchers made the leap from instilling machines with data, to instilling them with knowledge. The essential truth behind subsymbolism is that language and behavior exist in relation to an environment, not in a vacuum, and they gain meaning from their usage in that environment. To use language is to use it for some purpose. To behave is to behave for some end. In this view, any attempt to generate a universal set of rules will always be riddled with exceptions, because contexts are constantly shifting. Without the drive toward concrete environmental goals, representation of knowledge in a computer is meaningless, and locked in the realm of data.



Researchers made the leap from instilling machines with data, to instilling them with knowledge.

For certain classes of problems, modern subsymbolic approaches have proved far more generalizable and ubiquitous than any previous symbolic approach to the same problems. This success speaks to the advantage of not worrying about whether a computer “knows” or “understands” the problem it is working on. For example, genetic approaches represent algorithms with varying parameters as chromosomal “strings,” and “breed” successful algorithms with one another. These approaches do not improve through better *understanding* of the problem. All that matters is the fitness of the algorithm with respect to its environment—in other words, how the algorithm behaves. This black-box approach has yielded successful applications in everything from bioinformatics to economics, yet one can never give a concise explanation of just why the fittest algorithm is the most fit.

Neural networks are another successful subsymbolic technology, and are used for image, facial, and voice recognition applications. No representation of concepts is hardcoded into them, and the factors that they use to identify a particular subclass of images emerge from the operation of the algorithm itself. They can also be surprising: Pornographic images, for instance, are frequently identified not by the presence of particular body parts or structural features, but by the dominance of certain colors in the images.

These networks are usually “primed” with test data, so that they can refine their recognition skills on carefully selected samples. Humans are often involved in assembling this test data, in which case the learning environment is called “supervised learning.” But even the requirement for training is being left behind. Influenced by theories arguing that parts of the brain are specifically devoted to identifying particular types of visual imagery, such as faces or hands, a 2012 paper by Stanford and Google computer scientists showed

some progress in getting a neural network to identify faces *without* priming data, among images that both did and did not contain faces. Nowhere in the programming was any explicit designation made of what constituted a “face.” The network evolved this category on its own. It did the same for “cat faces” and “human bodies” with similar success rates (about 80 percent).

While the successes behind subsymbolic artificial intelligence are impressive, there is a catch that is very nearly Faustian: The terms of success may prohibit any insight into how thinking “works,” but instead will confirm that there is no secret to be had—at least not in the way that we’ve historically conceived of it. It is increasingly clear that the Cartesian model is nothing more than a convenient abstraction, a shorthand for irreducibly complex operations that somehow (we don’t know how) give the appearance, both to ourselves and to others, of thinking. New models for artificial intelligence ask us to, in the words of philosopher Thomas Metzinger, rid ourselves of an “Ego Tunnel,” and understand that, while our sense of self dominates our *thoughts*, it does not dominate our *brains*.

Instead of locating where in our brains we have the concept of “face,” we have made a computer whose code *also* seems to lack the concept of “face.” Surprisingly, this approach succeeds where others have failed, giving the computer an inkling of the very idea whose explicit definition we gave up on trying to communicate. In moving out of our preconceived notion of the home of thought, we have gained in proportion not just a new level of artificial intelligence, but perhaps also a kind of self-knowledge. ☺

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Beer Domesticated Man

Early man chose pints over pastry. Wouldn't you?

BY GLORIA DAWSON

THE DOMESTICATION OF WILD grains has played a major role in human evolution, facilitating the transition from a hunter-gatherer lifestyle to one based on agriculture. You might think that the grains were used for bread, which today represents a basic staple. But some scientists argue that it wasn't bread that motivated our ancestors to start grain farming. It was beer. Man, they say, chose pints over pastry.

Beer has plenty to recommend it over bread. First, and most obviously, it is pleasant to drink. "Beer had all the same nutrients as bread, and it had one additional advantage," argues Solomon H. Katz, an anthropology professor at the University of Pennsylvania. Namely, it gave early humans the same pleasant buzz it gives us. Patrick E. McGovern, the director of the Biomolecular Archaeology Project for Cuisine, Fermented Beverages, and Health at the University of Pennsylvania, goes even further. Beer, he says, was more nutritious than bread. It contains "more B vitamins and [more of the] essential amino acid lysine," McGovern writes in his book, *Uncorking the Past: the Quest for Wine, Beer, and Other Alcoholic Beverages*. It was also safer to drink than water, because the fermentation process killed pathogenic microorganisms. "With a four to five percent alcohol content, beer is a potent mind-altering and medicinal substance," McGovern says, adding that ancient brewers acted as medicine men.

In fact, McGovern has found that the ancients used beer as medicine. Working with the Abramson Cancer Center of the University of Pennsylvania, McGovern

discovered traces of sage and thyme in ancient Egyptian jars. Luteolin, which is in sage, and ursolic acid, which is in thyme, both have anti-cancer properties. Similarly, artemisinin and isoscopolein from wormwood fight cancer, and were found in ancient Chinese rice wine. "The ancient fermented beverages constituted the universal medicine of humankind before the advent of synthetic medicines," McGovern says.

Beer also played an important societal role in bonding early communities together. It was popular at religious ceremonies, communal events, and celebrations. Brian Hayden, an archaeology professor at Simon Fraser University in Canada, believes that communal feasting fostered social bonding—and lots of beer was consumed during those feasts. Moreover, beer was thought to be a necessary component in the afterlife—throughout the Middle East, the dead were buried with jugs of frothy refreshments. It was even used as currency—in Egypt, the pyramid workers were paid in beer.

The beer thesis is not universally accepted, however, and the debate over its truth goes back to the 1950s. It was around then that Robert Braidwood, a leading scholar in Middle East prehistory at the University of Chicago, discovered sickles and hollow casts of grain in clay in the early settlements of the Natufians, who from 13,000 to 9,000 B.C. inhabited a region in the Eastern Mediterranean which is now Syria, Jordan, and Israel. Braidwood argued that domestication of wild barley motivated early humans to build permanent homes and switch to a sedentary way of life. Others have since extended this argument.

ILLUSTRATION BY DANIEL FISHEL

The great advantage of grain is that it didn't spoil like fruit or berries, and could be kept for months and used as needed. That motivated our ancestors to build permanent structures to store their grains, and homes close to their fields—which in turn led to the creation of villages. Archeologists have found stone silos dating from the Neolithic to the Bronze Age at sites in the Middle East.

Braidwood believed Natufians used the grain as food, and not for fermentation. But his work led to a symposium titled “Did Man Once Live on Beer Alone?” Braidwood's main opponent, Jonathan Sauer, a botanist at the University of Wisconsin, took a firm pro-beer stand. Sauer argued that growing grain with the primitive tools Natufians had would gain them a “pitifully small return of grain for their labor.” Natufians had to have been motivated by something more rewarding than mere food, Sauer believed. “Thirst rather than hunger may have been the stimulus behind the origin of small grain agriculture,” he said.

The symposium came to little consensus, but the debate continued. In the 1980s, Katz concluded from his own research that there was little evidence of bread's popularity among the ancient tribes of the Middle East, particularly the Levant. To bolster his claim, Katz used a well-preserved sample of carbonized plant remains from about 7,000 to 6,000 B.C. recovered from the Ali Kosh site in southwestern Iran,

where only 3.4 percent of the plants were domesticated cereals. If cereals didn't make up a large part of early humans' diet, what motivated them to begin to farm these grains? Katz argued the tribesmen were farming and storing the grain to make beer.

Today, the earliest chemical evidence of barley-based beer is at the Godin Tepe archaeological site near the Iran and Iraq border; it dates back to 3,500 B.C. But scientists believe that grain-based fermented drinks have a much longer history than that, and were used around the world. “It isn't just wheat and barley in the Middle East,” says McGovern. “It's rice in China—rice wine was made from grain, similar to beer. It's corn in the new world—Chicha is made from corn.”

How did man originally discover beer? McGovern and Katz theorize that man first learned to make some sort of gruel from barley. Then, natural yeast, likely supplied by insects, would have fermented the gruel, leading to a primitive form of beer. Beer was actually easier to make than bread. Once early humans sipped these ancient suds—whether barley, corn, or rice-based—they began cultivating grain, becoming sedentary creatures. “All of these grains could have jump-started civilization as we know it because you really have to stick around the whole year to take care of your plants,” McGovern says.

In 2010, Hayden and his colleagues set off to prove that the primitive tools of the Paleolithic era, such as mortar and pestle, were sufficient for brewing. The team created three different types of beer using the ancient grains—einkorn wheat, rye, and barley. “They all tasted a bit bland,” Hayden admits, but the brews had about 2.5 percent alcohol content—enough to pique early man's interest.

“The question is really a no-brainer,” McGovern writes. “If you had to choose today, which would it be: bread or beer?” ☺

Beer was thought to be a necessary component in the afterlife.

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CHRIS BUZELLI



The Periodic Stranger

When exile becomes home

BY DOMINIC PREZIOSI

MY ROOTS ARE IN a hilltop village west of Matera, where rabbit and boar run riot in the fields. Figs, apricots, and pears hang in heavy clusters, at eye-level and within easy reach. There, the local girls are famous for their calves, made firm and strong from hauling earthen jugs up steep and stony paths. The weather is as a rule clement, neither too humid nor too arid. The air smells of limes.

I think of it the way I think of the afterlife. It's an improbable place conjured in equal parts from the gauzy descriptions of my parents and my own wishful longing. The crumpled photograph my father kept in the inner pocket of his leather satchel told me little other than the size of his mustache at the time he was forced to leave the village for good. The shapeless gray forms in the background, which he swore were self-sustaining orchards of peach and black cherry, looked like nothing of the sort. No girls were evident.

I have lived on this rock in the sea since two days after my birth. In all the years since I have not seen any sign of game—an honor of classification I do not confer on the gray, greasy-feathered gulls that sometimes take perch on the higher crags. I have never been to the village near Matera, the one from which my father was exiled with his wife and me, his newborn son, for reasons he never made clear. There was something

about a fugitive Austrian soldier, a missing scabbard, a dented helmet, but the pieces have never come together, and by the time I was old enough to press for details my mother would interrupt with a shake of the head and say: Don't even ask.

This rock is really two rocks, which are linked by a short natural bridge that twice a day is quietly submerged by the tides and, several times a year, somewhat less gently overtaken by the storm-churned seas. Lampedusa—and I understand there is much to recommend about that island—lies three turbulent hours away by supply boat, a small, steel-sided skiff that brings lemons and whatever fruit might be in season, along with cheese, bottled water, flour, ink, medicine, tobacco, wine, and the occasional newspaper. The skiff leaves with the octopus my wife and I catch in submerged pots arrayed like the beads of a necklace drawn snugly around the island. Octopus fetches an adequate return, and this exchange of goods, this bartering, is how we make our living, such as it is. And as it is, we need nothing more.

“See you in two weeks, God willing!” shouts Pallucci, the short, sun-burned captain, as he fires the outboard and guides his dented craft back into the open sea.

I still have my father's books, his writings, and the crumpled photograph of him. I have the education my mother provided, measured in the painstaking hours she took in teaching me to read, calculate, sing, and sew. I have a wife with whom I still occasionally make love. I'm seventy-two years old, but I know now that I know less than ever of what it would take to live in the world.

My father always implied that others decided his exile, an unjust punishment handed down by petty bureaucrats. Yet, what if he were its sole engineer? What if his exile was self-imposed? In that case, he made me a party to an obsession I had no say in indulging.

At dawn a pair of figures appears on the other rock. They are silhouettes against the eastern sky, only harder, like pillared extensions of the island itself, two stone fingers thrust up from the earth overnight. My wife asks, “Is that a rifle?”

I follow her concerned gaze and spy the barrel of a weapon taking shape above the shoulder of one of the men. It is not like any firearm I have ever seen, but that is saying little. My wife passes me the single-bolt carbine my father brought here with him, its black stock polished smooth from years of handling. It seems to weigh more than the painted wooden boats we drag into the water every day in checking the octopus pots. Surely this mysterious pair must know someone else is here; signs of habitation are all around, from the strung nets on which we dry our meager catch of fish to the pecking chickens that roam freely about—to say nothing of the tricolor Italian flag fluttering atop the rock on our side (my father may have lost his home, but not his patriotism). One of the men now lifts a pair of heavy binoculars to his face, makes a great show of taking in the surrounding sea, then swings back to train them directly on us.

“Fire a warning,” my wife urges.

Before I can answer one way or another, the man lowers the binoculars and raises his right hand high in greeting. There seems to be no hostile intent, and if such a simple gesture seen from this distance can be said to seem friendly, then friendly it is, and I feel I have to accept it as such.

“No,” I answer, knowing my father would have reacted the same way. “Let’s find out why they are here.”

SUFFICE TO SAY YOU LEARN a lot about a woman when you are the only inhabitants of a rock in the sea. My wife is as capable of pulling in pots of octopus as I, and she has never hesitated in sinking her teeth between the eyes of the eight-armed creatures to sever the main nerve to the brain. (The salty, rubbery texture and the sudden pop—like biting into the thick-skinned plums Pallucci sometimes brings, but not quite—have troubled me since youth. Still, this is the quickest and most efficient method of dispatch.) She knows how to read the colors of the sky, and if there’s a pale, pink-orange hue at the southern horizon as the sun sets, she’s quick to haul our three painted boats to higher ground before the thunder sounds. She picks bits of battered shell and crab leg from the wrack of the high-tide line and turns it into chicken feed, a process I liken to alchemy.

After my father died, my mother decided I needed a wife and made the treacherous journey to Malta.

“To use the phone,” she answered simply, when I asked why she was going. I was seventeen then, and I knew from her tone that that was all the information I would get. (I knew that she wasn’t lying, either, since no lines had yet been installed in Lampedusa.) Six months later, a boat appeared on the horizon, and as it came closer I could make out two figures aboard. One proved to be a girl, who, from her appearance, I determined was not much younger than I. She had black hair that fell between her shoulders and wide, flat feet that turned out, like paddles, when she walked.

I found her beautiful, and when my mother confirmed that we were to wed I had no objection. The captain of the tiny boat who’d brought her—an ancestor of Pallucci’s—quickly muttered the vows and declared us married, even as he seemed to be shoving off. Later, my mother—holding a hand-hewn crucifix above our joined heads—blessed us in her church Latin. We hiked to the other rock for our honeymoon, and though the shed in which we spent our first nights has long since been lost to the winds, I will never forget the sight of my new wife’s face bathed in the moonlight that seeped through the window hole, the way she whispered, “Sixteen” when

Octopus fetches an adequate return, and this exchange of goods, this bartering, is how we make our living, such as it is. And as it is, we need nothing more.

I asked her age, or how we joined ourselves repeatedly in the three days that followed. “Twenty-one times?” I might still ask her, all these decades later, and she will touch her rough, callused hand to the inside of my thigh and correct me with a smile that reveals the only two teeth remaining in her blackened gums: “Twenty-six.”

We would have no children, it soon became apparent, a prospect that seemed to trouble us less than it did my mother. “She’s as barren as this rock!” she said of my wife, regret over the intemperate remark immediately flooding her face. Still, even on her deathbed, the light rapidly leaving her eyes, she managed to extract a promise from me that we would keep trying. And we did. We do.

THE NEWCOMERS CLAMBER DOWN with a grace that makes me think they have done this kind of thing before. The one in the lead—the one with the binoculars, not the weapon—raises his hand again. His face, flat and broad as a table-top, splits cross-wise in a smile showing many even, white teeth. They look like tiles in his mouth. His skin is slightly freckled as if by the sun, and his hair—like that of the other man—is cut close against the temples.

“Please don’t be afraid,” he says in formal, clear Italian. “We come in peace.”

“I’m not afraid,” I inform him. “We live in peace.”



This gets a laugh, from both of them. My wife looks up at me with a mix of fear and fury. She wears her honor proudly, and she does not like to feel as if we have been belittled.

The men have the kind of clear, colorless eyes that in the books my mother made me read always signaled malevolence of character. Both are clad in smooth-textured black pullovers that fit snugly and are banded at the wrists. On their feet are thick-soled boots whose tops and sides are made of a mesh that looks metallic, silvery, like the sides of Pallucci's skiff. Each wears a wide-banded watch with a large face—one on his right wrist, the other on his left.

"Signore," says the one with the binoculars. The smile has yet to leave his face; the other one seems to be evaluating the immediate surroundings. "Please, sir. Do you mind if we take a look around?"

"What for?" My wife's distrust is instinctive. With her squinting eyes and black mouth, she is suddenly every bit the crone. She rests her hands on her waist and plants her outward-turning feet wide: Just try to pass through me. She must sense something deeply in her bones to be acting in this manner. I try to placate her by placing a fingertip on her wrist, but she will have none of it, and brushes it off.

The one with the weapon speaks. "What for?" he repeats. The momentary amusement he showed earlier has vanished. "What if we say we're in search of fugitives that you and your husband are hiding on this island?"

"Criminals?" She turns to me. "Hiding?"

"Please," I whisper. "Calm down."

"Signora," the first man says. "Listen to your husband. Why get so upset? We look around a bit, turn a stone or two, and we leave. You'll never know we've been here. Understand, please—" His smile never falters, but is it really a smile? "Understand that our work is serious. These fugitives are dangerous. Not just to you, but to millions of people, all over the world."

"What do I care about the world?"

"What did I tell you?" the one with the weapon says, turning to his companion. "We're better off not even asking. If they're not going to cooperate, then what's the point in being polite? Their understanding is primitive. The solitude—they're disconnected from reality."

"Sir," I say, interjecting. "We are not disconnected, I assure you. My mother, she educated me. We can read—we read the newspaper a couple of times a month." I swallow, hoping for my wife's support, or that the one with the binoculars will understand. "We know about things that are happening. Events. We have visitors—" and here I am thinking of Pallucci, who sometimes brings news of the world—"who tell us?"

"Visitors?" asks the one with the binoculars. His colorless eyes reflect the high clouds. "Maybe, with a look around, we'll find these 'visitors.' What do you say?"

SOME YEARS AGO WE endured a storm unlike any I had ever lived through. My wife and I watched from the shelter of our dwelling as huge

silver claws of lightning pulled the night apart, ripping it from top to bottom and side to side. The thunder with its heavy detonations moved closer with each blinding flash, and I thought of all the descriptions I'd read of rolling artillery advancing over the plains. My wife held my hand between hers, and I swear I could feel the tendons and muscles beneath her skin quiver and jump with every concussive blast, as if her nerves were somehow directly attached to whatever dynamo was powering this fury. When the sky finally gave up its burden, the rain it released didn't fall straight down but came in waves, as if over the bow of a ship plowing through mountainous seas. Rivers formed; we heard the cascading waters in the darkness and wondered whether they might sweep us down the side of the rock and into the ocean. It went on for hours. We didn't sleep.

Only at dawn did the tempest subside, and in the weak but growing light we made a preliminary tally of the damage. The chickens had vanished, as had the goat Pallucci had brought us only a month before. My father's tricolor banner dangled in shreds from its mast. Water still ran in

the newly carved channels, carrying silt and gravel and shells and the fragments of any number of the small, ordinary objects that had accumulated since my parents' long-ago arrival. One of our boats lay in pieces against the rocks, and I surmised it had been dragged from the shore.

"We are not disconnected, I assure you. We read the newspaper a couple of times a month."

"We're alive," my wife said, kissing me furiously, her tongue familiar yet somehow mysterious and unknown against mine.

Pallucci reached us later that day, a journey he clearly regretted having made. His face was white with terror: The trailing winds, he told us, had generated waves so high on the open sea that he feared the ocean would swallow him. We located a bottle of wine, and then another. Only after the third did he begin to laugh. He couldn't go back that night, of course, and he told us later that his absence had sparked less worry than vindication—his relatives had warned him it was too dangerous to go out. "They would rather be proven right than be happy at my survival," he said. "They'd rather I drown so they could say, 'See, we told him what would happen.'"

We made repairs in due time. We replaced the chickens and goat. I re-stitched the flag. My wife shaped new pots, swept away the sand and grit the storm had deposited in our doorway, replenished the stores of feed. I began to see things with a fresh perspective, telling her that it was like starting anew. Sometimes it's good to have our lives turned inside out, I said; it helps us see what we have within us.

She rested on her broom a minute, looking out over the water. "I thought," she said, "that we might die."

But we didn't, I told her; look at us now!

She resumed sweeping. "Yes. Maybe. I suppose you are right. But someday one of us will die. You first, me first, it doesn't matter. And the other will be left alone."

It was a prospect I'd contemplated, of course, but never did it sadden me as apparently it did her.

"We'll do it together," I blurted, "so that neither of us will be left alone." In that moment I meant it: There clearly could be no other way. I listened then to the rasp of the broom on the stone while a single, dark-gray seagull wheeled overhead. If I thought it strange how talk of a new beginning could so quickly turn to the subject of our inevitable end, I don't recall.

Yet I do remember thinking this: Wouldn't it be better for her to go first? If I were to face the facts rationally, to dispense with emotion, wouldn't this be the preferable development? To be truly alone, if only for a little while, on this blessed isle of beloved solitude. To take the days one at a time, by myself...

I felt closer to my father at that instant than I ever had when he was alive.

THE MEN SCATTER THE chickens and tip the bins of feed. They pull down the rope to which the flapping laundry is pinned. My wife arranges urchins on the single colorful platter she brought with her when she came here—"It reminds me of my birthplace," she says—and this they knock over too, and when it falls to the ground it cleaves cleanly down the center. A sound like a wave sucked back toward the sea escapes her. The one with the weapon offers a thin smile, then—for good measure and with apparent relish—overturns the table on which the platter had rested.

They work with a grim sort of happiness, seeming to take pleasure not in the destruction itself but its efficiency. The one with the weapon begins to chant something, a barely audible incantation that seems almost religious—though it is perhaps less like a prayer than something self-motivational. The intensity of the chant rises with the speed of his great, sweeping arm, which moves back and forth like a scythe across the shelves of our rough-hewn kitchen and along the mantle beam—reclaimed driftwood shot with the perforations of bore worms—that is mounted above our cooking fire. Down go jars, pots, earthen canisters of salt, and the tiny vials holding the tinctures my wife uses to dye fabric.

"What's in here?" the one with the binoculars says, stopping beside a curtain hung in a crooked doorframe.

"It is just the bedroom," I say.

He nods to his companion, who uses the weapon to pull the curtain back. They take a moment to regard what's revealed—which, I can admit without shame, isn't much. I could have told them all they'd find: An iron bedstead holding a flat mattress filled with ticking that's decades old, four flat pillows brown with sweat, a striped blanket so smooth from the nightly turn of our bodies that it's almost see-through. The crucifix that was my mother's hangs above the headboard on the stippled, stucco-like wall.

“God bless you,” the one with the binoculars says, “for making so simple a home.” His distaste is unmistakable.

“God,” my wife spits. “How dare you even say ‘God!’ ”

The one with the weapon uses the toe of his strange mesh boot to lift the bed frame. “No trap door? No cellar?”

“Cellar?” I almost have to laugh. “Do you think it possible we could have dug a hole into this rock?”

“Any tunnels?” the one with the binoculars says. “Hide-outs? Spider holes?”

“Spider holes?” I look at my wife.

“Places where you might store things to keep them dry. Places that could serve multiple purposes. Places,” he says, “for a fugitive to hide.”

“Caves,” the one with the weapon adds. He has taken the crucifix from the wall and is running his fingers along its vertical shaft.

“The only cave we know of is underwater half the day,” my wife says, “and a moray eel twice the size of your leg calls it home. You’re more than welcome to look inside it. I’ll even take you there.”

They ignore her. The one with the weapon returns the crucifix to the wall and resumes the strange, wordless chant, which grows louder and more insistent with each syllable.

The other one leans close. He has a distinct smell, an alien odor unknown to this island. His words are for me only. “All we need is a little help. You don’t have to stay here living like this, you know. A little help, and we give you back to the world.”

“If only it were so simple,” I tell him.

LONG AFTER MY FATHER died, I would ask my mother to tell me the true account of their exile. By this time her memory was failing and her conversation had a way of wandering off into lazy whirlpools of unrelated and unverifiable recollection. I knew that if I wanted to have the facts in my possession, the facts of how this place came to be my home, I needed to collect them from her before it was too late.

Night after night, once the dinner plates were clean and the stars had stretched their blanket across the sky, I tried to steer her back to the hilltop village outside Matera. She cited with maddening consistency the details I already had used to draw my own half-formed picture—the abundance of game, the fruit hanging in clusters, the strong-calved girls, and the air that smelled like limes. The Austrian soldier, the missing scabbard, and the dented helmet all made their requisite but unconnected appearances, and I began to suspect my mother of a willful obstinacy in withholding the vital linking information, as if with eternity in sight it was now more necessary than ever to stick to the story as she and my father had always told it.

One night I finally asked her directly: Was the Austrian soldier my father? And if so, why was it that the man I understood to be my father was the one who was exiled? Or did he do it on his own, choosing to absent

himself from the rest of the world?

My wife—having admitted to puzzlement over my sudden interest in a matter she found unworthy of pursuit—made a disapproving noise in her throat and sidled away to make the coffee. I could hear waves gently slapping the base of the rock. My mother chewed on her gums. It wasn't clear she had heard the question. But just as I was about to ask it again, she began to speak.

"There was an Austrian soldier," she said.

"Yes?" I leaned forward, detecting something new in her tone, an acquiescence that had not been there before. I would learn it all now.

She turned her gaze to the nighttime sky. She coughed, then ran the back of her hand across her mouth. "A missing scabbard," she continued.

"And a dented helmet."

The last words escaped from her with a stubborn, wheezing sound.

"But," I persisted, "but was he my father?"

Once more she looked into the nighttime sky, where a small light made steady progress from west to east. "I see those up there from time to time and wonder what guides them. Or what's in

them. Could they see us down here, on this rock? Maybe our cooking fire?"

My wife returned, the clattering espresso pot clattering between her rag-wrapped hands.

"But the soldier," I persisted.

"He didn't have to leave," my mother said.

"Who? The soldier?"

"He didn't have to stay."

These riddles were maddening, "Who?" I demanded again.

"That's enough now," my wife said, putting the pot before us. She looked at me and shook her head. I watched my mother follow the blinking light—I'm not sure she ever knew of airplanes—until it was no longer visible. Soon we drank our coffee. It was as close as I ever got to learning anything for certain—which is to say, it wasn't close at all. She may as well have told me, as she did when I was a boy: Don't even ask.

The Austrian soldier, the missing scabbard, and the dented helmet all made their requisite but unconnected appearances, and I began to suspect my mother of a willful obstinacy in withholding the vital linking information.

THE STRANGERS ARE NOT interested in the underwater cave, once they confirm its inaccessibility. Perhaps, too, my wife's mention of the moray has dissuaded them. But they explore the rest of the island with relentless attention, bringing me along to turn over rocks or peer into crevices while

the one waits alongside with his weapon raised. Much of the morning passes in this fashion. They are meticulous. They are patient, and not easily discouraged. The sun moves higher, and they take off their black pullovers to reveal muscled arms and, beneath tight undershirts, the spread of their torsos. I haven't seen them eat or drink anything since they came down to accost us all of those hours ago.

"What's this?" they both demand to know when we reach a small outcropping that becomes visible only after passing behind the opposite rock. Two slabs of roughly the same size lay side by side, the dusty space between invaded by spike-stemmed weeds with flat, serrated leaves. I explain that we are at my parents' gravesite.

The one with the binoculars spits what must be a curse in his language. His partner seems unfazed by the sudden lack of composure and lowers the weapon so he can wipe his brow.

"You're sure you've shown us everything?" the one with the binoculars says. When I nod, he kneels on one knee at the foot of my father's slab, slips a folding knife from an all-but-hidden pocket, and scratches in the dirt beneath the stone. After a minute or so of this, he seems satisfied, although I cannot fathom his intent. He closes the knife, stands, and looks out over the ocean. "Let's go."

I'm hustled back to the other rock, where my wife waits. The worried look I see from far away is transformed once more to anger as we approach. The strangers sit us down.

"Listen, the both of you," says the one with the binoculars. "If you've been anything less than truthful, we'll find out."

"Know now that we know you're here," the other one says.

"What he means is that no one is ever truly alone anymore. Including you. Someone will always be here, or just over the horizon or behind that cloud, which is still close enough to keep an eye on you. You can be sure of that."

They climb down the side of the rock to where they've hidden their craft, knocking over some octopus pots for good measure. My wife shouts a parting shot: "That's right! Go back to the whores that birthed you!"

I try to hush her, but the strangers don't respond anyway. The one with the weapon activates the engines—a quiet, medium-pitched hum—and then the vessel races north, trailing a frothy white wake. Before long, they are gone, lost on the vastness of the flat sea. They might not have even been here at all, except, of course—and I can see it in my wife's tears—they have.

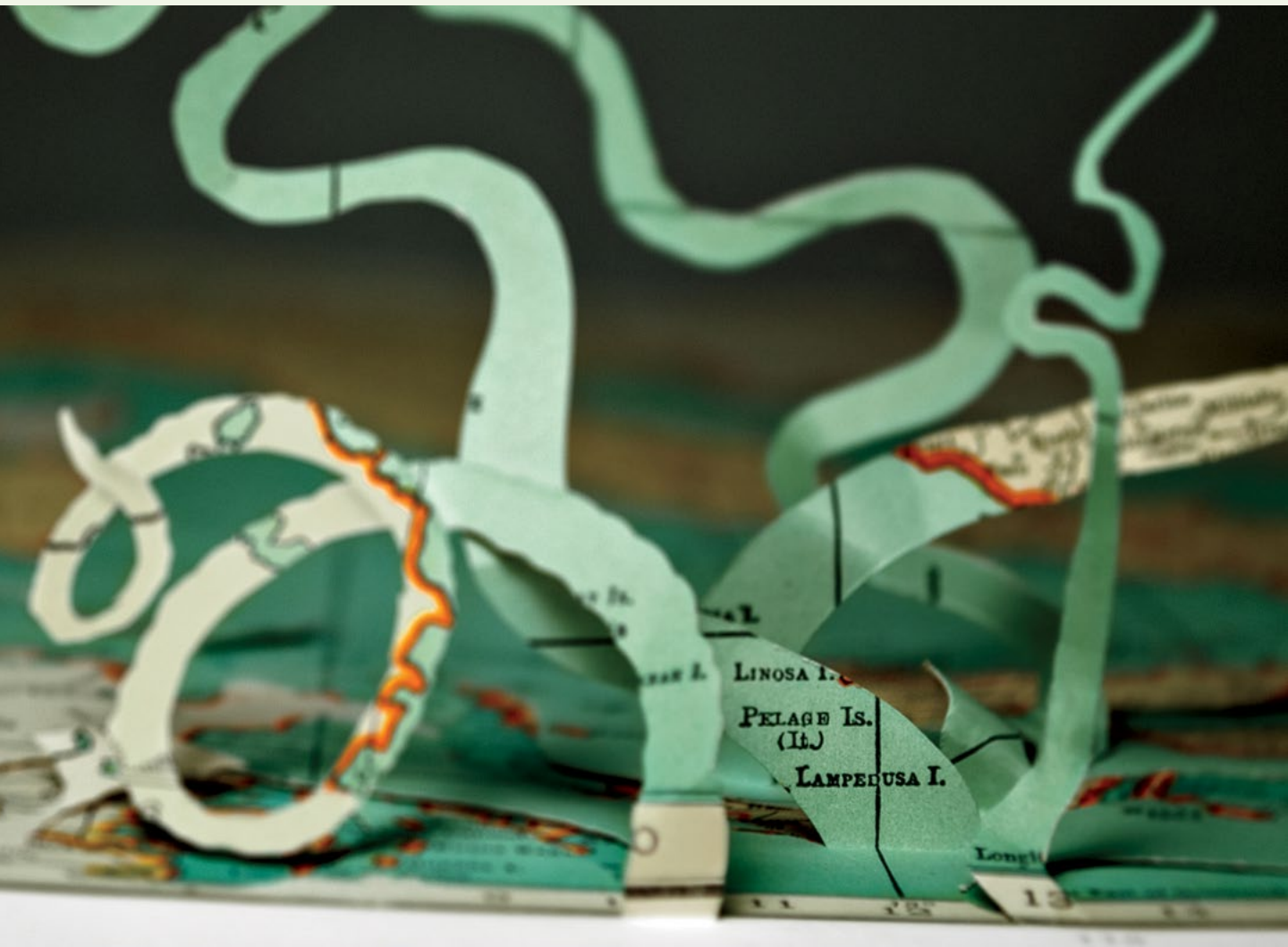
WHEN MY MOTHER WENT to Malta to find this woman who would become my wife, I remained on the rock island alone. She was gone for more than a month, my mother, and in that uniquely solitary time I adhered to the regimen in which I'd been raised, a routine of necessity when one has only oneself on which to rely—for survival and for sanity.

I began my mornings as I always had, as I'd been taught to, by pushing

out into the moderate depths of the close sea, hauling in the clay pots I'd lowered twenty-four hours earlier, and returning to shore. Weighted with writhing catch and sloshing seawater, these heavy, homely pots represented not just my labor but the growing body of my good work—the work done daily over the course of a lifetime that was just then beginning to lengthen, like a growing yet flexible muscle. This was the work I wanted to do, the work that resulted in someone, somewhere, having food, the work that becomes good work by dint of sheer, unwavering attention to its completion.

The only thing I added to this routine in my mother's absence was a trek to my father's tomb—still just a single slab up there at the time—on the small outcropping hidden by the opposite rock. I can't say I prayed, exactly, unless handling the increasingly battered photo of him—his mustache eternally dark and thick, the shapeless forms in the background forever giving fruit—can be considered prayerful. Whatever it was, however, it seemed to increase the state of peaceful contemplativeness I'd begun to feel.

At night I'd check the cistern-like tank in which we'd keep the captured octopus until Pallucci came. Once, a couple of anxious, unfruitful days



after I'd shipped off my most recent catch with him, there was only one animal in there. He was a big fellow, maybe twenty pounds or so. The pots remained empty for a day or two more, a fact I attributed to the stormy weather to the south, a system that seemed to hug the horizon without getting any closer but that nevertheless spawned waves that churned the immediate depths and sent my prey into hiding. Such spells weren't unknown to me.

In any event, the big fellow was alone in that stone tank for several nights, and I soon found myself whispering to him as if we were fellow travelers now stranded here, the only survivors of some unidentified apocalypse. After looking in on him I'd replace the lid, a plank of plywood that had washed ashore some months earlier, and then go to bed. In the mornings, however, I began to notice that the bin of shells nearby would be disturbed. At first I assumed it was the seagulls, except that there was never any guano or footprints to suggest their presence. Yet some of the shells—which my mother saved to spread on the paths or convert into some helpful tool or another—would be shattered, or would have a single hole in them as if pierced by a probing beak.

My father always said that the octopus is as smart as any animal that walks on land, and this comment came back to me one evening when I checked on the big fellow. I looked down at him in the clear, cold water of the cistern, then moved the lid back into place. Rather than go to sleep, I decided to stay up and see if what I theorized was happening could in fact be true.

The moon was at its apogee when I heard something rattle. I inched forward. With a noise like someone clearing his throat, the lid began to slide across the stone. In the moonlight I could see one searching arm make an appearance, and then another. Each gray appendage advanced individually, with slow but unstoppable progress. Soon all eight arms had made purchase on the outer edge of the tank, and then the thing hauled itself up, seemed to look around, and, still dripping water, lowered itself to the ground.

I knew octopuses could move across land, but the speed and singleness of purpose that this one exhibited nonetheless came as a surprise. He—and by now I had officially settled on this more specific pronoun—he reached the bin of shells in a matter of seconds, pulled himself up, and dropped himself on top. Now and then I heard a crack as he used his sharp, powerful tooth-like beak to search for any remnants of food. Such strange physical features in this prehistoric animal! But then again, strange maybe only to me. This went on for some time—twenty minutes, maybe more—until he seemed to have satisfied his curiosity. He pulled himself out of the bin, slithered across the stony ground, and returned to the tank. A moment later I watched the plywood lid slide back into place, the grating sound that this produced the only disturbance in the otherwise silent, moonlit night.

I've since witnessed an octopus pull a cork from a jug. I saw one sit up and watch the seagulls turning against the sky, as if contemplating

flight itself—or maybe calculating the odds of snatching one from the air. I've seen their severed arms set off on their own, wriggling instinctively toward the sea before expiring with an almost audible gasp. I've seen them generate new arms, sometimes within minutes. These things once struck me as a kind of miracle, since clearly they are not supposed to happen. But happen they do, and with an inexorability that suggests there is perhaps a lot more going on in the universe than I or anyone else can ever be aware of.

When I see the tears on my wife's face, I want to tell her about this. It is something I've always kept to myself, the story about the octopus. Look, I want to tell her—look at the things we don't think can happen but do. Look not at what we know but what we don't. There is probably something else going on, something we might not be able to explain or identify, but something we must allow ourselves to contemplate, even if we don't know what that thing is. Even if we can't possibly imagine it, we have to try to imagine it, even when it seems pointless to do so. Look at us—how did we get here, and why are we still here, the two of us alone on these rocks yet in need of no one else? I want to tell her because if it is not voiced then it is not heard, and if it is not heard then it might as well not even be contemplated in the first place.

But I remain silent. There is no such thing as true solitude, my father said, a declaration echoed by the pair of strangers who appeared from nowhere at dawn. But now, having kept this story to myself for so long, I realize there can be, if we allow it to take hold of us. We can put ourselves into exile. My wife silently sets about restoring order. What is going through her head, I cannot say. The rasp of the broom and the grunts of her labor tell me she is present, but she might in fact be on an island of her own.

The morning after I observed the startling journey of that solitary octopus, I gathered his enormous body against my chest. We might have looked like awkward dancers the way we embraced, heads bent back, all of our arms intertwined. He smelled of brine and of the coldness of his species, unchanged over millions of years. I wasted no time in delivering the killing kiss, my teeth piercing the salty outer membrane and snapping the root that made everything inside work. There was a shudder of what seemed like surprise, and then everything was still.

The blood of the octopus is blue, and that was the color of my skin when my mother returned later that day, bringing to an end the only time there was no one to bear witness to this, the fact of my living. ☹️

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The Harshest Return

Living in Antarctica is hard; coming home can be harder

BY ALEXANDER KUMAR



PHOTOGRAPHY BY THE AUTHOR



WHEN I RETURNED TO ENGLAND, I knew that Antarctica had distorted my personality. The rolling green hills of Derbyshire, near where I grew up, looked different than I recalled. At a reunion, I found it difficult to connect to my friends and relatives. I had trouble choosing between double skinny latte coffee or caramel mint mocha. My mood fluctuated between anxious and underwhelmed.

The feeling of home is ingrained deeply into most of us. It sometimes feels indelible. When we are submerged into an alien environment, some place very different from the home we're used to, we may feel helpless, irritable, or ignored. Our normal reinforcements no longer exist, and our locale is at odds with our identity. We experience culture shock. But we humans are expert adapters, and faced with a new environment, we are able to adjust and survive.

For many of us, however, that is not the end of the story. When we return home, we are again confronted with a very different environment—and the culture shock that comes with it—except, this time, disturbingly, it is our own home that we cannot cope with. Psychologists call this response reverse culture shock, or re-entry syndrome. An early record of the syndrome dates back to a 1944 paper on veterans returning from World War II, and it continues to be studied today. The syndrome is characterized by feelings of loss, disorientation, and isolation. Some feel the urge to run away. Others develop patterns of substance abuse, mood instability, apathy, and increased risk-taking. Psychologists know relatively little about who will develop these long-term problems.

My own encounter with re-entry syndrome began after I spent nine months in Antarctica, as part of a long-running experiment by the European Space Agency (ESA) to simulate the living conditions that astronauts will encounter on a manned mission to Mars.

I called my Antarctic outpost “White Mars,” but my motivation wasn’t limited to astronauts and space travel. At the hospital where I work in England, I watch over some patients who have suffered neurological injuries, who cannot speak and who are imprisoned in their bodies by disease or illness for long stretches of time. I thought that if I experienced something similar, I might be able to better help them handle the sense of isolation, and the transition back to normal life.

I had joined a long and illustrious history of those who took a timeout from civilization, even if briefly. A fabled newspaper advertisement from the early 20th century aimed to recruit people to join explorer Sir Ernest Shackleton on a trip to Antarctica. It read: “Men wanted for hazardous journey. Low wages, bitter cold, long hours of complete darkness. Safe return doubtful. Honor and recognition in event of success.” Incredulously, it is said that hundreds or thousands of people signed up. Little has changed. This year, the Mars One project, which aims to send four human settlers on a one-way mission to Mars in 2022, received more than 200,000 applicants. There is something tantalizing, it seems, in the great beyond. Not much thought is spared for the return journey.

My own destination was Antarctica—under extreme conditions. I was doing what is called an “overwinter,” which means that there was no possibility of leaving until the time allotted for my visit had passed, regardless of reason or need. I was stationed at Concordia Station, a joint French-Italian initiative located in the Eastern Antarctic Plateau, the world’s driest, coldest, and largest desert. It’s a pancake expanse and a featureless landscape. Being only one of three inland Antarctic stations, it is as far away from civilization as anyone can get. The last plane departed my outpost in February 2012, leaving me isolated with 11 other men and one woman.

Some of us had come to Antarctica for adventure and knowledge gained from the experience. Others wanted

Disturbingly, it is our own home that we cannot cope with.

money, realizing that they could earn a salary without spending any of it. A few just wanted to disappear.

We spent three of the next nine months in 24-hour darkness as the continent metamorphosed around us, its icy coastal area expanding to roughly twice the size of Europe. Temperatures dropped to below -105 degrees Fahrenheit (-76 degrees Celsius)—as cold as dry ice. Plastic earphone cables snapped like breadsticks, corneas of the eyes might freeze and fracture, and ice crystals might form in airways, potentially causing the lungs to bleed. Daily life was a monotonous slog peppered with moments of beauty and flashes of terror. The isolation was complete. Once, NASA headquarters patched us in for a live video call to astronauts onboard the International Space Station. When Dutch astronaut Andre Kuipers turned his camera around to face planet Earth, I gasped, feeling utterly separated for the first time in my life from the world on the screen.

As the medical doctor among us, I managed my team's mental and physical wellbeing. By May, I began to see psychiatric symptoms poking through. Having signed non-disclosure forms, I'm not at liberty to elaborate, but I can tell you that in the empty darkness of the Antarctic winter, people's personal monsters come out to play. I made friends with the monsters in my mind, but some people did not. They vanished into their rooms for a week or two. I tried to predict who would struggle and eventually snap. But I got it wrong. There seemed to be no formula. This was something the ESA was interested in, too. If they could tell which category of person might not adapt, and suffer upon return, they could make safer astronaut choices. But the question was not an easy one to answer, even for someone who was observing subjects day by day.

Fortunately, the fine line as to when it was appropriate to turn observation into treatment was often obvious.

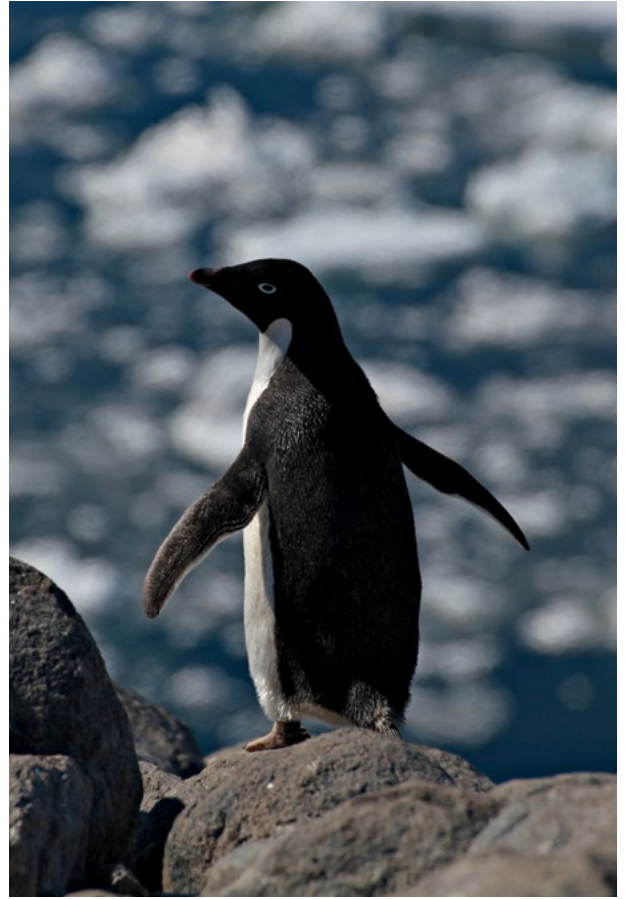
I was glad to return home, but I felt subtly detached. These feelings grew as the first weeks passed. While on walks through the nostalgic English countryside, I felt distant, as if I had lived a previous life, perhaps having been reborn by the new experience.

It took a great deal of effort and discipline to re-adjust: I had to force myself back into my old life. Even when I felt tired or uncomfortable, I kept appointments, worked, and managed to start living again. It took months before I felt normal, and longer for my urges to return to the ice to subside.

There were many valuable lessons I learned from Antarctica's harsh education. After the trip, when I visited the house that I learned to walk in as a baby, I saw it with new eyes—and today I feel more connected to it than ever before. Some react differently, choosing to straddle home and away without ever fully integrating into either. A fellow crew member who went down with me to Antarctica has returned for his fourth winter at Concordia Station. His home may no longer be his home—his identity has been transformed.

You won't know how your personality will adapt until you push it. I'm glad I did. T.S. Eliot wrote it best in the final of the *Four Quartets*: "We shall not cease from exploration and the end of all our exploring will be to arrive where we started and know the place for the first time." ☺

ALEXANDER KUMAR is a British medical doctor and scientific explorer.

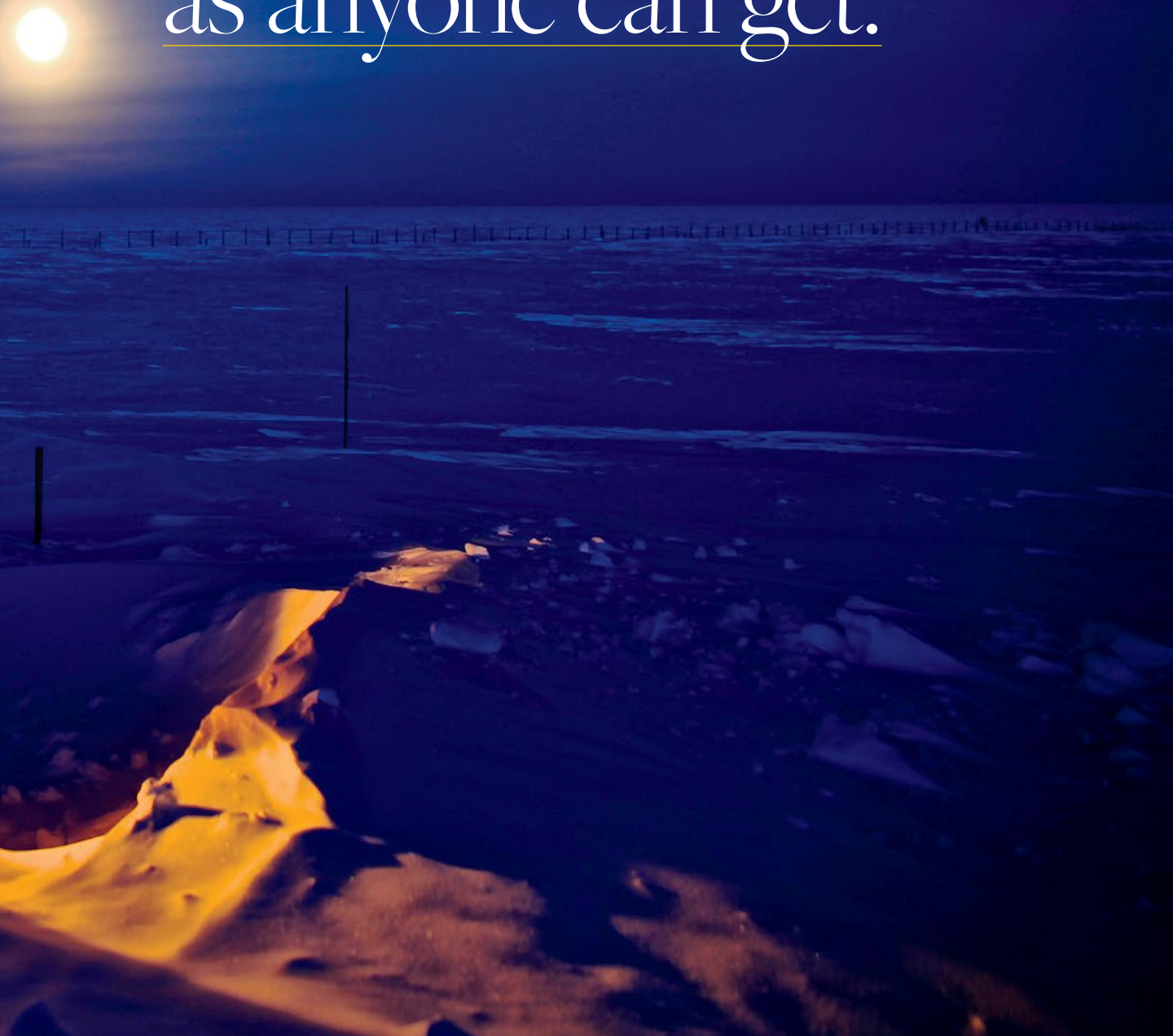


CONCORDIA ANTARCTIC RESEARCH STATION

Above, a crew member sets up scientific equipment on a tower, an Adélie Penguin stretches its wings, and author Alexander Kumar poses beside signposts on Earth's southernmost continent.



Only one of three
inland Antarctic
stations, it is as far
away from civilization
as anyone can get.





TEMPERATURES IN ANTARCTICA DROPPED TO -76 DEGREES CELSIUS, AS COLD AS DRY ICE

Above, small icicles form on author Alexander Kumar's beard.

Right page: Stars sparkle in the clear Antarctic sky.





The Termite and the Architect

Animal homes resist our understanding

BY LEE BILLINGS

IN 1991, THE MULTINATIONAL Old Mutual investment group approached the Zimbabwean architect Mick Pearce with an audacious assignment. The group wished to construct a retail and office complex called the Eastgate Centre in Zimbabwe's capital city of Harare that, at 55,000 square meters, would be the country's largest commercial building. What Old Mutual didn't wish to do was pay the high cost of air-conditioning such a massive space. Could Pearce, working with the Arup construction firm, devise a design that relied solely on passive, natural climate control?

Pondering the problem, Pearce found inspiration in the termite mounds that dotted the savannas across his country. The largest mounds could reach several meters in height, dwarfing the legions of termites who built them just as a modern skyscraper towers over an individual construction worker. Each funneled air underground through networks of channels into a spherical nest that housed termites by the millions, and even larger numbers of fungi and bacteria. In all, a typical nest contained about a small cow's worth

of hot, breathing biomass. Based on the ideas of the Swiss entomologist Martin Lüscher, many researchers believed the mounds acted as air conditioners, maintaining a nest's pleasant temperature, humidity, and oxygenation by continuously exchanging hot air rising from deep inside a colony with cooler drafts diffusing down from the surface. According to Lüscher, the mounds' towering height allowed the "hot breath" of the colony's biomass to drive this convective exchange. Lüscher's theory came to prominence in 1961, reaching a wide audience through an article in *Scientific American*.

Imagining the mounds as air conditioners, Pearce drew up plans for a masonry-insulated building of large, open spaces shot through with elaborate ductwork and clusters of tall heat-exchanging chimneys. The ducts would channel air through the building, while the chimneys would siphon heat from the bustling occupants and machinery during the day, venting it up and out to cool the building after dark. To get the design and engineering just right, Pearce ultimately became a bit like a termite himself, descending

ILLUSTRATION BY CHRIS BUZELLI

Most of today's biomimicry barely mimics biology at all.

from his lofty architect's perch to personally labor at the construction site, helping to cast and install some of the masonry blocks with his own two hands. The Eastgate Centre debuted in 1996, achieving world renown for its pioneering "biomimetic" design that regulated its temperature at a fraction of the cost and energy of conventional buildings of comparable size.

There was just one problem. While the Eastgate Centre did work as planned, the mounds on which it was based functioned in an entirely different manner. Around the same time that the Eastgate Centre opened its doors, the American scientist Scott Turner was using propane pumps and arrays of tiny electronic sensors to painstakingly measure gas exchange throughout nearly 50 South African termite mounds. He found that the mounds didn't regulate temperature so much as push oxygen and carbon dioxide into and out of the nest. This mixing of air was powered not by the colony's internal heat but by external air pressure: The termites built their mounds tall to catch the wind, not to promote convection. A mound's porous, permeable outer surface allowed air to suffuse into and through the colony, rather like the alveoli in a human lung. The mounds weren't crude air conditioners so much as a wildly complicated external respiratory system.

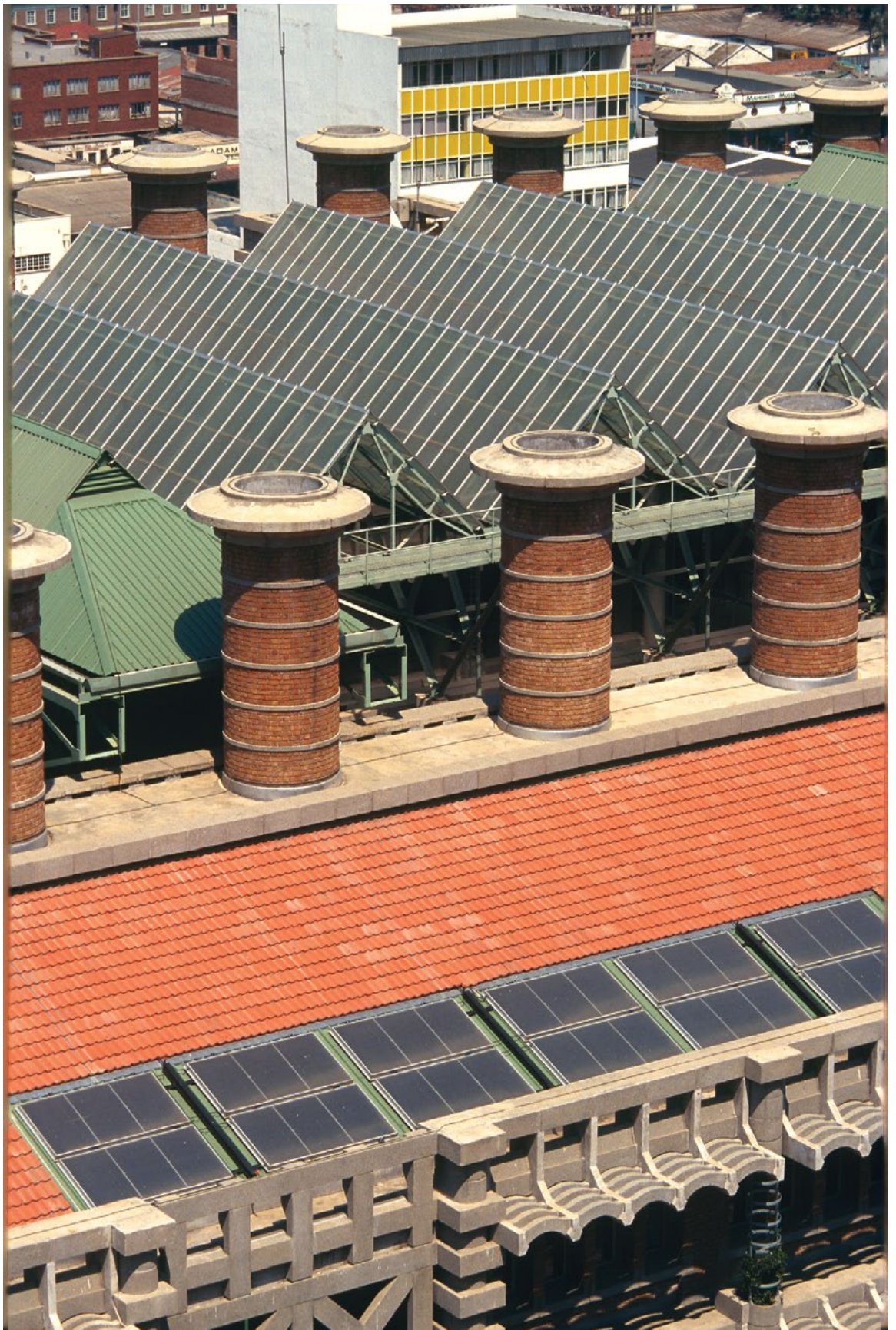
Though it was partially inspired by a flawed understanding of termite mounds, Pearce's biomimetic design for Eastgate Centre had ironically worked so well because it unintentionally mimicked the termites' true temperature-regulating solution, which was the mound's permeable outer surface paired with the simple thermal capacity of surrounding soil. In addition to its duct-laced atriums and soaring chimneys, the building relied on massive foundational concrete slabs as

heat sinks to store thermal energy during warmer daylight hours before releasing it during the cooler nights. "Eastgate Centre succeeded because Pearce was a very good architect rather than a crude imitator of nature," Turner says. "And being so, he managed to converge on a lot of the same functionality the mounds actually have. It's really pretty remarkable."

The Eastgate Centre is one of many stories of people looking to nature for both inspiration and justification—and getting it wrong. But getting it right is no easy task. The more we try to draw inspiration from natural architecture, the more we understand that even the simplest structure is deeply entangled with the character and identity of its builder, making it difficult to interpret. Our first reaction is often to use concepts from our own world as a Rosetta Stone. Termite mounds *look* like cooling towers, after all. The elegance and simplicity of this equivalence made it easy to believe Lüscher's model. Even today, descriptions of Pearce's design in the architectural literature reference Lüscher's model as correct, and many scientists still colloquially describe termite mounds as "air conditioners." But the early waves of biomimicry, which were driven by simple qualitative comparison, are now giving way to a more sophisticated and complex understanding of animal homes.

Nowhere is the relationship between builder and home as clear as with social insects. Small, collaborative creatures such as wasps, bees, ants, and termites are nature's greatest builders, despite the fact that their homes are made by following elegantly simple rules. "The animals that make the most intricate and orderly structures tend to be ones with more limited intelligence," says John Wenzel, an entomologist and expert on wasp nests at the Carnegie Museum of Natural History in Pennsylvania. "Instead of starting at zero and learning everything each generation, they have a baseline of innate, instinctive behavior that can be polished up relatively quickly through successive generations of natural selection." Larger and more intelligent creatures are restricted in what they can build both by their brains and their brawn. Other than humans, if big animals

INSPIRED BY TERMITES The Eastgate Centre's chimneys (right) vent heat in a manner thought to be used by termite mounds.



build at all, they usually just dig holes or pile up sticks.

These hardcoded behaviors in all their diversity can be seen as extensions of an insect's genes' influence beyond the confines of its body, forming a blurred boundary between physiology and environment in what the biologist Richard Dawkins has dubbed the "extended phenotype." Where Pearce interpreted the termite mound directly in terms of functional units familiar to humans, other researchers use insect architecture primarily to gain insight into its inscrutable residents. "You don't have to even see the animal in order to have an excellent record of its behavior," says Wenzel. "You just examine the structure and figure out how it was built."

Almost inevitably, Wenzel says, those examinations yield surprises not only about the animal being observed, but also the observer. A telling example is the comparative architecture of orb-weaver versus tangle-web spiders. Imagine a spider web, and chances are you summon an orb-weaver's work in your mind: A branch-hung mesh of silk spiraling around a central hub so orderly and symmetrical you would consider it beautiful, and certainly superior to the irregular skein of strands of a tangle web in a wood pile. An orb web's beauty comes from the simple algorithm the spider follows to construct it within a single plane. By comparison, a tangle web is the result of a significantly more dynamic behavioral process of trial-and-error construction, methodically stringing and testing silk between any available surfaces until an ideal prey-trapping tension is reached. It looks messy, and primitive.

But the tangle web is actually derived from the more primitive orb web. A tangle web can be built almost anywhere, and it doesn't require airflow to catch prey. Its marvelous, asymmetric design allowed the spiders that developed it to begin a great radiation into thousands of new species. "Humans like symmetry and order, I think because symmetry and order help us recognize patterns, and we like to think we understand things," says Wenzel. "A tangle web shows where this can go wrong."

A more subtle structural lesson lay at the root of a mystery Wenzel repeatedly encountered as a student at the University of Kansas in the late 1980s. He was studying the nest-building of *Polistes annularis*, a common North American paper wasp that builds large, curved nests beneath the eaves of houses. He watched,

day after day, as workers labeled with dabs of paint laid down row after row of hexagonal paper cells. Very rarely, he'd notice a worker place a pentagon instead, and the array's perfection would seemingly be spoiled. Following their simple rules, other workers would tear out the aberrant cell and replace it with a hexagon, only to have their efforts undone by the very same first worker, who would again lay down a pentagon. A back-and-forth tug-of-war would ensue until one side or the other gave up. Often the pentagon would remain. One day, Wenzel made the mistake of mentioning these "errors" within earshot of his professor, the distinguished animal behaviorist Rudolf Jander, who scolded him mercilessly.

"Are you in the mind of the wasp?" Jander had asked. "Do you know what an 'error' is? You can't say, can you? You can only measure. Just measure. The wasps will tell you what this is about; you don't tell them anything."

Chastened, Wenzel returned to his studies, measuring and counting the pentagons until a pattern formed. The placement of the pentagons wasn't random; instead, they appeared at points of anticipated structural stress, where subsequent layers of the nest would be built with curvature. The aberrant pentagons—and the rare wasps who placed them—proved to be strengthening the nest's structure in the same way a tailor takes in pleats in pants.

"In my studies I've seen things many times that I think are anomalies, pathologies, almost like mutations," Wenzel says. But what seem like pathologies can cross an adaptive valley and reach a peak of fitness in the landscape of selection. In other words, they can become useful, even essential. And difficult to understand.

Later, I catch up with Turner, now a professor at The State University of New York College of Environmental Science and Forestry in Syracuse. He has just flown back from an urban-planning conference in Holland, where he discussed termite mounds and other animal architectures as possible inspirations for future biomimetic "organic cities." I ask him if there are biomimetic lessons to be learned from termite mounds.

"Sure," he says. "We sometimes look to nature to validate our own solutions. If the unsentimental natural world has settled on something similar, that makes us feel good. But you simply can't make great explicit leaps between the societies of humans and



social insects like termites. There are different value systems at play.”

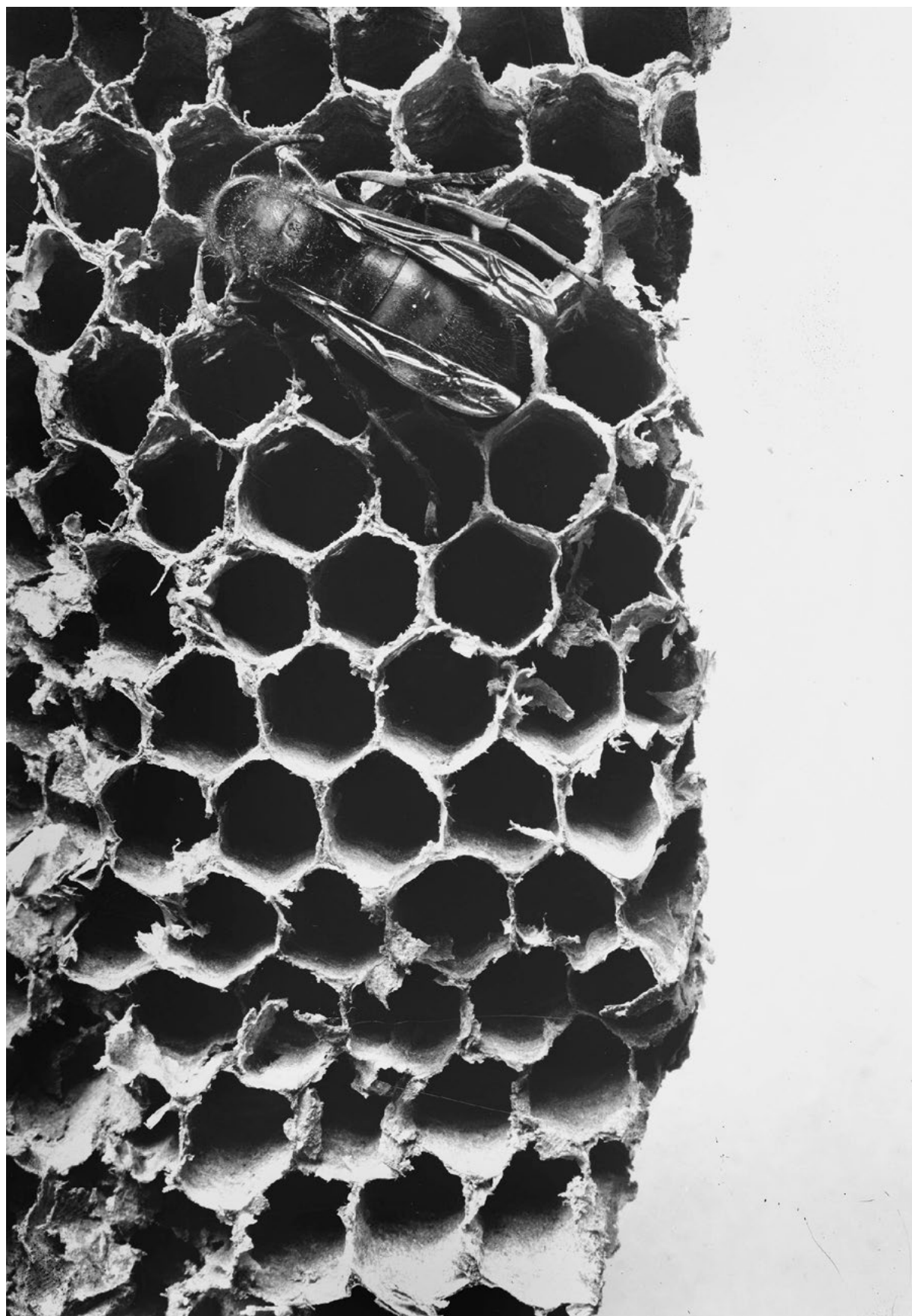
THIS HASN'T STOPPED CLASSICAL biomimicry from its myriad successes. Japanese bullet trains blast through tunnels with barely a whisper thanks to aerodynamic shells inspired by the beaks of diving birds. Olympic swimmers shatter world records by wearing suits coated with a drag-reducing texture resembling sharkskin. Rising energy and materials costs have led to a new generation of skyscrapers and “smart buildings” in cities around the world with bio-inspired passive cooling systems and lightweight structural supports.

But, according to Rupert Soar, an engineer and entrepreneur who has studied termite mounds in collaboration with Turner, most of today’s biomimicry barely mimics biology at all. It would be better described as an expression of “biophilia,” an instinctive human tendency to seek connections with other

living things. To Soar, true biomimicry is more of a process than a product, and, like the sophisticated chaos of a tangle web, it’s not always pretty.

“Architects are still looking at this in terms of designing specific structures, shapes, and forms for specific functions,” Soar says. “But in nature that’s not how we see solutions and innovations emerge! We just see organisms following very simple sets of rules, algorithms playing out again and again as related to some objective.”

A truer biomimicry, Soar believes, would abandon simple biophilia and its crude design metaphors—bullet trains as bird beaks, sharkskins as swimsuits, or termite mounds as skyscrapers. Instead, architects and designers would begin building things as nature builds them. That is, iteratively and algorithmically, with each form sculpted by many optimized functions, each of which acts as its own independent agent. Soar and many others have experimented with simulating insects and insect homes using “agent modeling systems” in which thousands, millions,



Are you in the mind of the wasp?

even billions of individual programs—each a very primitive “virtual insect” with its own objective—compete over limited resources within some carefully arranged digital domain. Following the “right” set of rules in their virtual world, the agents can replicate the structures and morphologies actual insects create in reality. These systems are not limited to replication, however—they can also be used for innovation. Sometimes, complex optimizations can emerge that bear little resemblance to anything produced by the minds of insects or of humans.

“For architectural problems, one agent may want to resolve a door, another a window, another the flow of water or of heat, and collectively they negotiate a solution,” Soar says. “This is possible now because computers can handle the massive amounts of information required.”

This agent-based approach suggests that we needn’t fully understand the minds and societies of insects or their home-building habits to leverage their power. Yet integrating these techniques into human architecture can be risky. An agent modeling system may arrive at a highly-optimized solution for any given problem, but it can never tell you how it got there, or if the resulting solution is truly the best. The organic constructs that emerge may be wondrously optimized and ornate, but they still develop through an inefficient, sometimes brutal process. Such structures are typically closer to instability and collapse than would be tolerable in modern architecture. Perhaps worst of all, because the products of an agent modeling system often embody so many functions within one form, they can be asymmetric, chaotic, and unappealing to the human eye.

And so we recoil, retreating to something orderly, symmetrical, and sturdy, some simple shape of concrete and steel—and something we can control, which

does not involve yielding top-down influence over a building’s design and construction.

Nevertheless, Soar suspects architecture will eventually enter a more biomimetic phase as the need grows for more energy-efficient buildings. Agent-based optimizations could become commonplace, along with new construction technologies such as 3D printing, which would allow unprecedented architectural experimentation and innovation. A revolution may occur in how humans construct and live within their homes. Boxy, self-similar houses and office buildings could give way to a wild profusion of easily produced and altered organic forms. Everyday people might then interact with architecture almost like insects, forming social swarms that rely on bio-inspired environmental cues to build and maintain their homes—their hives.

In this strange future, biomimicry could become less a fashionable conceit and more a basic mode of interaction—a building’s occupants would collectively work from the bottom up to maintain its structure, each individual’s actions attuned to the needs of the many in new ways. “[These environments] will be smelly, noisy, flashy, and textural, full of attention-catching sensory inputs that people will feed off to decide what they do next,” Soar says.

These far-out possibilities and deep connectivities between habitat and inhabitants do sound bizarre, perhaps because they ask us to jettison some of what seems to make us human. Would we ever choose the dynamic chaos of a tangle web over the simplicity of an orb weaver’s web, or a van der Rohe home? Aren’t we more comfortable in static, sturdy structures of stone, glass, and steel than we would be in any flexible biomimetic confection? Perhaps we are. But it is also true that we have continually made our cities and our economies increasingly complex, interconnected, and responsive—organic, in one sense of the word. For better or worse, we are already more similar to nature’s greatest builders than we realize. And, as our understanding of animal homes becomes more sophisticated and we transition more completely from biophilia to biomimicry, this convergence can only accelerate. 🐝

Freelance writer **LEE BILLINGS** is the author of *Five Billion Years of Solitude: The Search for Life Among the Stars*.

09

THERE'S A TICKING BOMB in the corner of your awareness. The danger isn't the bomb, though—it's the clock. Time, that most pedestrian, over-measured, and tightly regulated quantity of our daily lives, is in a perpetual state of crisis.

There's the problem of what to do with your time, of course. We'll leave that as an exercise for the reader. But there are some bigger issues. For instance: Nobody knows what time really is. Imagine a universe in the distant future, which may very well consist of a diffuse and completely unstructured skein of homogeneous matter. Many physicists contend that, because time can't be measured in such a universe, time won't exist. Therefore time has to end. But when, and by whose clock? And if it ended, did it begin?

The difference between future and past is in trouble, too. Quantum mechanics describes a blurry kind of time that can't be measured exactly. Once time blurs, so do causality and directionality. Can we cause something in the past by doing something in the future? Hard to say.

Then, in typical fashion, we humans obscure things even further. We stretch, compress, cut, and stitch time together to suit our own ends, then lie to ourselves about doing it. In many ways we are actually in a war with time: We fight our body's clocks, our mind's clocks, and the Earth's clocks. Some of these battles are going our way, letting us wrestle our own definitions onto the stage.

Welcome to "Time."

—MS

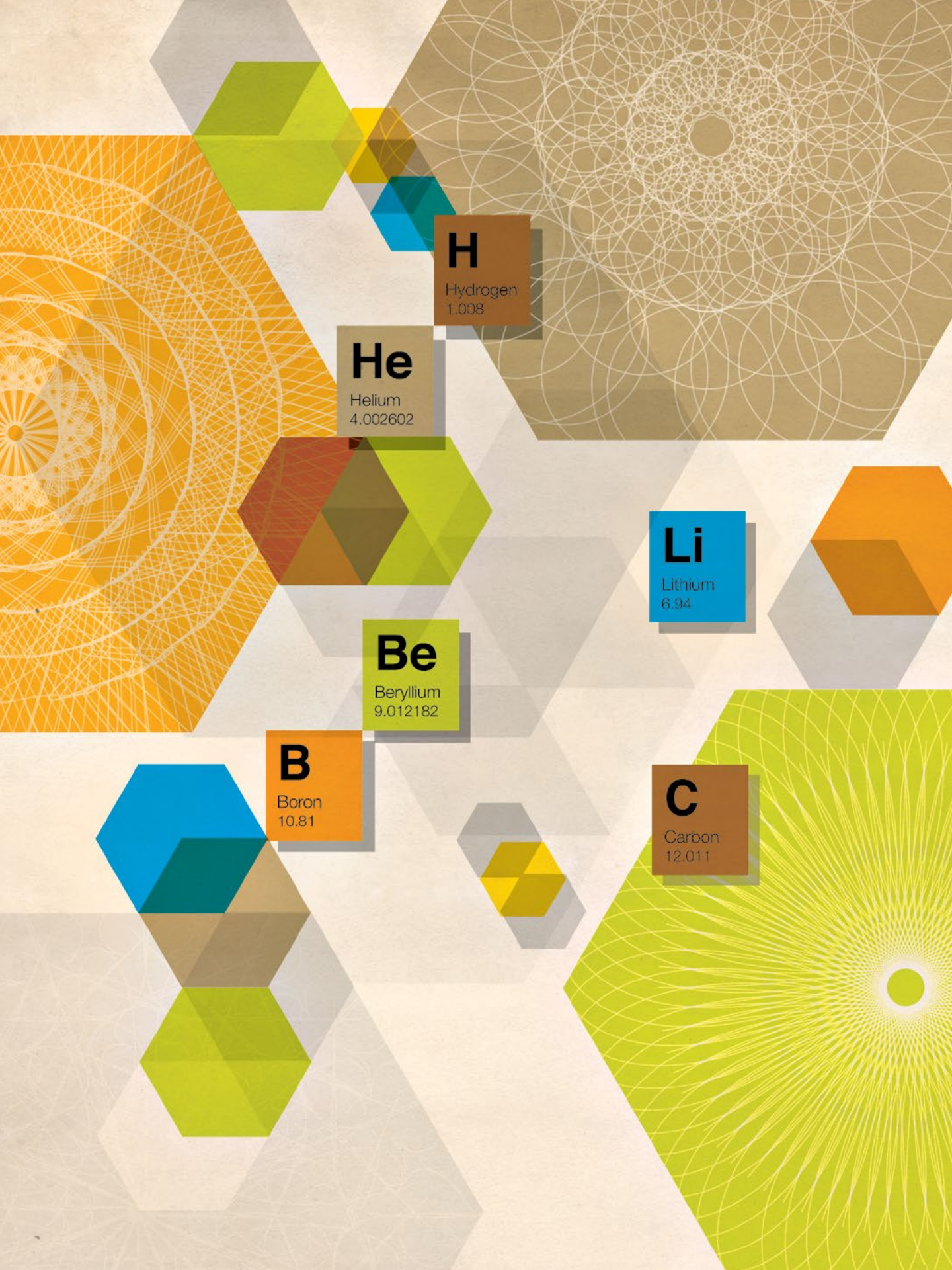
"The arrow scientists envisioned between simplicity and complexity actually spins like a weather vane caught in a tornado."

AMY MAXMEN

"Evolution, You're Drunk" p.166

Time

MYSTERIES OF THE MOMENT



H

Hydrogen
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He

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Beryllium
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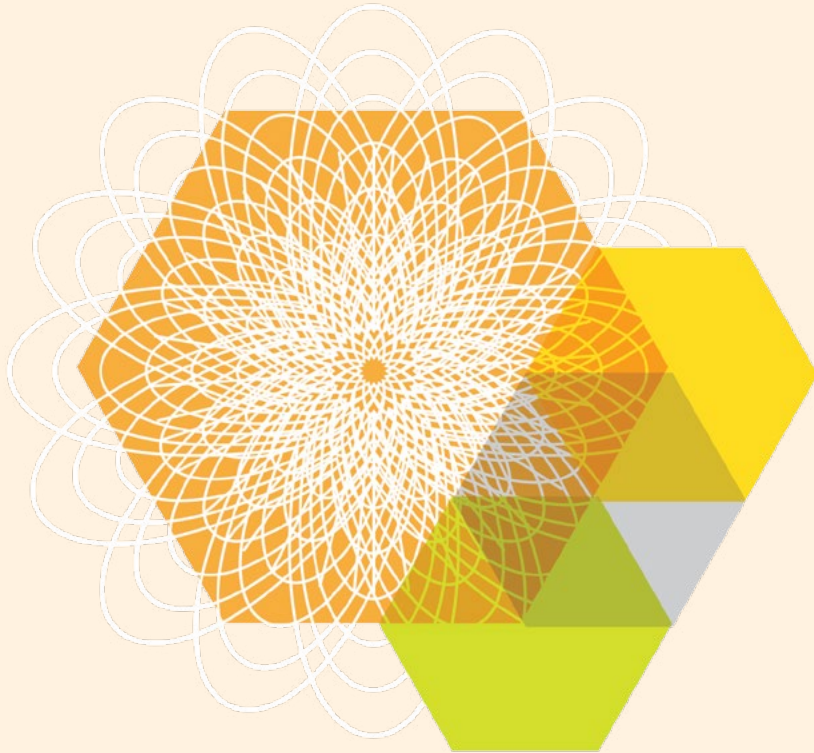
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Over Time, Buddhism and Science Agree

Understanding the impermanence of everything—including ourselves

BY DAVID P. BARASH



ILLUSTRATIONS BY CHAD HAGEN

REMEMBER MY GRANDFATHER COMMENTING—

wry amusement tinged with grim resignation—that what made him finally feel old was seeing his children reach middle age. I was a child then. Now I see my own children, not quite middle aged, starting to have children of their own.

Becoming a grandparent is quite lovely, an affirmation of continuity and a front-row-seat to watch (and even, on occasion, participate) as life itself is conveyed into the future. But aging is also our most undeniable *memento mori*, a reminder not so much of life as one's own eventual death. My grandfather's death frightened me as few things have since, except for the recurring recognition (usually at night, alone, in the dark) that his life, everyone's life, even—astoundingly—my own, is short indeed.

All things, especially living ones, are marinating in the river of time. We see and understand that our bodies will wear out and we will die. At least that's how it looks through the lens of Western science, where all things come to an end, winding down in a final surrender to entropy. But there's another perspective, surprisingly in harmony with science, that helps us revisit that huge and ancient terror—fear of time itself—in a new and perhaps even reassuring way. And that is the perspective offered by Buddhism.

For Buddhists, the “center cannot hold,” as the poet W.B. Yeats pointed out, because it doesn't exist as something rigidly separate from everything else. Nothing is permanent and unchanging, ourselves included. Attempting to cling to a solid, immutable core of a self is a fool's errand because time not only creates anarchy, it provides the unavoidable matrix within which everything—animate and inanimate, sentient and insentiate—ebbs and flows.

As Buddhists see it, all organisms are necessarily unavoidably—even marvelously and gloriously—impermanent. In Sanskrit, the word for impermanence is *anitya*. To understand *anitya* is to achieve something remarkable: opening a door onto the accord between modern western science and ancient eastern wisdom.

In his book, *Physics and Philosophy*, Werner Heisenberg—one of the commanding figures in the development of modern quantum physics—wrote that “in the history of human thinking the most fruitful developments frequently take place at those points where two

different lines of thought meet.” Contrary to Rudyard Kipling’s injunction, “East is East, and West is West, and never the twain shall meet,” I have found, as a trained biologist, that some of the most fruitful developments in modern thinking occur precisely where the twain of biology and Buddhism meet.

Even inanimate objects that appear solid and persistent are revealed by modern physics to be in a constant state of flux. An iron bar is mostly empty space, and even the ostensibly solid, subatomic particles occupying that space are either moving so rapidly as to be unimaginable or, alternately, exist as clouds of probability rather than as stationary monuments to permanence.

With living things, the world is even less fixed. As Yeats observed: “O body swayed to music, O brightening glance / How can we know the dancer from the dance?” Biologists as well as Buddhists know that living stuff is always dancing, constantly replenished by, and created from, nonliving components. At every moment, our existence takes place only on the instantaneous, knife-edge of Now, which can never be captured and held immobile.

The story goes that, as a young man, the Buddha sought to overcome the imperfections of the real world—sickness, old age, and death—by following the path of traditional Hindu asceticism, mortifying the flesh and nearly starving himself. His eventual enlightenment, however, is said to have involved recognition that all things are temporary, ever-changing, and impermanent. Unlike Christ, who promises eternal life, the last words of the Buddha reportedly began, “Decay is inherent in all things.”

But even decay—an unavoidable consequence of time impacting the real world—isn’t something to regret. As the Vietnamese Buddhist monk and scholar, Thich Nhat Hanh, put it, impermanence (*anitya*) is intimately tied to continuity. “Look back,” he counsels, “and you will see that you not only exist in your father and mother, but you also exist in your grandparents and in your great-grandparents.” Look again, and you will see we “have been gas, sunshine, water, fungi, and plants,” he writes. “Nothing can be born and also nothing can die.” To understand this, and to do so deep in our ever-changing bones, may forever change our sense of time and what it means to participate in life on earth.

As Buddhists see it, all organisms are necessarily—even marvelously and gloriously—impermanent.

AGING IS UNDOUBTEDLY THE most apparent and unavoidable manifestation of how *anitya* is both revealed by time and produced by it, how impermanence is manifest in every body. Precisely how bodies age is the domain of biological gerontology, which studies such events as the increased accumulation of somatic mutations, reductions in tissue elasticity, increase in autoimmune responses, and diminished length of telomeres (end-pieces of chromosomes that can be likened to the plastic tips at the end of shoelaces, and which evidently protect chromosomes as they undergo cell division). Most human cells poop out after about 60 or so replications, apparently in conjunction with the loss of telomeres, which become a bit shorter with every bout of mitosis—although it isn’t clear whether aging-related decrepitude results from this reduction in telomere length, or vice versa.

Whatever the causative sequence, there is no fountain of youth. We can reduce the rate of decline by eating healthy foods, reducing stress, and exercising regularly. But the effect, at best, is to slow the process, never to stop it altogether. To be a museum conservator, exercise fanatic, or just a dedicated daily dental flosser is to be more Sisyphus than Ponce de León.

But this is too pessimistic. A Buddhistically informed view suggests that even as everything changes over time, this very impermanence is connected to a deeper kind of persistence. One of the more striking visual demonstrations of this is the practice among Tibetan monks of constructing gorgeous sand mandalas, complex designs and patterns laboriously built



SANDS OF TIME Tibetan Buddhist monks create a mandala of colored sand, a symbol of impermanence.

over many days, after which they are ceremoniously swept away. Proxies for ourselves, mandalas symbolize the impermanence of everything, no matter how lovely, complex, treasured, or important.

Some years ago, while waiting for a wilderness permit at a Forest Service ranger station in the small town of Sedro Woolley, Wash., I overheard a radio message sent in by a ranger: “Dead elk in Agnes Creek decomposing nicely. Over.” The ranger was ecologically sophisticated as well as Buddhistically accurate. Although a decomposing elk might not be everyone’s idea of “nice,” the process is as necessary to a healthy ecosystem as it is unavoidable. (The “over” was an especially nice touch.)

For another good example of biological *anitya*, one that overturned prior biological dogma, consider Dolly, who famously emerged as the world’s first artificially cloned sheep. Before Dolly, it was widely held that

once vertebrate cells had fully differentiated—becoming, say, muscle or skin or, in the case of Dolly’s “mother,” mammary gland tissue—they were permanently fixed and couldn’t become a different kind of cell.

Dolly was created when an already differentiated nucleus was implanted into an enucleated egg cell, and a new animal emerged, complete with a full array of distinctly different cell types. Cell differentiation is evidently not a one-way street, as previously believed. One of the things built into life itself is, ironically, impermanence and the capacity to change.

The reality of *anitya* extends to whole genomes, which are permeable to genes introduced from other lineages. This is why we can put cold-resistance genes from halibut into frost-vulnerable tomatoes. (Whether we should is another question.) Even without high-tech human intervention, the evolutionary reality of continuity among all living things is inseparable from

the fact that all lineages have themselves evolved—that is, they have changed over time, and continue to do so. The seemingly rigid boundaries between cells and within species are flexible and inconstant. Living things do not simply have the capacity for impermanence; rather, at what we might oxymoronically call their “core,” they are profoundly and deeply impermanent and ever-changing.

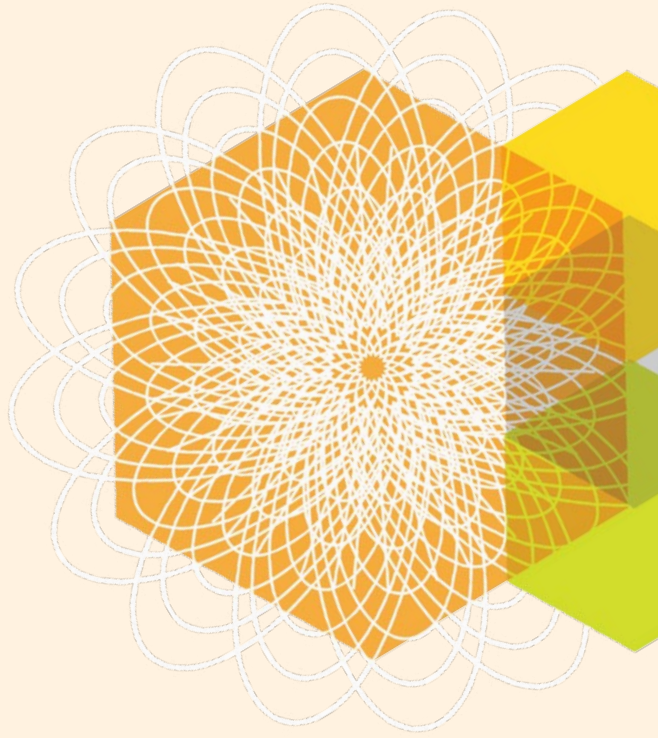
What about whole organisms taken in their entirety? After all, each halibut, hickory tree, or human being appears to be distinct and fixed in time—or at least identifiable as this object, this creature, this person. But each “this” is largely an artifact of our own limited perception of time and its impact. Wait long enough, give time the opportunity to work its way, and every living thing changes, undergoing embryogenesis, growth, senescence, and finally death. In short, time will tell.

Question: When a Buddhist nun goes to a beauty parlor, what is she likely to get? Answer: an impermanent.

IT WOULD SEEM, NONETHELESS, that living things struggle to defy *anitya*, to resist change. The technical term among physiologists is “homeostasis,” the process whereby organisms maintain their internal environment within limits. This is notably true of mammals, which possess various adaptations to keep their internal temperature independent of the outside environment. At least as important, however, is the internal chemical environment: not too acid, not too alkaline, enough sodium, potassium, and calcium. Without a precisely stable Goldilocks balance, life ceases.

In a narrow sense, that is a defiance of *anitya*. But the physiological constancy required by life can only be achieved in what physicists label an “open system,” which receives regular inputs of energy and material from elsewhere. In the case of living things, this means that even the temporary, seeming defiance of impermanence can only occur via a never-ending introduction of new stuff. In the short term, that means energy-carrying molecules that permit respiration and metabolism; in a longer perspective, that means proteins and other substances involved in growth, maintenance, and repair.

Paradoxically, maintaining a state of apparent constancy (i.e., life) requires continual openness to change, in this case exchange with an organism’s environment.



Every few days we essentially recycle ourselves, reminiscent of an old advertising jingle for milk, “There’s a new you coming every day!”

When that exchange ceases, so does life; although even then, every body continues to change, whether via decomposition, incorporation into another body, or incineration. Recall that elk undergoing its mandatory changes oh so nicely.

Let's consider that elk—or ourselves—in an earlier and more sprightly state, and look at two phenomena essential to that condition we call “alive”: respiration and digestion/metabolism. We regularly inhale about a half liter of air, relatively high in oxygen and low in carbon dioxide. Our bodies combine some of that oxygen with food molecules we earlier consumed, generating energy. The half-liter that we subsequently exhale contains less oxygen and more CO₂, a by-product of metabolism. “New” atoms are incorporated into our bodies at every moment, and “old” ones are rearranged, while some are pushed out. Every few days we essentially recycle ourselves, reminiscent of an old advertising jingle for milk, “There’s a new you coming every day!” Except it’s more like every hour, minute, second, instant.

Then, of course, there is evolution, the process that has produced and underlies all life. Evolution is change—change in the make-up of a lineage over time. Although certain organisms have evolved rapidly (human beings, elephants, bacteria), others do so slowly. They include such peculiar creatures as coelacanths (lobe-finned fishes believed extinct before one was caught in the deep ocean off Madagascar in the 1930s), tuataras (peculiar lizards found only on several islands off the coast of New Zealand), or horseshoe

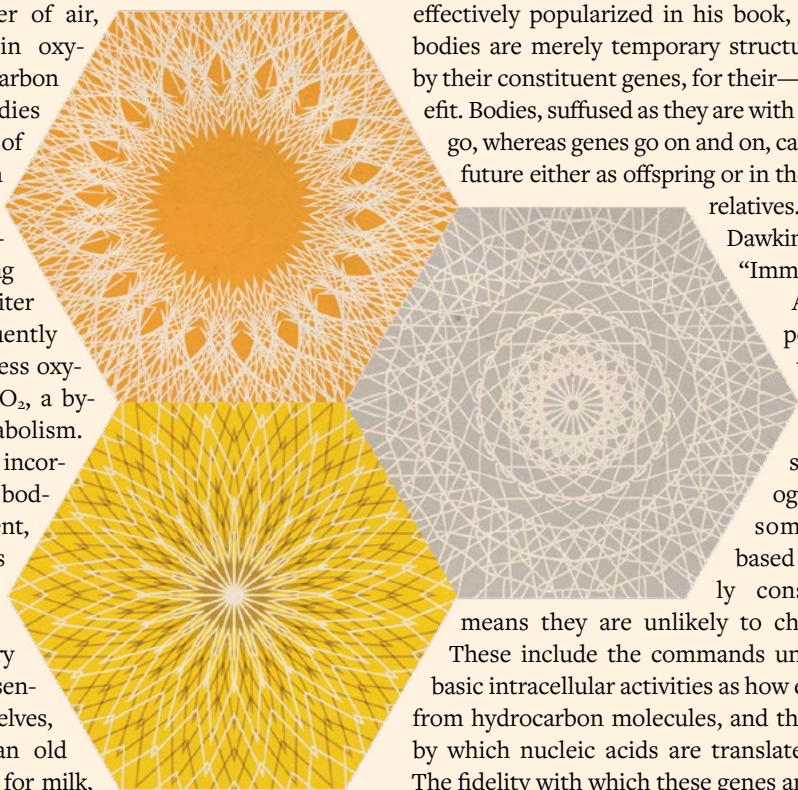
“crabs” (closely related to spiders and which appear not to have changed significantly in a few hundred million years). But even these “living fossils” have themselves evolved—that is, changed over time—compared to their ancestral, soft-bodied pre-Cambrian ancestors, just as they will continue to do so—or go extinct—when their environment changes.

What about genes themselves? Aren't they permanent rather than temporary? As Richard Dawkins effectively popularized in his book, *The Selfish Gene*, bodies are merely temporary structures constructed by their constituent genes, for their—the genes'—benefit. Bodies, suffused as they are with *anitya*, come and go, whereas genes go on and on, catapulted into the future either as offspring or in the bodies of other relatives. One chapter in Dawkins' book is titled “Immortal Coils.”

Although the potential immortality of genes is an effective simile, it is not strictly true. Biologists know that some genetically based traits are “highly conserved,” which

means they are unlikely to change over time. These include the commands undergirding such basic intracellular activities as how energy is derived from hydrocarbon molecules, and the coding system by which nucleic acids are translated into proteins. The fidelity with which these genes are accurately replicated between generations is remarkable, but also not surprising, given that errors in such fundamental processes are quickly selected against, leaving the unchanged to persist.

But not forever. Mutations happen. On average, genes mutate at a rate of about once in a million replications. Given enough time, errors are inevitable. Given changes in their environment, beneficial mutations are selected for, while hurtful ones are selected against. Everyone's eventual and unavoidable death has been dramatically expressed by W. Somerset Maugham as “The Appointment in Samarra.” Even



genes do not—and cannot—escape their appointment with *anitya*.

Most mutations result from incorrect base pairings, involving the four key molecules of heredity: adenine (A), cytosine (C), thymine (T), and guanine (G), when by accident they fail to line up according to the normal pattern of A-with-T and C-with-G. By contrast, the remarkably rigid spiral backbone of DNA—which gives rise to its double helix structure—consists of repeating sugar and phosphate groups, which are more stable than the base pairings, since the former rely on “regular” chemical bonds whereas the latter occur via weaker “hydrogen bonds.”

But even here, change is inevitable, although presumably less consequential. Hydrogen atoms that are ubiquitous throughout DNA molecules are constantly switching places with other hydrogen atoms in their immediate surroundings; the resulting “hydrogen exchange” is well documented, insuring that even a non-mutated DNA molecule is something of a shape-shifter, even when it is ostensibly resting. So even the most unchanging component of potentially immortal DNA is immersed in *anitya*, constantly refashioning itself.

ZEN KOANS ARE RIDDLES intended to shake seeker-monks free of their excessive dependence on linear thought processes. A famous koan asks the novice to describe her face before she was born. A good answer these days would have something to do with DNA, but it would also have to incorporate ebb and flow, process and pattern, contingency and probability, a paradoxically permanent state of impermanence.

Over time, *anitya* is manifested at many different levels: the ecological flux of biogeochemical cycles, the unavoidable conveyor belt of birth to aging to death, and the instantaneous transformations in all parts of living organisms. While our illusion of permanence may be fostered by our sense of continuous memory, psychologists now understand that memories are not only frequently incorrect but as impermanent as our physical substance.

From a scientific perspective, there is every reason for biologists to join with Buddhists in rejecting what the latter call *svabhava*, fixed and unchanging essence. At our deepest, molecular levels, we have no essence. “Time is the substance I am made of,” wrote Jorge Luis

Borges. “Time is a river which sweeps me along, but I am the river; it is a tiger which devours me, but I am the tiger; it is a fire which consumes me, but I am the fire.”

In Eastern mythology, the story is told about a king who called his Wisdom Council together and asked for an observation that would always be true, for all living things, at all times. They agreed upon the following: “This too shall pass.” The universal recipe for *anitya* is as simple as it is inevitable: Start with the stuff of the world, then marinate in tincture of time.

When Alice Munro was awarded the 2013 Nobel Prize for Literature, a *New York Times* editorial observed that the writer “can do anything with time that she wants, hasten it, elide it, slow it down. But when we put the story down, we feel that time has happened to us.” My grandfather felt that time was happening to him most keenly when he saw its impact on those around him, especially those he loved, who were much younger than he was, and should have been less impacted by it.

But the truth, of course, is that time happens to all of us, well, all the time! And a Buddhist perspective helps us to understand and even revel in the impermanence that results. ☺

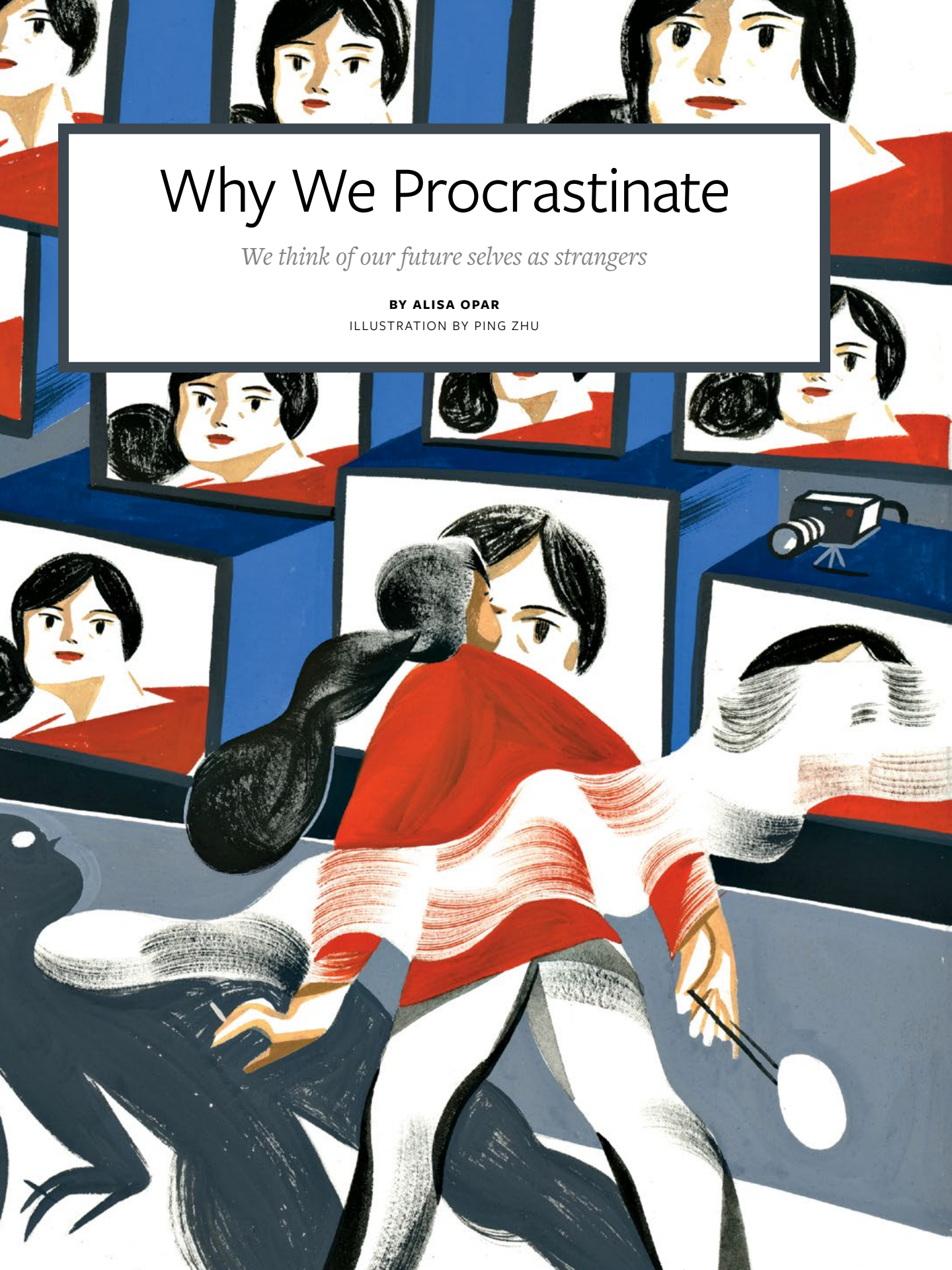
DAVID P. BARASH is an evolutionary biologist and professor of psychology at the University of Washington. His most recent book is *Buddhist Biology: Ancient Eastern Wisdom Meets Modern Western Science*.

Why We Procrastinate

We think of our future selves as strangers

BY ALISA OPAR

ILLUSTRATION BY PING ZHU



THE BRITISH PHILOSOPHER DEREK PARFIT espoused a severely reductionist view of personal identity in his seminal book, *Reasons and Persons*: It does not exist, at least not in the way we usually consider it. We humans, Parfit argued, are not a consistent identity moving through time, but a chain of successive selves, each tangentially linked to, and yet distinct from, the previous and subsequent ones. The boy who begins to smoke despite knowing that he may suffer from the habit decades later should not be judged harshly: “This boy does not identify with his future self,” Parfit wrote. “His attitude towards this future self is in some ways like his attitude to other people.”

Parfit’s view was controversial even among philosophers. But psychologists are beginning to understand that it may accurately describe our attitudes toward our own decision-making: It turns out that we see our future selves as strangers. Though we will inevitably share their fates, the people we will become in a decade, quarter century, or more, are unknown to us. This impedes our ability to make good choices on their—which of course is our own—behalf. That bright, shiny New Year’s resolution? If you feel perfectly justified in breaking it, it may be because it feels like it was a promise someone else made.

“It’s kind of a weird notion,” says Hal Hershfield, an assistant professor at New York University’s Stern School of Business. “On a psychological and emotional level we really consider that future self as if it’s another person.”

Using fMRI, Hershfield and colleagues studied brain activity changes when people imagine their future and consider their present. They homed

in on two areas of the brain, called the medial prefrontal cortex and the rostral anterior cingulate cortex, which are more active when a subject thinks about himself than when he thinks of someone else. They found these same areas were more strongly activated when subjects thought of themselves today, than of

themselves in the future. Their future self “felt” like somebody else. In fact, their neural activity when they described themselves in a decade was similar to that when they described Matt Damon or Natalie Portman. And subjects whose brain activity changed the most when they spoke about their future selves were the least likely to favor large long-term financial gains over small immediate ones.

Emily Pronin, a psychologist at Princeton, has come to similar conclusions in her research. In a 2008 study, Pronin and her team told college students that they were taking part in an experiment on disgust that required drinking a concoction made of ketchup and soy sauce. The more they, their future selves, or other students consumed, they were told, the greater the benefit to science. Students who were told they’d have to down the distasteful quaff that day committed to consuming two tablespoons. But those that were committing their future selves (the following semester) or other students to participate agreed to guzzle an average of half a cup. We think of our future selves, says Pronin, like we think of others: in the third person.

The disconnect between our present and time-shifted selves has real implications for how we make decisions. We might choose to procrastinate, and let some other version of our self deal with problems or chores. Or, as in the case of Parfit’s smoking boy, we can focus on that version of our self that derives pleasure, and ignore the one that pays the price.

But if procrastination or irresponsibility can

derive from a poor connection to your future self, strengthening this connection may prove to be an effective remedy. This is exactly the tactic that some research-

We think of our future selves, says Pronin, like we think of others: in the third person.

ers are taking. Anne Wilson, a psychologist at Wilfrid Laurier University in Canada, has manipulated people’s perception of time by presenting participants with timelines scaled to make an upcoming event, such as a paper due date, seem either very close or far off. “Using a longer timeline makes people feel more



DIGITAL OLD AGE A photograph (left) and digitally aged avatar (right) of Professor Hal Hershfield.

connected to their future selves,” Wilson says. That, in turn, spurred students to finish their assignment earlier, saving their end-of-semester self the stress of banging it out at the last minute.

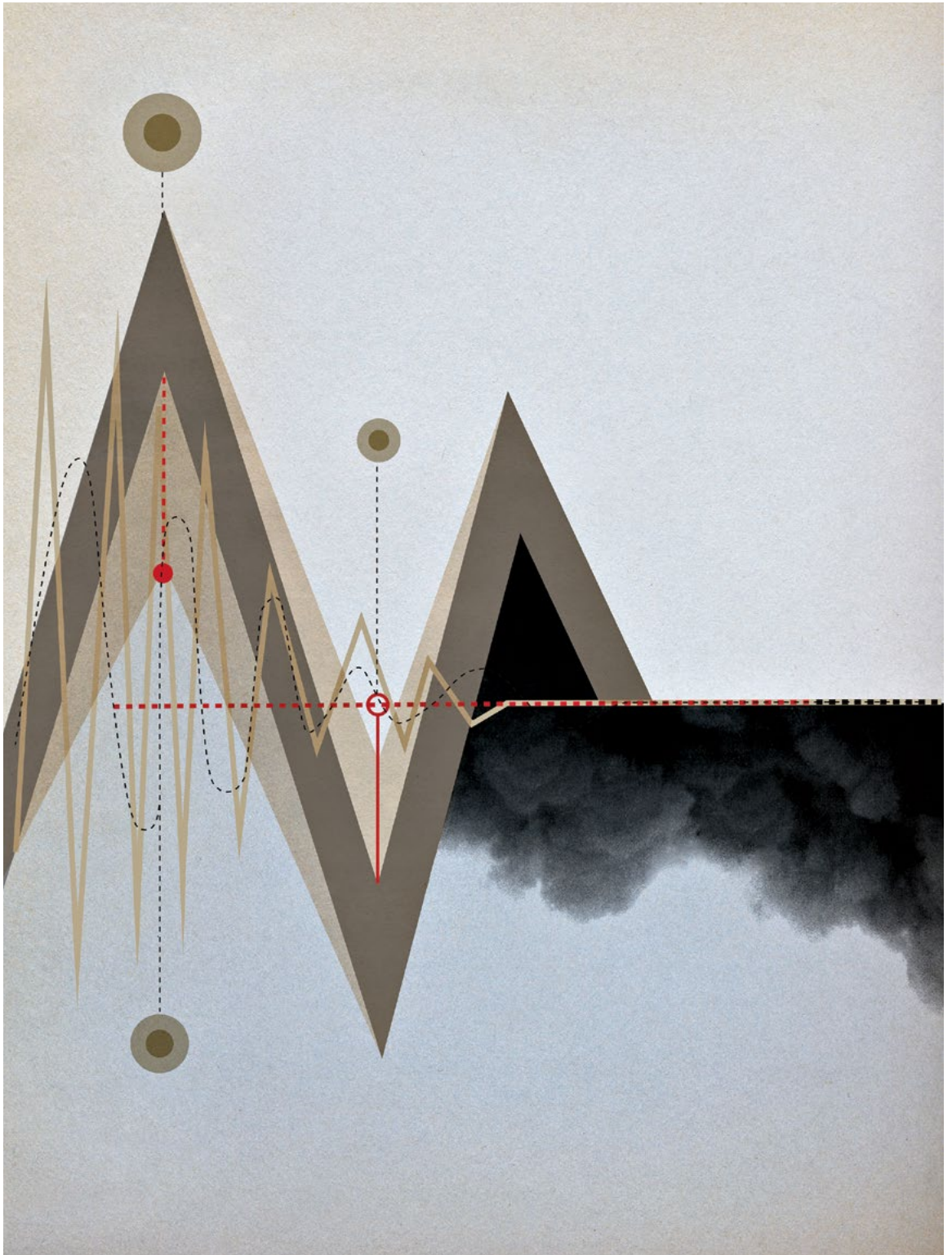
Hershfield has taken a more high-tech approach. Inspired by the use of images to spur charitable donations, he and colleagues took subjects into a virtual reality room and asked them to look into a mirror. The subjects saw either their current self, or a digitally aged image of themselves (see “Digital Old Age”). When they exited the room, they were asked how they’d spend \$1,000. Those exposed to the aged photo said they’d put twice as much into a retirement account as those who saw themselves unaged.

This might be important news for parts of the finance industry. Insurance giant Allianz is funding a pilot project in the midwest in which Hershfield’s team will show state employees their aged faces when they make pension allocations. Merrill Edge, the online discount unit of Bank of America Merrill Lynch, has taken this approach online, with a service

called Face Retirement. Each decade-jumping image is accompanied by startling cost-of-living projections and suggestions to invest in your golden years. Hershfield is currently investigating whether morphed images can help people lose weight.

Of course, the way we treat our future self is not necessarily negative: Since we think of our future self as someone else, our own decision-making reflects how we treat other people. Where Parfit’s smoking boy endangers the health of his future self with nary a thought, others might act differently. “The thing is, we make sacrifices for people all the time,” says Hershfield. “In relationships, in marriages.” The silver lining of our dissociation from our future self, then, is that it is another reason to practice being good to others. One of them might be you. ☺

ALISA OPAR is the articles editor at *Audubon* magazine. She often consigns “Future Alisa” to dealing with deadlines and chores.



CHAD HAGEN



Life is a Braid in Spacetime

How to see yourself in a world where only math is real

BY MAX TEGMARK

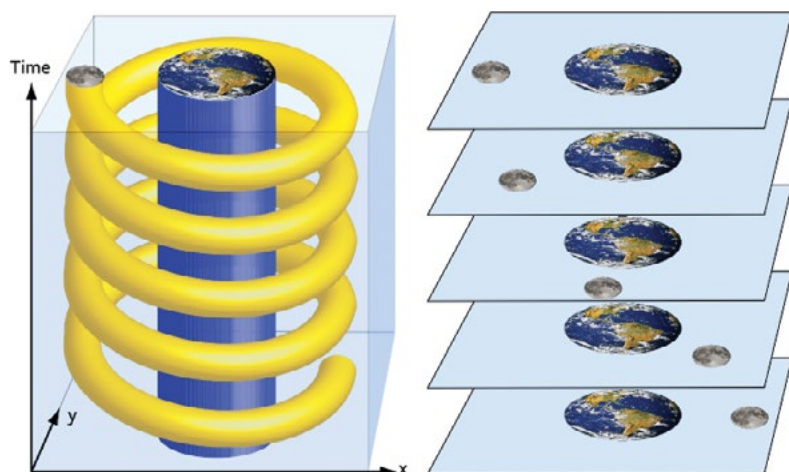
EXCUSE ME, BUT WHAT'S THE TIME?" I'm guessing that you, like me, are guilty of having asked this question, as if it were obvious that there is such a thing as *the* time. Yet you've probably never approached a stranger and asked "Excuse me, but what's the place?". If you were hopelessly lost, you'd probably instead have said something like "Excuse me, but where am I?" thereby acknowledging that you're not asking about a property of space, but rather about a property of yourself. Similarly, when you ask for the time, you're not really asking about a property of time, but rather about your location in time.

But that is not how we usually think about it. Our language reveals how differently we think of space and time: The first as a static stage, and the second as something flowing. Despite our intuition, however, the flow of time is an illusion. Einstein taught us that there are two equivalent ways of thinking about our physical reality: Either as a three-dimensional place called *space*, where things change over time, or as a

four-dimensional place called *spacetime* that simply exists, unchanging, never created, and never destroyed.

I think of the two viewpoints as the different perspectives on reality that a frog and a bird might take. The bird surveys the landscape of reality from high "above," akin to a physicist studying the mathematical structure of spacetime as described by the equations of physics. The frog, on the other hand, lives inside the landscape surveyed by the bird. Looking up at the moon over time, the frog sees something like the right panel in the figure, "The Moon's Orbit": five snapshots of space with the moon in different positions each time. But the bird sees an unchanging spiral *shape* in spacetime, as shown in the left panel.

For the bird—and the physicist—there is no objective definition of past or future. As Einstein put it, "The distinction between past, present, and future is only a stubbornly persistent illusion." When we think about the present, we mean the time slice through spacetime corresponding to the time when we're having that



THE MOON'S ORBIT We can equivalently think of the moon as a position in space that changes over time (right), or as an unchanging spiral shape in spacetime (left), corresponding to a mathematical structure. The snapshots of space (right) are simply horizontal slices of spacetime (left). To keep things legible, I've drawn the orbit much smaller than to scale and made several simplifications. To get snapshots of space (right) from spacetime (left), you simply make horizontal slices through spacetime at the times you're interested in.

thought. We refer to the future and past as the parts of spacetime above and below this slice.

This is analogous to your use of the terms *here*, *in front of me*, and *behind me* to refer to different parts of spacetime relative to your present position. The part that's in front of you is clearly no less real than the part behind you—indeed, if you're walking forward, some of what's presently in front of you will be behind you in the future, and is presently behind various other people. Analogously, in spacetime, the future is just as real as the past—parts of spacetime that are presently in your future will, in your future, be in your past. Since spacetime is static and unchanging, no parts of it can change their reality status, and all parts must be equally real.

The idea of spacetime does more than teach us to rethink the meaning of past and future. It also introduces us to the idea of a *mathematical universe*. Spacetime is a purely mathematical structure in the sense that it has no properties at all except mathematical properties, for example the number four, its number of dimensions. In my book *Our Mathematical Universe*, I argue that not only spacetime, but indeed our entire external physical reality is a mathematical structure, which is by definition an abstract, immutable entity existing outside of space and time.

What does this actually mean? It means, for one thing, a universe that can be beautifully described by mathematics. That this is true for our universe has become increasingly clear over the centuries, with evidence piling up ever more rapidly. The latest triumph in this area is the discovery of the Higgs boson, which, just like the planet Neptune and the radio wave, was first predicted with a pencil, using mathematical equations.

That our universe is approximately *described* by mathematics means that some, but not all, of its properties are mathematical. That it *is* mathematical means that all of its properties are mathematical; that it has no properties at all except mathematical ones. If I'm right and this is true, then it's good news for physics, because all properties of our universe can in principle be understood if we are intelligent and creative enough. It also implies that our reality is vastly larger than we thought, containing a diverse collection of universes obeying all mathematically possible laws of physics.

This novel way of viewing both spacetime and the stuff in it implies a novel way of viewing ourselves. Our thoughts, our emotions, our self-awareness, and that deep existential feeling "*I am*"—none of this feels the least bit mathematical to me. Yet we too are made of the same kinds of elementary particles that make up everything else in our physical world, which I've argued is purely mathematical. How can we reconcile these two perspectives?

The first step is to consider how we look as a spacetime structure. The cosmology pioneer George Gamow entitled his autobiography *My World Line*, a phrase also used by Einstein to refer to paths through spacetime. However, your own world line strictly speaking isn't a line: It has a non-zero thickness and it's not straight. The roughly 10^{29} elementary particles (quarks and electrons) that your body is made of form a tube-like shape through spacetime, analogous to the spiral shape of the moon's orbit (see "The Moon's Orbit") but more complicated. If you're swimming laps in a pool, that part of your spacetime tube has a zig-zag shape, and if you're using a playground swing, that part of your spacetime tube has a serpentine shape.

However, the most interesting property of your spacetime tube isn't its bulk shape, but its internal structure, which is remarkably complex. Whereas the particles that constitute the moon are stuck together

in a rather static arrangement, many of your particles are in constant motion relative to one another. Consider, for example, the particles that make up your red blood cells. As your blood circulates through your body to deliver the oxygen you need, each red blood cell traces out its own unique tube shape through spacetime, corresponding to a complex itinerary through your arteries, capillaries, and veins with regular returns to your heart and lungs. These spacetime tubes of different red blood cells are intertwined to form a braid pattern as seen in the figure "Complexity and Life" which is more elaborate than anything you'll ever see in a hair salon: Whereas a classic braid consists of three strands with perhaps 30,000 hairs each, intertwined in a simple repeating pattern, this spacetime braid consists of trillions of strands (one for each red blood cell), each composed of trillions of hair-like elementary particle trajectories, intertwined in a complex pattern that never repeats. In other words, if you imagine spending a year giving a friend a truly crazy hairdo, braiding the hair by separately intertwining all their individual hairs, the pattern you'd get would still be very simple in comparison.

The most interesting property of your spacetime tube isn't its bulk shape, but its internal structure, which is remarkably complex.

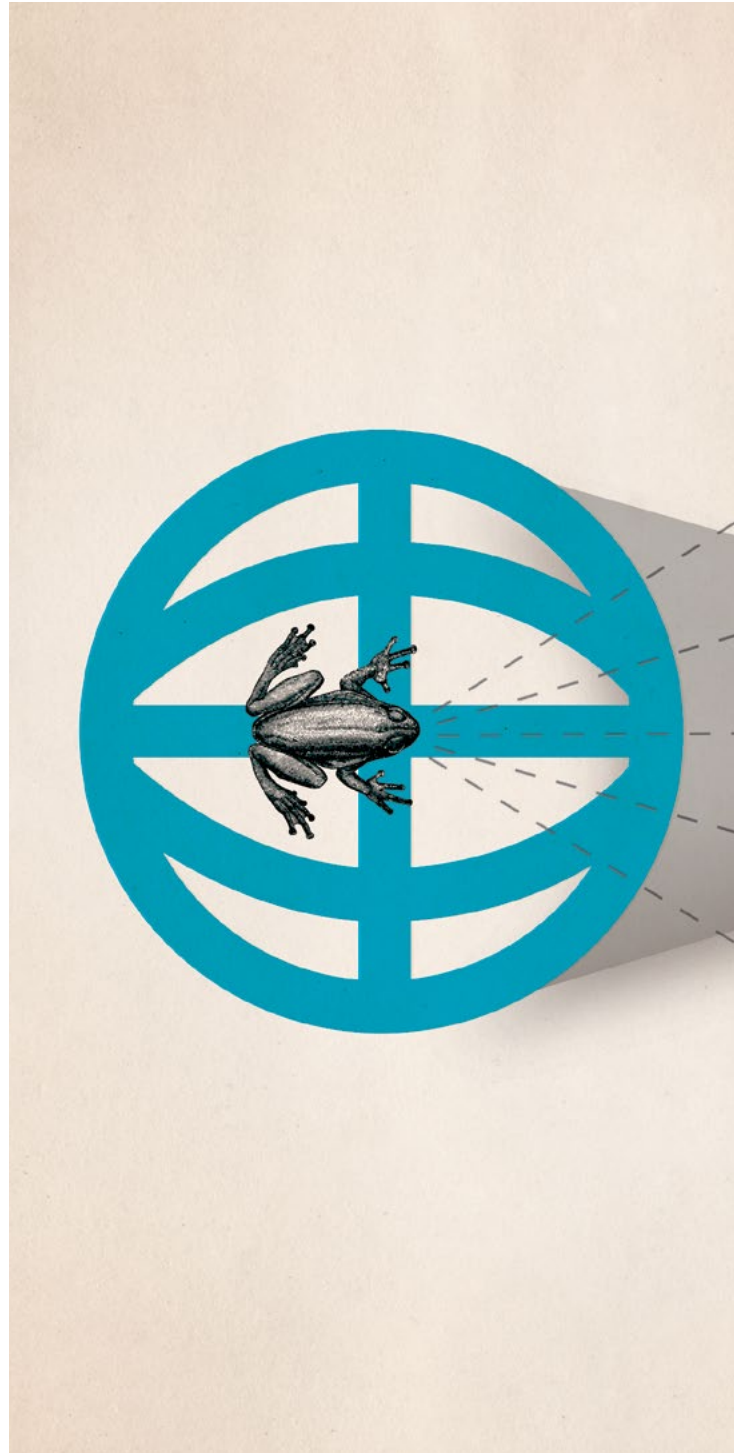
Yet the complexity of all this pales in comparison to the patterns of information processing in your brain. Your roughly 100 billion neurons are constantly generating electrical signals ("firing"), which involves shuffling around billions of trillions of atoms, notably sodium, potassium, and calcium ions. The trajectories of these atoms form an extremely elaborate braid through spacetime, whose complex intertwining corresponds to storing and processing information in a way that somehow gives rise to our familiar sensation of self-awareness. There's

broad consensus in the scientific community that we still don't understand how this works, so it's fair to say that we humans don't yet fully understand what we are. However, in broad brush, we might say this: *You're a pattern in spacetime.* A mathematical pattern. Specifically, you're a braid in spacetime—indeed, one of the most elaborate braids known.

Some people find it emotionally displeasing to think of themselves as a collection of particles. I got a good laugh back in my 20s when my friend Emil addressed my friend Mats as an “*atomhög*,” Swedish for “*atom heap*,” in an attempt to insult him. However, if someone says “*I can't believe I'm just a heap of atoms!*” I object to the use of the word “*just*”: The elaborate spacetime braid that corresponds to their mind is hands down the most beautifully complex type of pattern we've ever encountered in our universe. The world's fastest computer, the Grand Canyon or even the Sun—their spacetime patterns are all simple in comparison.

AT BOTH ENDS OF your spacetime braid, corresponding to your birth and death, all the threads gradually separate, corresponding to all your particles joining, interacting and finally going their own separate ways (as seen in the bottom panel of “Complexity and Life”). This makes the spacetime structure of your entire life resemble a tree: At the bottom, corresponding to early times, is an elaborate system of roots corresponding to the spacetime trajectories of many particles, which gradually merge into thicker strands and culminate in a single tube-like trunk corresponding to your current body (with a remarkable braid-like pattern inside as we described above). At the top, corresponding to late times, the trunk splits into ever finer branches, corresponding to your particles going their own separate ways once your life is over. In other words, the pattern of life has only a finite extent along the time dimension, with the braid coming apart into frizz at both ends.*

This view of ourselves as mathematical braid patterns in spacetime challenges the assumption that we

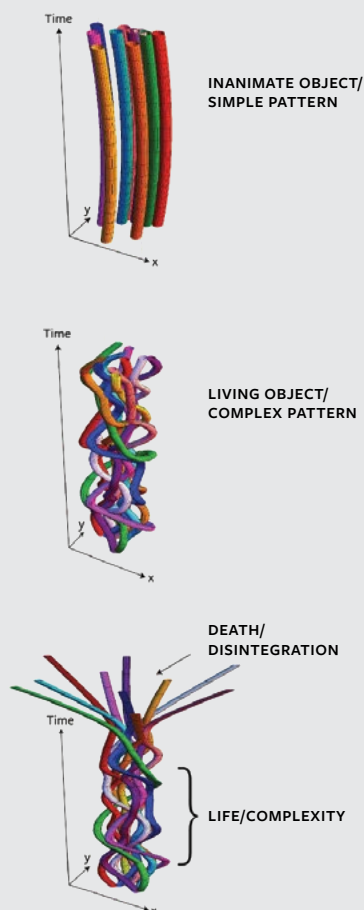


* Quantum mechanics endows you with an even more interesting—but no less mathematical—structure, since a single you (the tree trunk) can split into many branches, each feeling that they're the one and only you.



Complexity and Life

The motion of an object corresponds to a pattern in spacetime. An inanimate clump of 10 accelerating particles constitutes a simple pattern (top), while the particles that make up a living organism constitute a complex pattern (middle), corresponding to the complex motions that accomplish information processing and other vital processes. When a living organism dies, it eventually disintegrates and its particles separate from each other (bottom). These crude illustrations show merely 10 particles; your own spacetime pattern involves about 10^{29} particles and is mind-blowingly complex.



can never understand consciousness. It optimistically suggests that consciousness can one day be understood as a form of matter, a derivative of the most beautifully complex spacetime structure in our universe. Such understanding would enlighten our approaches to animals, unresponsive patients, and future ultra-intelligent machines, with wide-ranging ethical, legal, and technological implications.

This is how I see it. However, although this idea of an unchanging reality is venerable and dates back to Einstein, it remains controversial and subject to vibrant scientific debate, with scientists I greatly respect expressing a spectrum of views. For example, in his book *The Hidden Reality*, Brian Greene expresses unease toward letting go of the notions change and creation as fundamental, writing “I’m partial to there being a process, however tentative [...] that we can imagine generating the multiverse.” Lee Smolin goes further in his book *Time Reborn*, arguing that not only is change real, but that time may be the only thing that’s real. At the other end of the spectrum, Julian Barbour argues in his book *The End of Time* not only that change is illusory, but that one can even describe physical reality without introducing the concept of time at all.

If we discover the ultimate nature of time, this will answer many of the most exciting open questions facing physics today. Did time have some sort of beginning before our Big Bang? Will it ultimately end? Did it emerge out of some sort of timeless quantum fuzz into which it will eventually dissolve? We physicists haven’t found the mathematical theory of quantum gravity required to convincingly answer these questions, but whatever this “theory of everything” turns out to be, time will be the key to unlocking its mysteries. ☺

MAX TEGMARK is an MIT physics professor who has authored more than 200 technical papers. Known as “Mad Max” for his unorthodox ideas and passion for adventure, his scientific interests range from precision cosmology to the ultimate nature of reality, all explored in his new popular science book *Our Mathematical Universe*.



ALICE WELLINGER



Evolution, You're Drunk

DNA studies topple the ladder of complexity

BY AMY MAXMEN

A **MOEBAS ARE PUNY, STUPID** blobs, so scientists were surprised to learn that they contain 200 times more DNA than Einstein did. Because amoebas are made of just one cell, researchers assumed they would be simpler than humans genetically. Plus, amoebas date back farther in time than humans, and simplicity is considered an attribute of primitive beings. It just didn't make sense. The idea of directionality in nature, a gradient from simple to complex, began with the Greeks, who called nature *physis*, meaning growth. That idea subtly extended from changes over an organism's lifetime, to changes over evolutionary time after Charles Darwin argued that all animals descend from a single common ancestor. When his contemporaries drew evolutionary trees of life, they assumed increasing complexity. Worms originated early in animal evolution. Creatures with more complex structures originated later. Biologists tweaked evolutionary trees over the following

century, but generally, simple organisms continued to precede the complex.

Take the textbook scenario on early animal evolution. It essentially goes as follows: Single-celled organisms gained the ability to adhere to and communicate with one another more than 600 million years ago, and from the resulting colonies, the first multicellular animals emerged. Today's sponges, sedentary animals on the sea floor with no guts, brains, or tissue layers, descend directly from some of these creatures. Some early animals then organized their cells into distinct tissue layers, and some of the cells formed nerve cells, muscle cells, and other cell types. Later yet, some animals developed serially repeated segments that served as a platform for legs and claws in their descendants. Then an animal with a spinal column evolved, and then one with a column surrounded by bony vertebrae. A recent branch to split from the tree blossomed into humans.

ILLUSTRATION BY DANIEL HERTZBERG

Scientists' belief in this scenario has remained relatively unchanged for a century. It reflects the growth we observe during an organism's development, and it's been tracked over evolutionary time, too. Paleontologists have found fossils to support this arrangement, and they've also quantified increasing complexity within animal lineages. For example, an analysis of the waves, or sutures, in shells of extinct mollusks called ammonoids—snail-like sisters to nautilus—shows that their designs became eight times as complex over 108 million years.¹

Before the advent of rapid, accurate, and inexpensive DNA sequencing technology in the early 2000s, biologists guessed that genes would provide more evidence for increasing complexity in evolution. Simple, early organisms would have fewer genes than complex ones, they predicted, just as a blueprint of Dorothy's cottage in Kansas would be less complicated than one for the Emerald City. Instead, their assumptions of increasing complexity began to fall apart. First to go was an easy definition of how complexity manifested itself. After all, amoebas had huge genomes. Now, DNA analyses are rearranging evolutionary trees, suggesting that the arrow scientists envisioned between simplicity and complexity actually spins like a weather vane caught in a tornado.

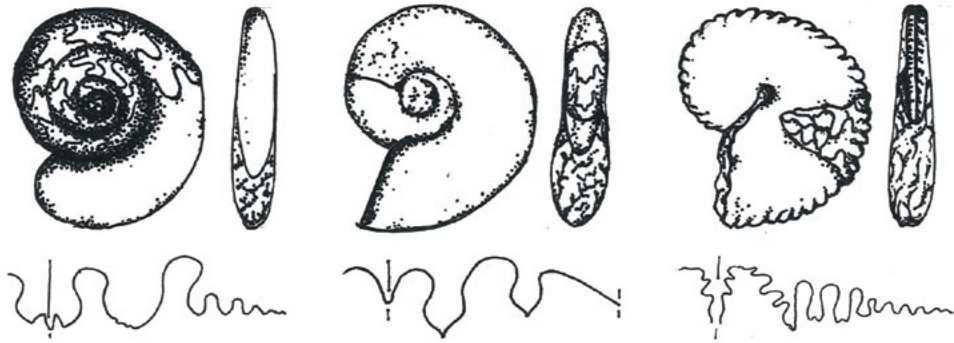
AFTER GENOME SIZES FAILED to fit notions of simplicity and complexity, researchers hypothesized that gene number—genes being the sections of the genome that encode proteins—might instead reflect them. For a few years, that seemed about right. Humans have about 22,000 genes, while the mosquito *Anopheles gambiae* has about 14,000. Then, in 2007, an international team of researchers sequenced the genome of the plant-like sea anemone *Nemastella vectensis*, a marine creature that lacks muscles, a head, rear-end, and brain. To their surprise, anemones had more genes than insects, including some genes that humans possess but flies do not. Even more perplexing: Sea anemones evolved before flies and humans, some 560 million years ago. That meant animals might have been genetically complex from the start. "When I was younger, and we knew less, we thought that organisms gained genes over millions of years and that the earliest animals were genetically very simple," says Bill Pearson, a

Winged stick insects evolved from wingless stick insects who had winged ancestors.

computational biologist at the University of Virginia who developed some of the first techniques to compare protein sequences among organisms. "We think that less now," he adds.

Then molecular analyses did something else. They rearranged the order of branches on evolutionary trees. Biologists pushed aside trees based on how similar organisms looked to one another, and made new ones based on similarities in DNA and protein sequences. The results suggested that complex body parts evolved multiple times and had also been lost. One study found that winged stick insects evolved from wingless stick insects who had winged ancestors.² Another analysis suggested that extremely simple animals called acol worms—a quarter inch long and with just one hole for eating and excreting—evolved from an ancestor with a separate mouth and anus.³ Biologists' arrow of time swung forward and backward and forward again.

Late last year, the animal evolutionary tree quaked at its root. A team led by Joseph Ryan, an evolutionary biologist who splits his time between the National Genome Research Institute in Bethesda, Md. and the Sars International Center for Marine Molecular Biology in Bergen, Norway, analyzed the genome from a comb jelly, *Mnemiopsis leidyi*, a complex marine predator with



AMMONOIDS The waves, or sutures, in the shells of one group of ammonoids became eight times more complex over 108 million years.

muscles, nerves, a rudimentary brain, and bioluminescence, and found that the animals may have originated before simple sponges, which lack all of those features.⁴

If comb jellies evolved before sponges, the sponges might have lost the complexity that the ancestor uniting them and comb jellies possessed. Or, that ancestor—the ancestor of all living animals—had the genes to build brains and muscles, but did not form those parts, and neither did sponges. If this is true, then comb jellies deployed the genome they inherited to build a brain, nervous system, and muscles independent of other animals. There's some support for this possibility: A unique set of genes seems to underlie comb jellies' muscles.

Both hypotheses run counter to scenarios in which organisms evolve to be increasingly complex. In one, a complex nervous system and muscles were lost in the sponges. In the other, the sponges had the genetic capability for complex features but stayed simple, while a more primitive group, the comb jellies, acquired brains and muscles that help them chase down prey. Furthermore, the idea that complex parts like a brain and nervous system—including nerve cells, synapses, and neurotransmitter molecules—could evolve separately multiple times perplexes evolutionary biologists

because parts are gained one at a time. The chance of the same progression happening twice in separate lineages seems unlikely—or so biologists thought. “Traditional views are based on our dependence on our nervous system,” says Ryan. “We think the nervous system is the greatest thing in the world so how could anything lose it,” he says. “Or, it’s the greatest thing in the world, so how could it happen twice.”

WITH COMB JELLIES AT the base of the tree, evolution suddenly seems less like a march towards complexity and more like a meandering stroll. This isn’t a new idea. Back in 1996, evolutionary biologist Stephen Jay Gould posited that evolution progresses like a drunkard’s walk. Organisms, he said, stand an equal chance of becoming simpler or more complex over millions of years—although sometimes there’s a lower limit on how simple they can possibly be, just as a drunk may fall into a gutter at the far left side of the road. An Internet meme even celebrates oddities that result from evolution’s stumble: “Go Home Evolution, You’re Drunk,” features organisms with sub-optimal traits that have managed to survive just fine.

It’s mutations that cause body parts to become simpler or more complex, so to see whether they naturally

Mother Nature does not work like Steve Jobs, continuously designing sleeker versions.

cause one state more often than the other, Jukka Jernvall, an evolutionary biologist at the University of Helsinki in Finland, experimented with teeth. According to the fossil record, mammals' teeth went from tiny, pointy daggers 200 million years ago to more complex shapes with bumps and grooves. "For the first half of [mammals'] existence, teeth were pretty simple," Jernvall says. "Then they went wild."

Jernvall's team induced mutations in genes involved in tooth formation in mice, and found that most of the mutations caused teeth to become simpler than they usually are.⁵ To form a more complex tooth, the team had to induce multiple molecular changes at once. The results suggest that reductions in complexity should evolve more easily than increases in complexity. Without pressure from the environment, teeth would have stayed simple. The fact that they did not means mammals with complex teeth were at a sizable advantage. Jernvall speculates that these mammals feasted on flowering plants that their pointy-toothed sisters

could not grind. “Tooth complexity was ecologically driven through diet,” he says.

Jernvall’s study shows how complexity in tooth shape can evolve, but it does not speak to other trends in mammalian features, such as the number of vertebrae, changes in intelligence, or the number of genes. The sheer number of features for any given organism makes complexity an ineffable trait to grasp, says Dan McShea, an evolutionary biologist at Duke University in Durham, N.C. Shell designs and tooth bumps aren’t inherently perfect reflections of complexity, they’re just amenable to study. Furthermore, he says, people often choose to define complexity by what puts humans on top. If complexity were instead defined by features that allow an organism to survive successfully, he says cyanobacteria might be at the pinnacle level because they have flourished for 3.5 billion years while many lineages of mammals have gone extinct within a fraction of that time. McShea warns, “This impression of directionality may be an illusion.”

Perhaps the fact that people are stunned whenever organisms become simpler says more about how the human mind organizes the world than about evolutionary processes. People are more comfortable envisioning increasing complexity through time instead of reversals or stasis. Physicist Sean Carroll calls humans “terrible temporal chauvinists” for this reason, because they desperately want the street from the past to the future to run in one direction. The textbook scenarios on early animal evolution might be correct, but they should be treated as hypotheses built by temporal chauvinists. When new data suggests a rearrangement, it must be considered no matter how perplexing the conclusion seems.

Casey Dunn, an evolutionary biologist at Brown University in Providence, R.I. who took part in the still-contentious comb jelly project, now doubts all notions of increasing complexity. Instead, he says the environment selects whatever form handles the challenges at hand, be it simple, complex, or plain ugly. Mother Nature, with her 4 billion years of experience, does not work like Steve Jobs, continuously designing sleeker versions. When asked whether de-evolution, a reversal from the complex to the simple, happens frequently, Dunn replies, sure. “But,” he adds, “I wouldn’t call that de-evolution, I’d call it evolution.” ☺

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The Metaphysical Baggage of Physics

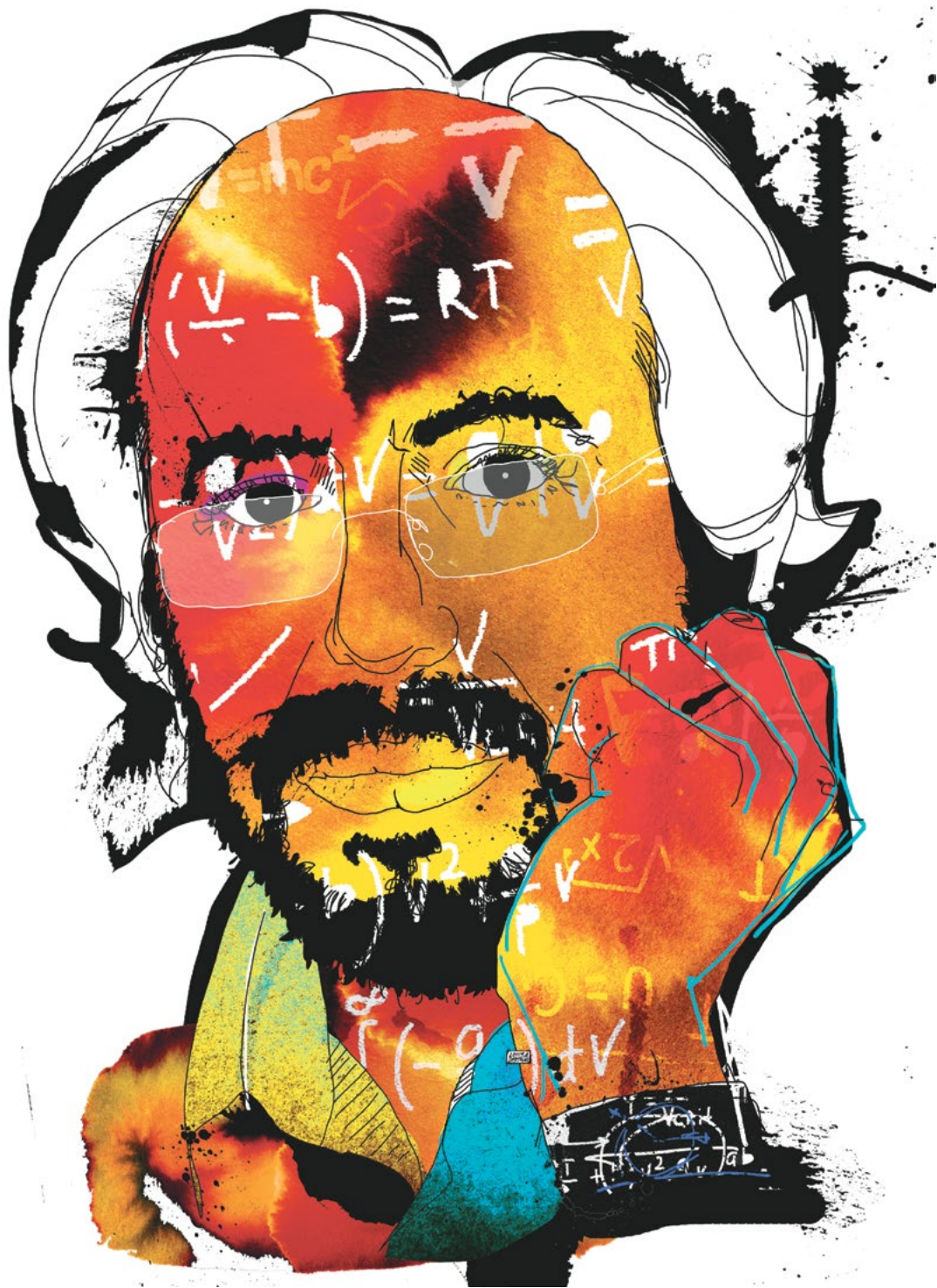
Lee Smolin argues that time is more fundamental than physical laws

BY MICHAEL SEGAL

AN ISSUE ON TIME would not be complete without a conversation with Lee Smolin. High school dropout, theoretical physicist, and founding member of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, Smolin's life and work reflect many of the values of this magazine. Constantly probing the edges of physics, he has also pushed beyond them, into economics and the philosophy of science, and into popular writing. Not one to shy away from a confrontation, his 2008 book *The Trouble with Physics* took aim at string theory, calling one of the hottest developments in the past 50 years of theoretical physics a dead end. In his thinking on time too, he has taken a different tack from the mainstream, arguing that the flow of time is not just real, but more fundamental than physical law.

He spoke to me on the phone from his home in Toronto.

ILLUSTRATION BY LOUISA BERTMAN



How long have you been thinking about time?

The whole story starts back in the '80s when I was puzzling over the failure of string theory to uniquely tell us the principles that determine what the laws of physics are. I challenged myself to invent a way that nature might select what the laws of physics turned out to be. I invented a hypothesis called Cosmological Natural Selection, which was testable, which made explicit predictions. This wasn't my main day job; my main day job was working on quantum gravity where it's assumed that time is unreal, that time is an illusion, and I was working, like anybody else, on the assumption that time is an illusion for most of my career. It took me many years for the indications of Cosmological Natural Selection to sink in—something like 20 or 25 years.

Your Cosmological Natural Selection hypothesis suggests that the laws of nature change in time. How can that be possible?

There are two kinds of explanations as to why some system is one way rather than another way. One is that it has to be that way because there's some fundamental principle that makes it so. In fact, my generation was raised to find the unique set of laws which would satisfy the principles of relativity and quantum mechanics. We thought we would find a unique answer. But now we know that there are many, many different possible laws compatible with the principles of nature. The only other way in science that things

get explained in a way that leads to testable hypotheses is if there's some dynamical process acting in time, which makes the world come out the way it did.

What does that mean for our understanding of time?

The standard view in physics is that time isn't fundamental, and that it emerges as an illusion out of the action of the laws. But if the laws evolve, that can't be the case; time has to be more fundamental. If laws can change in time, then I take that almost as a definition of time being real. The arguments that Einstein and other people give for time being an illusion assume that the laws of nature never change. If they do change, the case that time is an illusion falls apart. It means that time is more fundamental than the laws of nature.

Newton was revolutionary in part because he applied a timeless set of laws to the whole universe. Was he wrong to do so?

Physics was invented by people who happened to be very religious. Newton is one example. For him the laws of nature and their mathematical representations were synonymous with knowing the thoughts of God: Space was the sensorium of God and true time was the time in which God experienced the world and made things in the world. And Newton's style of doing physics works perfectly when you apply it to a small part of the universe, say something going on in a laboratory. But when you take Newton's style of doing physics and apply it to the universe as a whole, you implicitly assume that there is something outside the universe making things happen inside the universe, the same way there's something outside the laboratory system making things happen in the laboratory. What I think has happened is that even physicists who have no religious faith or commitment have gotten sucked into a form of explanation which has a religious underpinning, by which I mean it requires pointing to something outside the universe in order to give a complete explanation. Many people who think of themselves as atheists do this habitually. In my view, it makes them think sloppy thoughts about cosmology. When it comes to extending science to

I like the stories about angels, unicorns, and elves. Now I like those stories as much as anybody else, but when I'm seeking knowledge, the facts are with science.

the universe as a whole, you have to think differently than applying science to a laboratory system.

Is it not possible for our universe to be affected by other universes?

It is possible. But you know, science is not about what might be the case, science is about what we can demonstrate is the case through publicly available evidence. There's an infinite number of things that might be the case: There might be other universes, there might be a platonic realm in which mathematical objects move eternally, there might be God and heaven and angels. But science is not about that. If you want to explain the whole universe within science, you have to explain the laws in terms of things inside the universe itself. I think this is the only aspiration for cosmology that's true to the real spirit of science.

You like to tell a story on your book tours about a rock 'n' roll version of this idea.

My 7-year-old son listens to this CD sometimes to go to sleep, by the band They Might Be Giants. They're a New York rock 'n' roll band. They say, "I like the stories / About angels, unicorns, and elves / Now I like those stories / As much as anybody else/ But when I'm seeking knowledge / Either simple or abstract / The facts are with science." And they go on in succeeding verses to expound a pretty effective philosophy of science. I was so impressed by this.

Where does the cosmology community sit on this spectrum?

I think you have to think very carefully through these issues in order not to lose your way, because there is so much of what the cosmologist Jim Hartle used to call metaphysical baggage infecting our thinking. That's because the roots of our subject come from a time when mysticism, religion, philosophy, and physics were all mixed up. I think the community today is kind of drunk on speculation. Some cosmologists end up speculating about fantasies of the universe really being mathematics. Such things are just not testable, they're metaphysical fantasies. I think that they're

falling for the metaphysical structure that Newton imposed on physics.

If time is real and fundamental, how do we understand the fact that general relativity prohibits a synchronized universal clock for the whole universe?

There are good arguments, some of them coming from the philosopher Hilary Putnam, that if you assume the relativity of simultaneity then you can't objectively distinguish among the past, present, and future. I needed there to be something incomplete about this principle for my viewpoint to be coherent. This held me back for a long time. Then there was a development which was initiated by Julian Barbour himself, it's a little bit ironic, called shape dynamics. After many, many years of work, he and some colleagues came up with a formulation of a gravitational theory which was almost equivalent to general relativity, but with the difference that size is relative. That means you can't compare in absolute terms the sizes of two objects that are far apart. Then three young physicists at the Perimeter Institute, Sean Gryb, Tim Koslowski, and Henrique Gomes, finished it beautifully by making a version of general relativity called shape dynamics in which size rather than time is relative, so there's an absolute global sense of time. That was a very important step for me. It is only with the invention of shape dynamics that I was able to argue that you could believe in a global simultaneity which led to an objective distinguishing of the past, present, and the future.

Does your theory suggest an origin for the arrow of time?

In physics we explain things not just by laws but by initial states. A system starts out in an initial state and then evolves in time subject to a law. One of the great mysteries of cosmology is why is the universe out of thermal equilibrium, so many billions of years after its inception. In the standard thinking this is blamed on the universe having started off in an extraordinarily improbable initial state. The second law of thermodynamics says that systems evolve from a less probable to a more probable state. The arrow of time basically is that process of evolving to more probable states.

Some cosmologists end up speculating about fantasies of the universe really being mathematics. Such things are just not testable, they're metaphysical fantasies.

Now, if time is not real but it just emerges as an approximate description, you have to explain why the future is different from the past, why we remember the past and don't remember the future, why the future seems alterable by things we've tended to do in the past. Given that the initial state is just an accident, you have to explain that too. But if time is real, then these things can just be written into the laws of nature. You don't have to stretch so far to explain the initial conditions. In addition, shape dynamics and gravity explain how systems can be thrown out of equilibrium. That means that there's less to explain about why there's an arrow of time.

You wrote about some of these ideas in your recent book, *Time Reborn*. What has the reaction been?

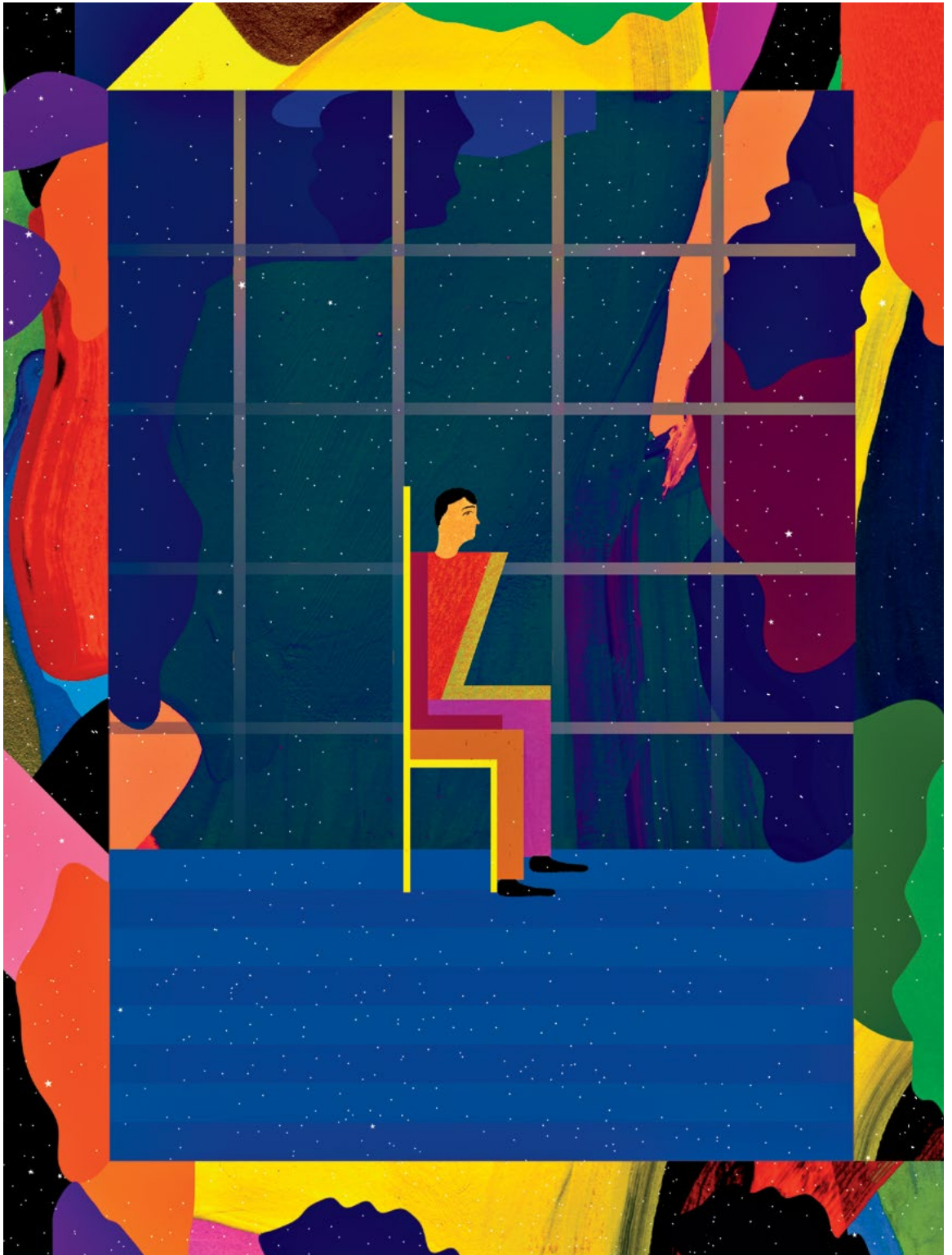
It is not what I thought it would be. I thought that physicists would understand the argument because it is an argument based in physics, and philosophers would be confused by it. But in fact, the opposite has happened. Philosophers really get it. There are symposia that have been organized to discuss the book by philosophers who understand the issue and understand the arguments that the book makes. But physicists really seem to have not gotten it, which I feel badly about since that's the community that I'm actually in and that's who I am—I'm a physicist.

You also have an argument for the realness of time based on philosophy of mind. Can you describe that?

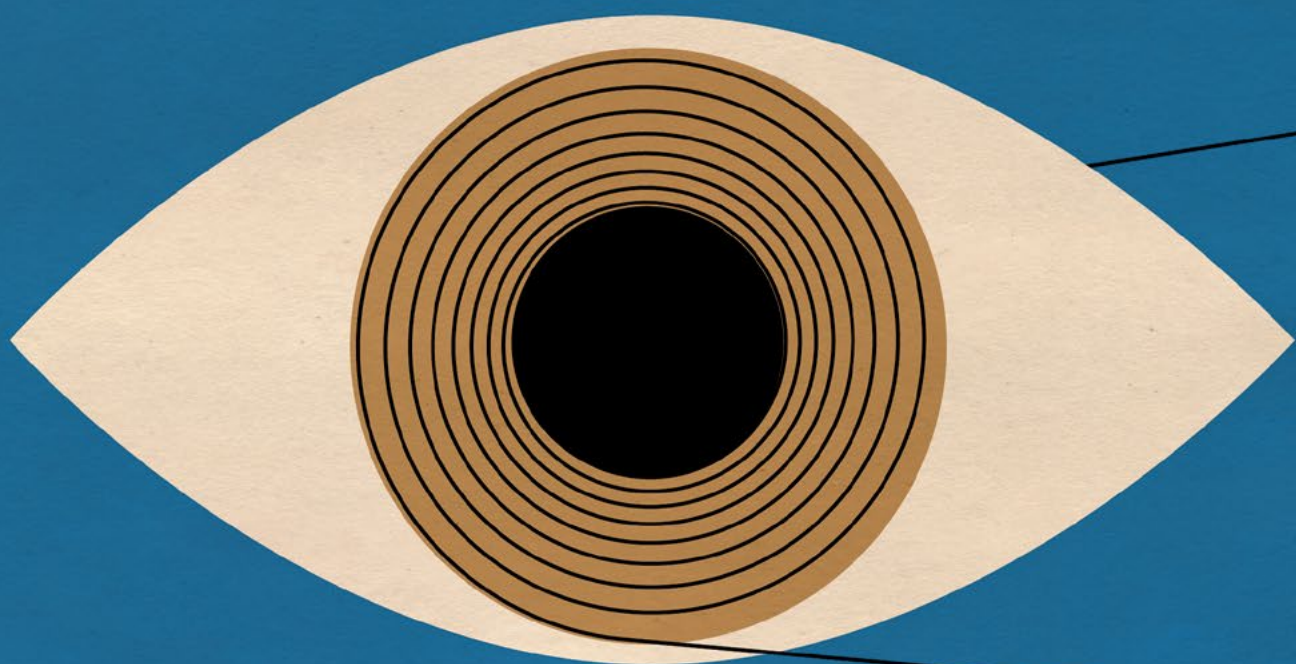
It has to do with wanting a version of naturalism in which the qualia of experience has a natural place, the way that the philosophers Galen Strawson and David Chalmers would argue for it. They want to be naturalists, they want to believe there's a single physical universe, but they also are unpersuaded by the arguments of people like Dan Dennett that qualia are illusions. They think that there is definitely something that we know when we know what the experience of the color red is like, and they want that to be something which is true about the natural world. In a paper called "Temporal Naturalism," I argue that for qualia to be part of the natural world, there have to be intrinsic qualities of that world, which are not relational.

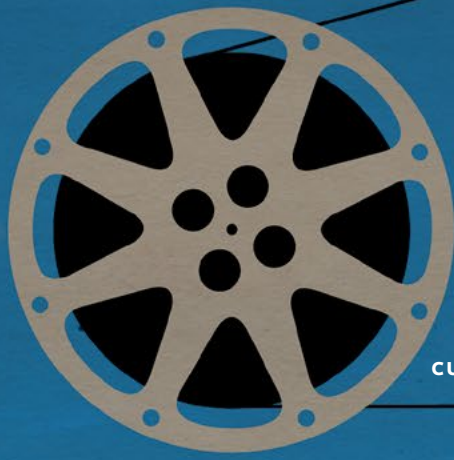
Has your perspective on time affected other parts of your life?

It had an effect on my thinking about my personal life. I was a new parent when I was writing *Time Reborn*. And parenthood certainly leads to a lot of reflections on time and life, and your own mortality, as well as on the miracle of life. To be thinking about those things at the same time as thinking about whether time is real or an illusion, whether there's anything which is permanent or persistent in the world or whether everything changes, these things naturally influence each other. ☺



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CULTURE | PSYCHOLOGY

The Pleasure and Pain of Speed

Are we willing to speed our lives up indefinitely?

BY TOM VANDERBILT

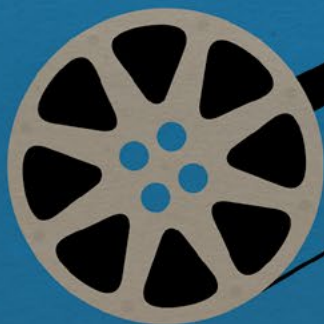


ILLUSTRATION BY CHAD HAGEN

HOW LONG IS NOW? According to Google, not much less than 250 milliseconds. In 2008, the company presented a research report that examined ideal “latency” times for search results. It concluded “that a response time over one second may interrupt a user’s flow of thought.” The ideal latency for a search engine, said Google, was right at the quarter-second mark.

Which seems safe enough, because psychologists have long estimated that it takes us humans at least a quarter of a second to do much of anything. William James, wondering more than a century ago what is “the minimum amount of duration which we can distinctly feel,” had it pegged around 50 milliseconds. James cited the seminal work of Austrian physiologist Sigmund Exner, who observed that people shown sets of flashing sparks stopped being able to recognize them as distinct entities around 0.044 seconds. This “now” time increases as you go up the ladder of complexity.

To do more than barely register an image as a stimulus, to actually see something for what it is, the neuroscientist Christof Koch notes in *The Quest for Consciousness*, requires an average of a quarter of a second (when we are told what to look for, recognition drops to 150 milliseconds). Google’s target response time is just on Koch’s cusp of perceivable consciousness. From there, went the implication of Google’s report, lay a sloping temporal despond: More slow, less happy.

A quarter of a second, then, is a biological bright line limiting the speed at which we can experience life. And the life that we are creating for ourselves, with the help of technology, is rushing toward that line. The German sociologist Hartmut Rosa catalogues the increases in speed in his recent book, *Social Acceleration: A New*

Theory of Modernity. In absolute terms, the speed of human movement from the pre-modern period to now has increased by a factor of 100. The speed of communications (a revolution, Rosa points out, that came on the heels of transport) rose by a factor of 10 million in the 20th century. Data transmission has soared by a factor of around 10 billion.

As life has sped up, we humans have not, at least in our core functioning: Your reaction to stimuli is no faster than your great-grandfather’s. What is changing is the amount of things the world can bring to us, in our perpetual now. But is our ever-quickening life an uncontrolled juggernaut, driven by a self-reinforcing cycle of commerce and innovation, and forcing us to cope with a new social and psychological condition? Or is it, instead, a reflection of our intrinsic desire for speed, a transformation of the external world into the rapid-fire stream of events that is closest to the way our consciousness perceives reality to begin with?

WHATEVER PROTESTS WE HAVE MADE to the march of modernity, notes the historian Stephen Kern, “the world opted for speed again and again.” If Kern is right, and we do like it fast, then there is a natural place to look for evidence: film. It is consumed for pleasure, and therefore a direct indication of our tastes; and also readily quantified, recorded, compared, and reexamined.

Princeton University psychologist Emily Pronin has suggested that film (among other things) does reveal a love of faster cognitive processing—in other words, that thinking faster is correlated with “positive affect.” When she and her colleagues showed clips of *I Love Lucy*—both at normal speed and slightly sped up—to

subjects, they reported feeling happier while watching the faster version (in a delicious turn, the episode in question was the famous *Modern Times* homage in which Lucy gets a job in a candy factory whose conveyor belt begins to accelerate out of control).

Our modern viewing habits are nothing if not consistent with Pronin's conclusion. If we take the human "now" to be, metaphorically, an individual cut of a film—a temporal interlude representing some kind of aesthetic consciousness—life is getting vertiginously fast. In the 2007 thriller *The Bourne Ultimatum*, as the critic Michael Phillips has noted, the set piece in which Bourne must dispatch a rival sent to kill him lasts approximately 109 seconds. From the time he crashes through the window to when he finally subdues the assassin, there are roughly 122 cuts—less than a second per cut. Still well above the threshold of visual perception, but in filmic terms, it is the kind of pacing we once associated with, at its extreme,

Google's target response time is just on Koch's cusp of perceivable consciousness.

the visually and psychically jarring "montage" film-within-a-film in Alan Pakula's 1974 conspiracy film *The Parallax View*. "The miracle," writes Phillips of *Bourne*, "is that it's not simply sickening to watch."

As James Cutting, a professor of psychology at Cornell University, has noted, where average shot lengths during the "classical Hollywood age" timed in around the languorous 10-second mark, today's films are lucky to hit the five-second mark. The average shot length for the *entire* running time of *Quantum of Solace* was 1.7 seconds.

The hyperkinetic nature of Hollywood films has been taken as symptomatic of a larger crisis of attention. In the post-MTV age, the general argument goes, we have lost our ability to endure the long shot,

the slow dissolve, the sustained monologue. "Intensified continuity" is film theorist David Bordwell's phrase for this heightened experience, which includes not only shorter cuts but, among



other things, more frequent close-ups. “Techniques that 1940s directors reserved for moments of shock and suspense,” Bordwell observes, “are the stuff of normal scenes today.”

There is just one thing that complicates this story: At the height of the silent film era, shot lengths were about as short as they are today. Long before MTV, or even television itself—a time when other indices of life were less rapid—audiences were being exposed to the same rapid-fire imagery they are today. Cutting suggests that modern films, rather than being exemplars of some winnowing of attention, may simply be returning toward some natural kind of pacing, featuring “shot patterns that mimic the attention patterns endogenous in our minds.”

While there are pragmatic reasons Hollywood likes shorter cuts—they are easier to edit, for one—Cutting says they also seem perfectly engineered to capture human attention. “Every time there’s a cut in a film,” he says, “it forces you to reallocate your attention.” With each new scene, the eyes typically move toward the center of the screen: *What have we here?* It is a virtually involuntary process.

We handle these quick cuts well, at least for a time, perhaps because they mimic our own vision processes. Koch notes that there is a reason that when we walk through the world, it does not resemble the jittery scene it would if we were to film that walk through a video camera. We have, in effect, our own steady cam. “During the time your eye is in transition, vision is partially shut down,” he writes. “This eliminates blur and the feeling that the world out there is jerked around every fraction of a second.” In the “running movie” of our everyday life, says Koch, there is a kind of director’s cut that is “missing” some 60 to 90 minutes of footage every day, through vision lost to blinks or the eye movements called saccades. According to Cutting, director John Huston believed that “a cut is a surrogate for the real-world combination of saccade and blink.” But the brain fuses these quick cuts together into a seamless whole.

There appears to be something intrinsically appealing about a sped-up subjective experience, and it is certainly one we appear to have chosen when it comes to film. But there is a broader question to ask: Having had this experience, what kind of feeling are we left with?



HERE IS WHERE WHAT Rosa calls the “television paradox” comes into play. While we are actually watching it, television (or movies), “displays all the features of short experiential time,” writes Rosa—intense action, emotional engagement, all those quick cuts, and so on. Time flies by. But once the show is over, “the remembered time rapidly shrinks.” Rather than seeming long in retrospect, as the classic psychological model has it, much of it vanishes. “Decontextualized” and “de-sensualized,” (i.e., we don’t touch, smell, or taste it), Rosa argues, there is little to hang on to after the fact. You binge-watch an entire season in a heady, compressed two-day period, and then what? As Rosa notes, studies have shown that people “express higher satisfaction during the activity of watching TV than after.”

Film and TV are not the only areas where this sort of thing is happening. A useful microcosm of the nature of acceleration is the slot machine, studied by MIT anthropologist Natasha Dow Schüll in her book *Addiction by Design: Machine Gambling in Las Vegas*. Schüll explains that there has been a gradual and consistent process over the past several decades to speed up play on the slot machine: The mechanical handle was dropped in favor of a button. Cumbersome cash payouts (which might disrupt a player’s “flow”) were scrapped for computerized credits. Putting in money was also done away with (no more fumbling for loose change). Mechanical reels, limited by physics, were replaced by “virtual reels,” which players could stop early if they wished. The ability to place a dizzying array of bets across several games at once was added. All of this temporal intensification, notes Schüll, had a curious (if desired) effect: Players actually stayed on the machines *longer* (“time on device,” rather than money, is how executives think about successful slots). As players play faster, so too are there more discrete episodes—“this constant beginning,” she writes, “that is discontinuous with all previous beginnings”—which themselves become less memorable, less *chronological*.

The ultimate goal here, of course, is to stoke the desire of the player to win. Research into what is called “positive approach motivation” has found that when people are in an “appetitive state,” they perceive time to be shorter (in order to help them pursue goals like food or water longer). The effect, argue psychologists Philip Gable and Bryan Poole in *Psychological Science*,

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goes both ways: “A perceived shortening of time causes stimuli to be perceived as more appetitive.” Faster slot machines keep players engaged. Similarly, the constant anticipation of the newest—and increasingly frequent—releases of any number of consumer products keeps us hungry, and makes time feel as if it’s moving faster.

In fact, the accelerated slot machine is a metaphor for what Rosa sees happening in modern life. Even as time-saving technology arrives to pare tedious tasks, there seems to be ever more to do. “We don’t have any time,” he writes, “although we’ve gained far more than we needed before.” Consider email. If writing and sending an email only takes half the time of writing a letter, says Rosa, one should be gaining time. But what happened to the time surplus? It has simply gone into the writing and reading of more emails.

Rosa says the “technical” acceleration of being able to send and receive more emails, at any time, to anyone in the world, is matched by a “social” acceleration in which people are expected to be able to send and receive emails at any time, in any place. The desire to keep up with this acceleration in the pace of life thus begets a call for faster technologies to stem the tide. And faced with a scarcity of time (either real or perceived), we react with a “compression of episodes of action”—doing more things, faster, or multitasking. This increasingly dense collection of smaller, decontextualized events bump up against each other, but lack overall connection or meaning. What is the temporal experience of reading several hundred Tweets versus one article, and what is remembered afterward?

Referring to the theorist Walter Benjamin, Rosa argues that the greater the number of “lived events per unit of time,” the less likely it is these are to transform into “experiences.” Benjamin argued that we tried to capture these moments with physical souvenirs, including photographs, which could later be accessed in an attempt to reinvoke memories. Of course, this process has accelerated, and the physical souvenir is now as quaint as the physical photograph. In Instagram, we have even developed a kind of souvenir of the present: An endless photography of moments suggests that we do not trust that they will actually become moments, as if we were photographing not to know that the event happened, but that it is *happening*.

IN HIS BOOK *Smarter Than You Think*, Clive Thompson suggests that we have long desired to bring technology up to our speed of thought. Nineteenth-century libraries, he notes, were overwhelmed by increasing numbers of books and patrons. “The slow speed,” he writes, “was not just a physical nuisance, but a cognitive one.” And so Melvil Dewey’s ordering schema arrived to hasten the connection between reader and the object of their search. Today, Google’s engineers deploy their algorithmic powers and the processing power of computer clusters to bring us results at the thresholds of our perception. The technology is eminently useful, and exactly what we’ve wanted all along.

We’ve also long been increasing our “transcriptional fluency”—essentially how fast we can write. That’s because writing itself gets in the way of thinking. “For novice and developing writers,” notes *The SAGE Handbook of Writing Development*, “the demands of handwriting and spelling and writers’ relative linguistic inexperience use up valuable capacity in working memory, which hinders cognitive attention to more sophisticated aspects of text creation.” The more we write, the more handwriting and spelling become automatic, the faster and presumably more thoughtful we get. But what about when technology stands as a bottleneck? Thompson notes that the act of note-taking was not so easy in the age of a technology like the fountain pen. Even pencils were considered so laborious, he notes, some educators suggested having early-20th century students use manual typewriters in class. “The faster you can write, the more complete your notes,” he says, “and studies show students with more complete notes tend to do much, much better on tests.” You want, in other words, to be able to write fast enough to keep up with what you are thinking.

As we have shifted from manual typewriters to electric to, finally, digital tools, he suggests that technological speed bump has been eroding. He cites the research of Stanford University literary scholar Andrea Lunsford, who has examined freshmen entrance essays from 1917 until the present. While grammatical error rates have stayed the same, the length and complexity of the essays have dramatically increased. “It’s not that the kids of 1917 were stupider,” says Thompson. “It’s just that their tools were getting in the way of their thought.”

Recent research suggests that there is plenty of acceleration left for us to squeeze out of life. There is evidence, for example, that we can process audio information far faster than we are routinely exposed to it. One study into “compressed speech” found that students’ ability to comprehend audio text did not begin to fall off until well above 300 words per minute—roughly double what they normally heard. The bottleneck is human speech: The most rapid-fire talkers begin to flame out around 200 words per minute.

William James and his 50-millisecond mark for perceiving distinct events may, too, soon look antiquated. In a recent study by M.I.T.’s Mary Potter and colleagues, subjects were able to identify images that they had been exposed to for just 13 milliseconds, even when they had not been told in advance what images to expect. Whether we are actually getting faster, or our technology for measuring the brain is improving, these results point to new possibilities for speed. And when our brains’ own speedometers do saturate, there will be tools promising to speed the brain to keep up with technology. Some are emerging even today. The foc.us headset, for example, uses tDCS (Transcranial Direct Current Stimulation)—i.e., electricity—to, as it claims, “make your synapses fire faster.”

That we enjoy accelerated time, and pay a price for it, is clear. The ledger of benefits and costs may be impossible to balance, or even to compute. As the sociologist John Tomlinson writes in his book *The Culture of Speed: The Coming of Immediacy*, speed “offers both pleasures and pains, exhilarations and stresses, emancipation and domination.” These are often “so intertwined that it seems impossible, as individuals, to say whether an increasing pace of life is, in essence, a good or a bad thing.” But it may be that the most salient feature of accelerating time is not pleasure or pain, but that it is useful, and that we are willing to go a long way for a little bit of extra utility. ☺

TOM VANDERBILT writes on design, technology, science, and culture, among other subjects. His most recent book is *The New York Times* bestseller, *Traffic: Why We Drive the Way We Do (and What It Says About Us)*.



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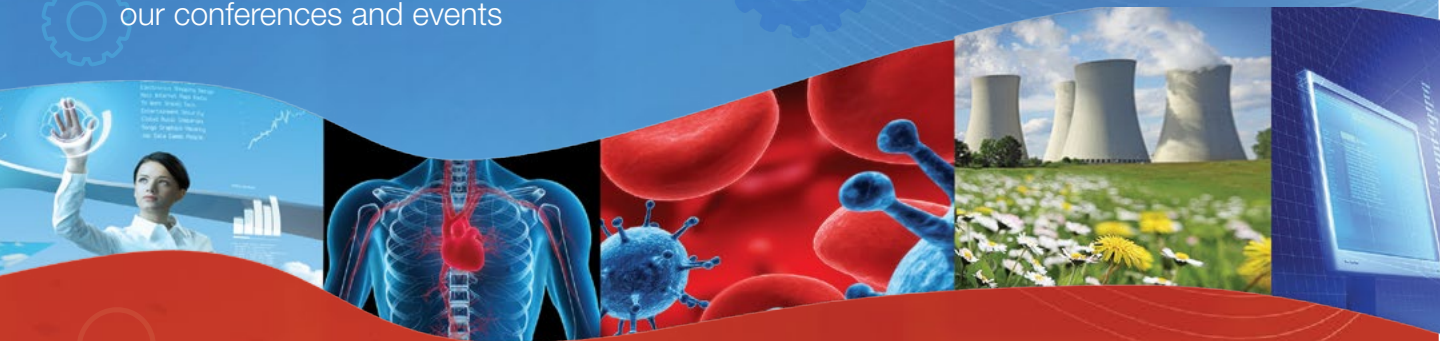
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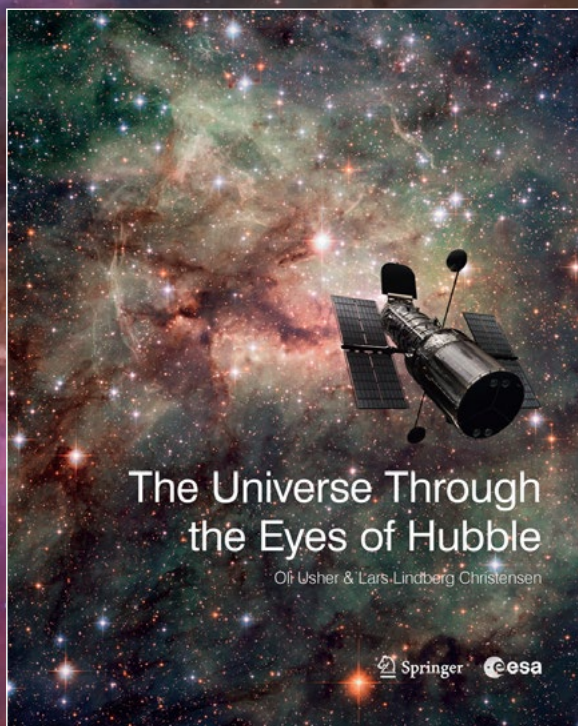
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“Many biological computations are so perfect that they bump up against the mathematical limits of efficiency; genius is our inheritance.”

KELLY CLANCY
“Nature, the IT Wizard” p. 58



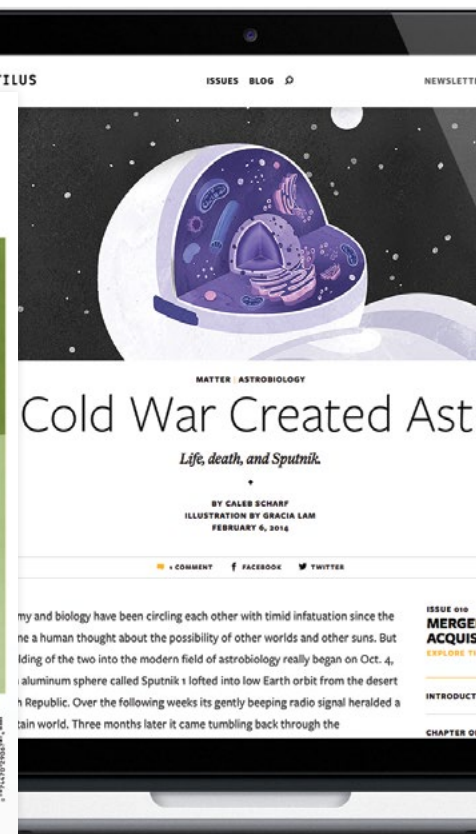
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INTERVIEW BY KEVIN BERGER

ON HOME

I've spent thousands of hours in the sea and lived in underwater laboratories on 10 occasions, the first time in 1970. I love my land-based home and being with my family, my children, my grandchildren. Our household in California includes cats, dogs, horses, chickens, geese, parrots, and goldfish. But I get a very peaceful feeling when I go into the ocean. It's like, "OK, I'm back, here I am!" For most of my life I've been trying to get people to understand the ocean is our home. We're sea creatures as much as dolphins or turtles, whales or barnacle blennies. Without the ocean we couldn't exist. It's part of a living system that makes the planet inhabitable for us. So if you care about life on Earth, yours included, you'll care about the ocean.

ON WASTE

In nature there is no waste. When a whale digests a meal of krill, that's sustenance. It's nitrates and phosphates and minerals that feed the phytoplankton that feed the krill that feed the whale. When a mollusk dies and discards its beautiful shell, hermit crabs say, "Oh, there's

home!" They adopt the shell and put their soft bodies inside for maybe another 40 years. Finally it will disintegrate, but it never goes away. It creates calcium carbonate in the water, and the minerals that have made up that shell become part of the ocean again. But humans, they do create waste. I once saw something glowing in the lights of my little submarine off San Diego. I thought I saw a strange and beautiful, sparkling, reddish-silver sea creature. I very carefully, quietly approached it. It was only when I got right up on top of it that I realized it was a Coke can!

ON TIME

Two years ago, I was in an underwater lab in Virgin Islands National Park. The water was clear, there were sea-grass beds, but where were the fish? What happened to those great forests of coral? About 80 percent of the living reefs in Caribbean water have disappeared since the '70s. The ocean is more acid, the fish populations are steeply declining. It makes me want to run and embrace people and say, "You have to understand, you need to go see for yourselves, we don't have a lot of time." But I also consider this to be the sweet spot in time, because we now know more about the oceans than during all preceding human history. If we can turn that knowledge into caring for the natural world, our oceans have an even chance of emerging from this century stronger than ever. ☻



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