NAUTILUS

Face of Things to Come

OUR TECHNOLOGY PARADOX p.18

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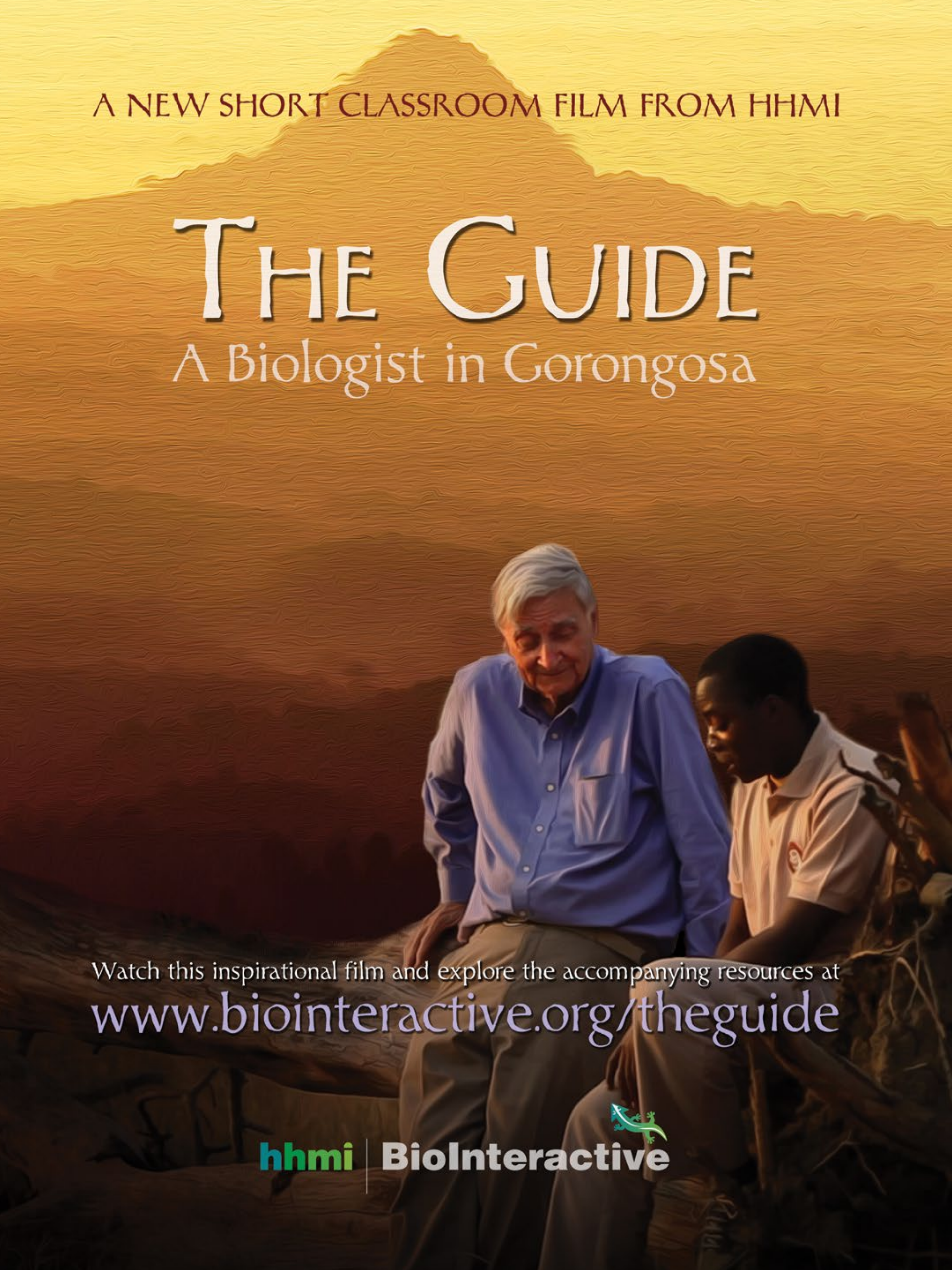
FALL 2014 Science Connected **NAUTIL.US**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The Distant Future, 30 Years On

THIS YEAR MARKS THREE DECADES since 1984, the titular year of George Orwell's classic novel. Among the many articles and events marking this anniversary, I was fortunate to participate in one—a panel discussion. It was unusual in a couple of ways. For one thing, it took place among the concert stages and art-filled forests of England's Latitude Festival. Later in the day, our pavilion was taken over by a rap artist in a feather boa. Rain-soaked revelers in headdresses tripped across the fields outside.

Also unusual was that the panel members were scientists and engineers, not historians or politicians. Wasn't the book really a social commentary, and not a technical one? In re-reading it, I discovered that it was both. In Orwell's dystopia, the ruling class squanders the unprecedented productivity of technology on endless war, to avoid ceding wealth and power to the lower class. They also construct a (vaguely familiar) surveillance state enabled by a diffuse and deeply embedded communications technology.

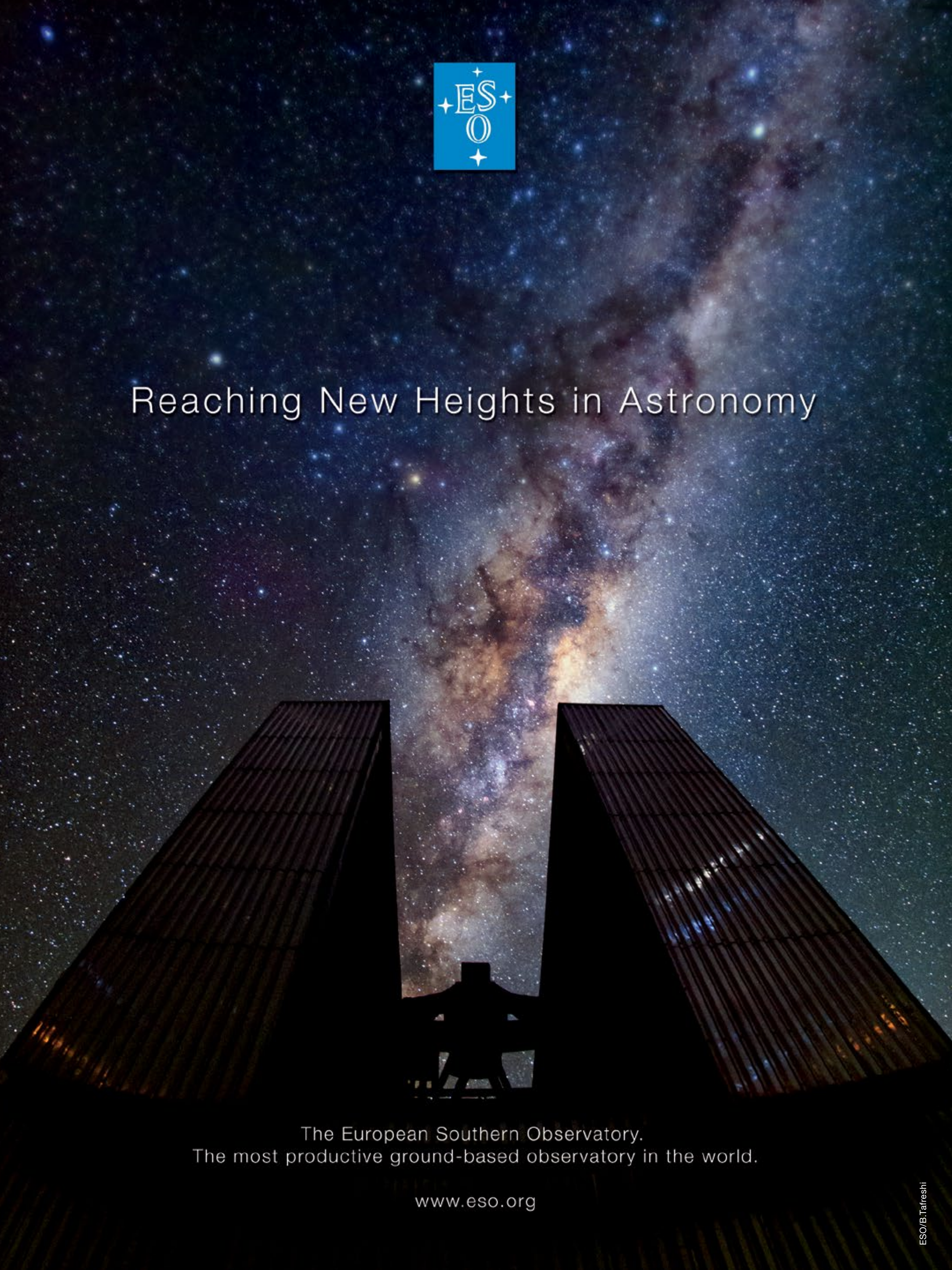
In technology as in culture, Orwell suggests that we are caught in the long, inevitable sweep of history. Are we in control of our technology, he asks, or is it in control of us? This question sits squarely in the *Nautilus* wheelhouse. How could it not? It is, after all, the subject of our fall *Quarterly* cover story.

On page 18, science writer Lee Billings tells us how, while attending a series of brashly optimistic conferences on the Singularity (our radical and imminent transformation through technology), he discovered a more nuanced, humanist, and rational view of the future in the writings of another mid-20th-century thinker: the Polish futurist and science fiction author, Stanislaw Lem. It is too early to celebrate our technological ascension, Lem says, since we will carry our very human strengths and weaknesses with us into the future. Paradoxically, Lem argues, we will be able control our fate only if we cede some of our agency to machines.

Like Orwell, Lem challenges us to think deeply about how we are changing ourselves, consciously or otherwise, and reminds us that, in the broadest view, questions of technology, science, and society become indivisible. And there's nothing more *Nautilus* than that.

Welcome to the fall 2014 *Nautilus Quarterly*.

—Michael Segal
Editor in Chief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Symmetry wields an unusual power, both objective and subjective.

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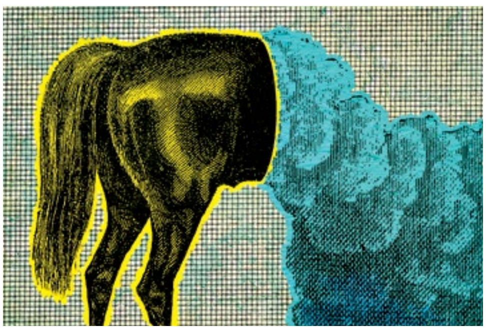

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Change is its own justification.

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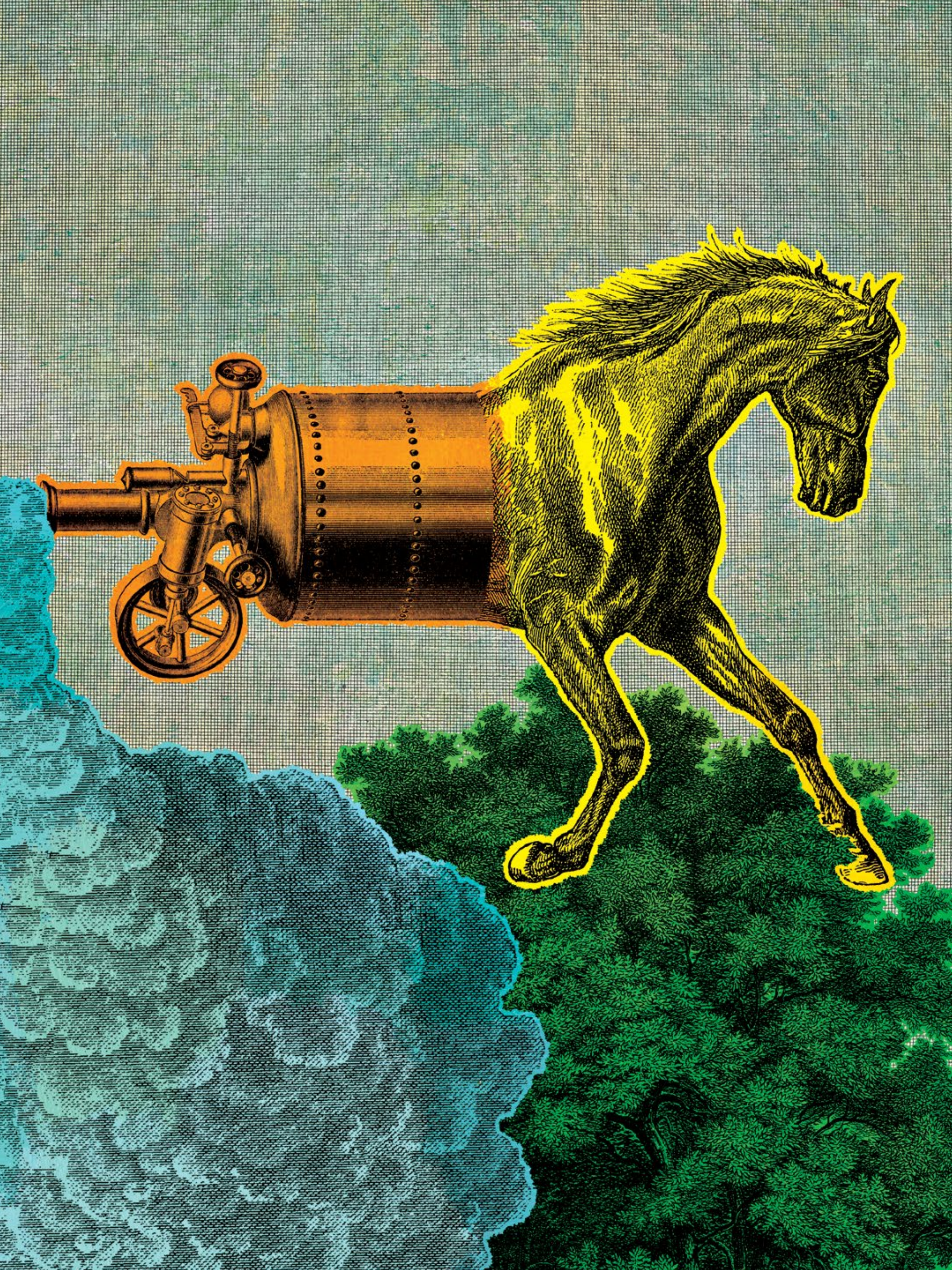

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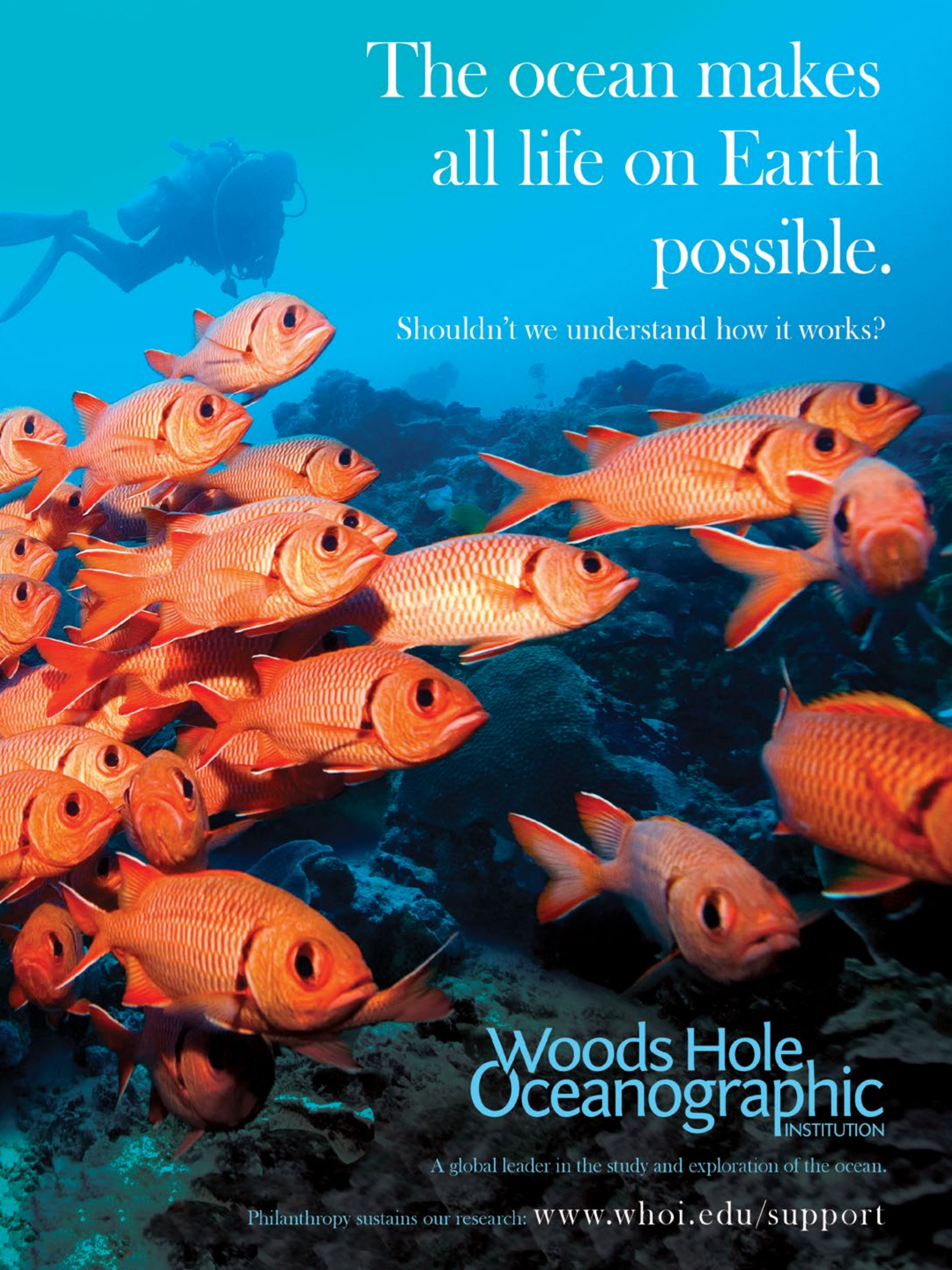
Turbulence

We feel turbulence as much as we know it.

THEME ART Josh Cochran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Publisher and Editorial Director, **John Steele** *Editor in Chief,* **Michael Segal**

500 7th Avenue, 12th Floor,
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212 221 3870 | info@nautil.us

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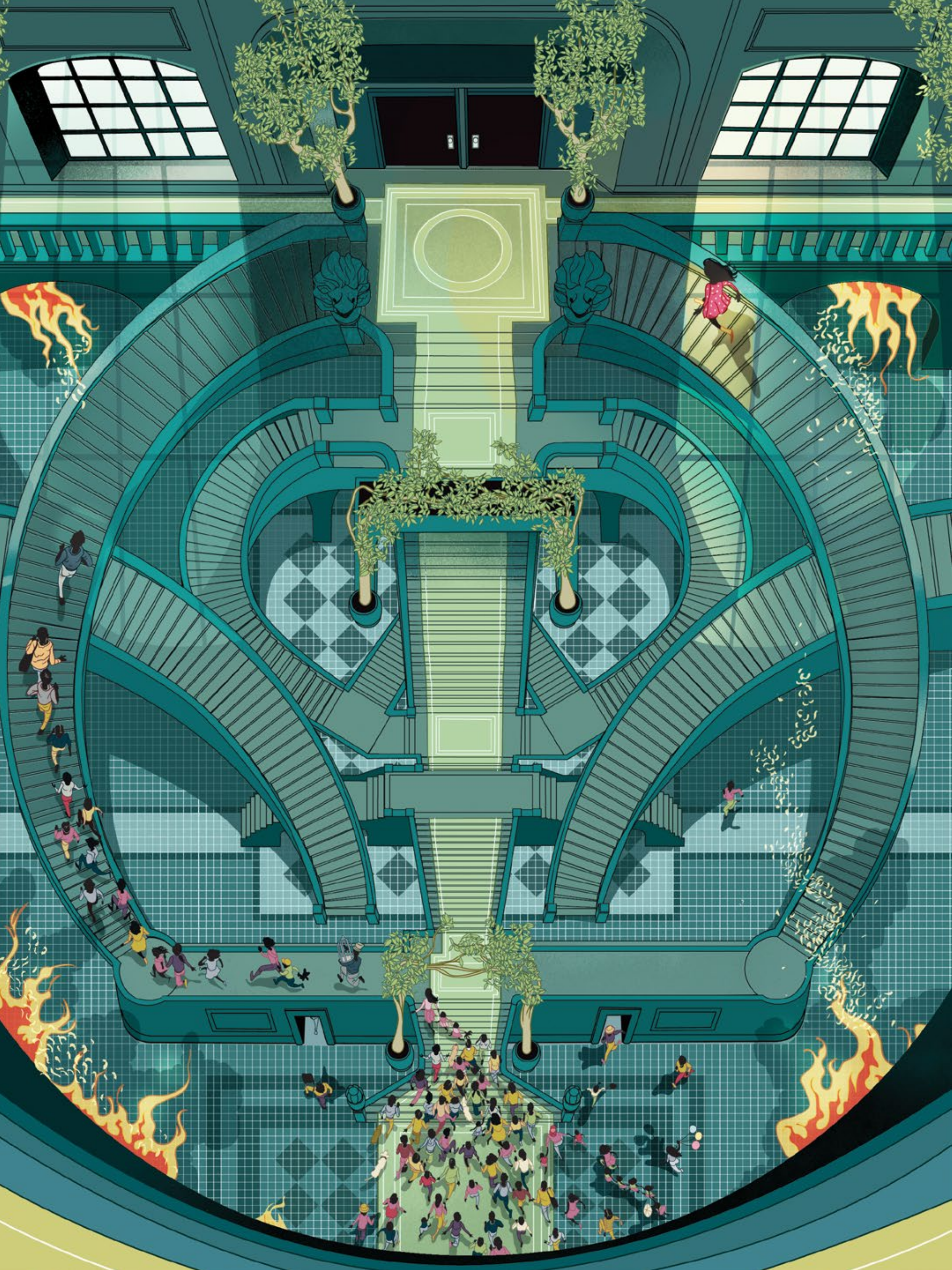


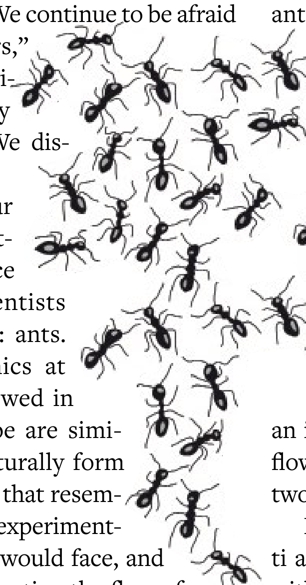
Preludes

PSYCHOLOGY

Wanna Get Out Alive? Follow the Ants.

Ants show that emergency exits can work better when they're obstructed

SINCE 2009, THERE HAVE been fatal stadium stampedes in Morocco, Cote d'Ivoire, Bangkok, and Egypt. Humans just can't learn to exit enclosed spaces properly. We have a tendency to clump together in the face of danger. There are advantages to that—it's easier for a herd to fight off a threat. When humans moved to agrarian and urban lifestyles, our dangers changed, but our responses didn't, says Randolph Nesse, a professor of psychiatry at Arizona State University who studies the evolutionary reasons behind anxiety. "We continue to be afraid of things that were dangerous to our ancestors," Nesse says. In a room with six exits, the most logical action would be for the crowd to divide evenly among all six. Instead, we stampede to just one. We disregard logic and get injured.



But while we may not be able to unlearn our instincts, we might circumvent them if we better understand the nature of escape panic. Since studying panicking humans is difficult, scientists turned to an unexpected source of inspiration: ants. Nirajan Shiwakoti, who studies crowd dynamics at Monash University in Melbourne, Australia, showed in 2011 that the mathematics describing ant escape are similar to those describing human escape. "Ants naturally form collective traffic and follow physical paths in ways that resemble human crowd movement," he says. He began experimenting with the location and nature of exits his ants would face, and discovered something surprising. Creatively obstructing the flow of the panicked ant crowd sped its escape.

Shiwakoti experimented with exit scenarios in petri dishes and found that an exit located in the middle of the dish wall with no obstacles in front of it was the least efficient. It took 50 ants 18 seconds to get through an unobstructed mid-side exit. Adding a column in front of the mid-side exit reduced that time to 14 seconds. A corner exit with a column in front had an escape time of less than 11 seconds. But the best escape time was achieved with a corner exit without a column in front—less than 9.5 seconds.

Shiwakoti says problems arise because these different streams of ants, or people, have to merge at the exit and take turns to pass. People are impatient so they start pushing and shoving. Columns help structure the flow. "The column gives you some channels on the left and on the right, and this reduces the conflict at the exit," he says. The reason the corner exit is so efficient is because it has an intrinsic ability to structure the flow—people are coming from only two directions, left and right.

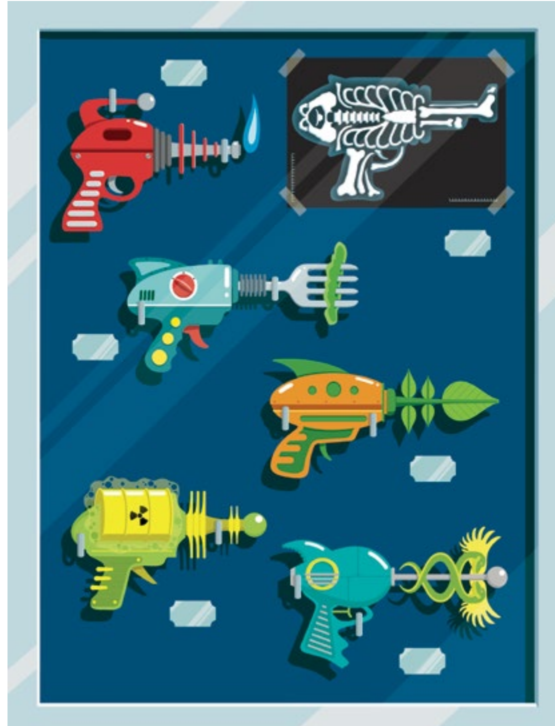
Encouraged by ants, Shiwakoti and his team are experimenting with placing barriers in front of the Melbourne football stadium exits—with promising results. Perhaps we shouldn't be surprised. Ants have been learning how to deal with congestion for millions of years. They might just show us the way out.

—By Conor Mhyrvold

ILLUSTRATION BY MARCOS CHIN

Why You Need Particle Accelerators

They're not just for Big Science anymore

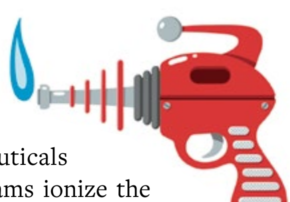


PHYSICISTS USE PARTICLE ACCELERATORS to answer questions of fundamental physics—how our universe was created and why objects have mass. But these machines have been used outside of research labs for decades, and new applications continue to be dreamt up.

MAKING COAL A CLEAN FUEL

Attach an accelerator to the smokestack, and coal may become a clean fuel. Burning coal produces flue gases like nitrogen and sulfur oxides: NO_2, NO_3, SO_2, and SO_3. They react with atmospheric water, producing sulfuric and nitric acids such as H_2SO_4 or HNO_3, eventually spilling back to earth as toxic acid rains. But when these oxides are mixed with ammonia (NH_3) and exposed to electron beams, they can be turned into ammonium sulfate and ammonium nitrate, common fertilizers. The reaction creates dust-like particles that could be gathered with an electrostatic or centrifugal particle separator and put on the field. "Even with the most optimistic projection of renewable energy sources and nuclear power, coal is likely to be providing 20 percent of our energy 20 years from now," says Bob Kephart, director of the Illinois Accelerator Research Center (IARC) at Fermilab. "This is a way to make it more environmentally acceptable." PAVAC, a company in British Columbia, Canada, is working on its first installation of this technology.

TURNING PHARMACEUTICALS INTO FERTILIZER



Sewage sludge is full of nitrogen and phosphorus, which cause algal blooms, and also hormones and antibiotics, which harm fish. But exposing sewage waste to electron beams breaks pharmaceuticals into harmless compounds. The beams ionize the water, producing H_3O^+ and OH radicals and creating a highly reactive environment in which oxidation and reduction reactions happen. This solution can break complex pharmaceutical compounds into basic elements, and kill pathogens as well. "Irradiated sludge can become a material that you could put on a lettuce field," Kephart says. A pilot accelerator plant that cleaned municipal waste was built in Miami in the early '90s, but never commercialized.

KEEPING SPINACH *E. COLI* FREE

Over 40 countries use electron beam irradiation to kill bacteria and parasites such as salmonella or *E. coli* in spinach and other produce. The beam is calibrated to destroy pathogens without affecting produce. The more complicated a molecule, the easier it is for the beam to break—bacterial DNA is more complex than that of a plant, so it falls apart first.

—Lina Zeldovich

ILLUSTRATIONS BY JAMES WALTON

HISTORY

The Surprisingly Useful Fruit of World War I

Strife is the mother of invention

J**UST OVER 100 YEARS** ago, the Archduke Franz Ferdinand of Austria-Hungary was assassinated in Sarajevo. That set into motion a chain of events that soon culminated in the European great powers declaring war on each other.

Once the fighting started, a stalemate emerged on the Western Front, between Germany on the east and the Allies on the west. “The deadlock on the Western Front forced armies to develop new technologies to overcome it,” says Paul Cornish, a British historian.

This race led to the first widespread use of major components of modern warfare like tanks, submarines, and airplanes. Here are some of the more surprising technical innovations that came from WWI:

INDUSTRIAL FERTILIZER

Shortly before the war, German chemists Fritz Haber and Carl Bosch developed a process to convert atmospheric nitrogen into a reactive form: ammonia. During the war, this allowed Germany to produce artificial nitrates used to create explosives, like TNT.

As deadly as this process proved to be during the war, today it sustains one-third of the population on Earth, as it allows the production of ammonia nitrate fertilizer.

AIR TRAFFIC CONTROL

In the early days of flight, pilots had no good way of communicating with each other or the people on the ground. By 1916 American flyers could exchange radio telegrams; in the following year, the first human voice was transmitted by radio from a flying plane to a controller on the ground. The two-way radio systems became the basis for the technology that developed into the air-traffic-control system of today.

PORTABLE X-RAYS

Using funds she raised in Paris, Marie Curie developed small, mobile X-ray machines and installed them in cars and trucks for the French army. She drove some of these portable X-rays to the front lines herself and used the X-rays to locate fractures, bullets, and shrapnel.

SANITARY NAPKINS & TISSUES

A small company in the U.S. called Kimberly-Clark started to make wadding for bandages from Cellucotton, a new cheap, absorbent material. Enterprising Red Cross nurses used it for their personal hygienic use. After the war, Kimberly-Clark re-purchased the surplus of bandages and created the first commercial sanitary napkins. The company also ironed out the material to make the first facial tissues: Kleenex.

— *Simone M. Scully*

SCIENCE COMMUNICATION

One Question for Robert Sapolsky

What would make popular science writing better?

W**HEN WRITERS HEAR SCIENTISTS** have found the gene for doing the bunny hop, or whatever the sound bite is, they should ask, How big of an effect is this? How big of a difference is there between those with this version of the gene and those without it? Is this just intellectually satisfying minutia or does this actually have a big effect? So even more important than getting down the jargon, non-scientists need to be trained to ask about the size and the variability of effects, which basically translates into, Yes, this is a fact that has just been found, but how important is it?

— *Robert Sapolsky is a professor of biology, neurology, and neurosurgery at Stanford University.*

Balloon Mania

Science goes pop

BY AMY MAXMEN

ILLUSTRATION BY JACOB WEINSTEIN

"BALLOON MADNESS" TOOK FLIGHT in Europe and the United States in the late 1700s. At first it was all about science—about exploration, barometric pressures, clouds, weather. Soon the public got in on the fun. Balloon rides became attractions at carnivals and newspaper headlines bursted with magnificent feats and dramatic crashes. Scientists frowned. They felt the excitable masses were making a mockery of their technology and work. Today "balloon madness" stands as a symbol of the excitement and anxiety surrounding the popularization of science.

THE FIRST FLIGHT

In 1783, French inventor Jacques-Étienne and brother Joseph-Michel Montgolfier launched a duck, a sheep, and a rooster aboard a hot-air balloon at Versailles, France.

> "SUCH WONDERS AS THESE FROM BALLOONS SHALL ARISE—
> AND THE GIANTS OF OLD, THAT ASSAULTED THE SKIES
> WITH THEIR OSSA ON PELION, SHALL FREELY CONFESS
> THAT ALL THEY ATTEMPTED WAS NOTHING TO THIS." *

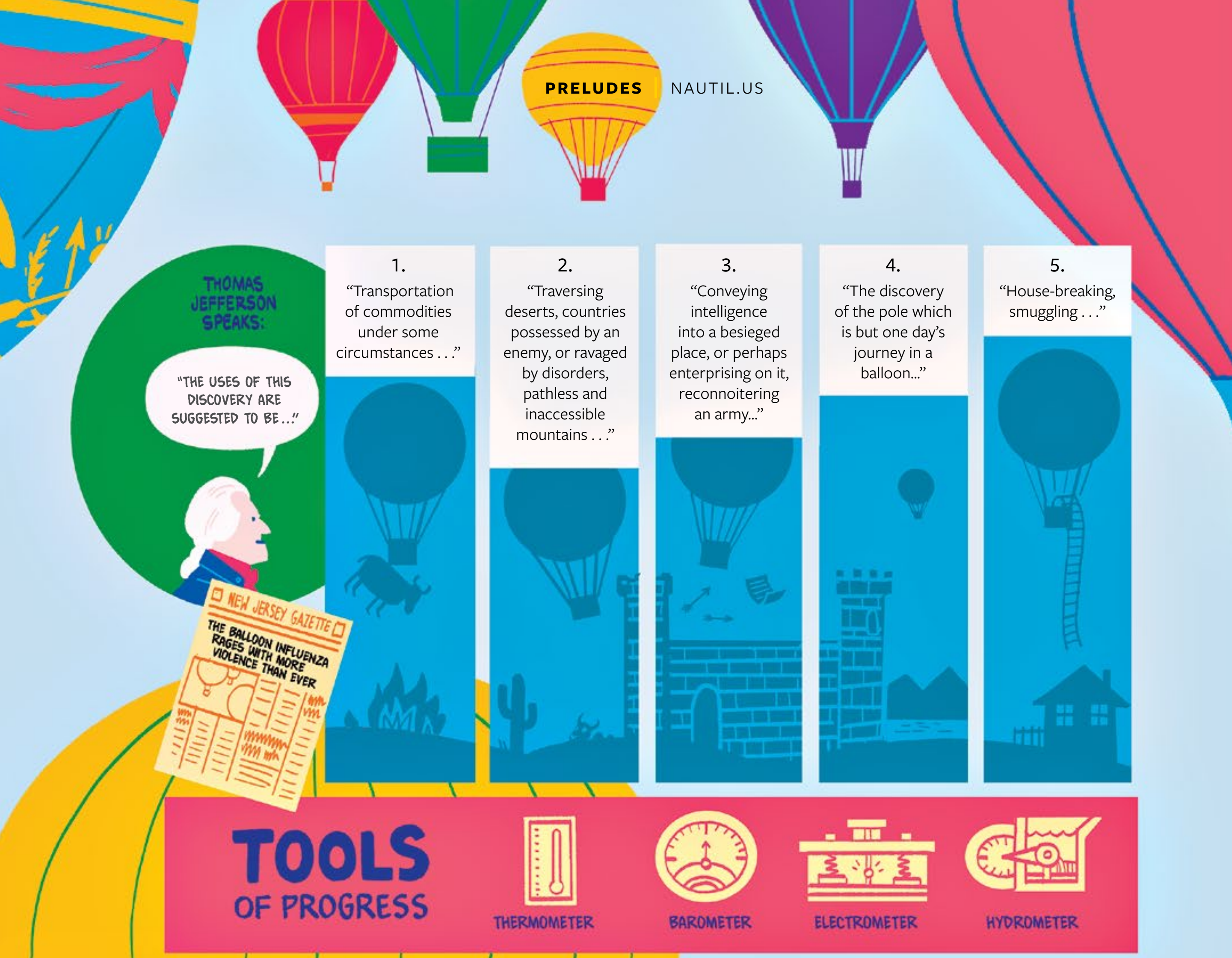
WHEELS

In 1784, Francis Hopkinson wrote to Ben Franklin to suggest a new way to navigate balloons—steering wheels.

* Excerpt from the 1784 poem "The Progress of Balloons"

BIRD DREAMS

In June 1786 the Charleston Evening Gazette reported that an Englishman had built and was exhibiting a balloon "to be drawn in the air by live eagles."



"COULD BACON, BOYLE, OR MIGHTY NEWTON SEE,
SUCH A WRETCHED SPAWN OF NEW PHILOSOPHY,
MERE CHILDREN, OF THEIR AIR BLOWN BUBBLES PROUD,
NO AIM BUT TO DELIGHT THE GAPING CROWD;
SUCH MERE MEN-MONKIES, IN MORTAL SHAPE,
THEY'D VIEW THESE HEROES AS WE VIEW THE APE." *

"I THINK IT VERY MUCH TO BE REGRETTED THAT THIS PURSUIT HAS BEEN UNDERTAKEN BY SO MANY IGNORANT ADVENTURERS… IT SEEMS TO HAVE SHUT THE DOOR AGAINST MEN OF SCIENCE, FOR BALLOONS AND AERIAL TRAVELLERS ARE NOW ON FOOTING WITH RARESHOWS AND ROPEDANCERS." **

**Excerpt from a letter by Jonathan Williams Jr. to his great uncle, Ben Franklin.

UP IN SMOKE

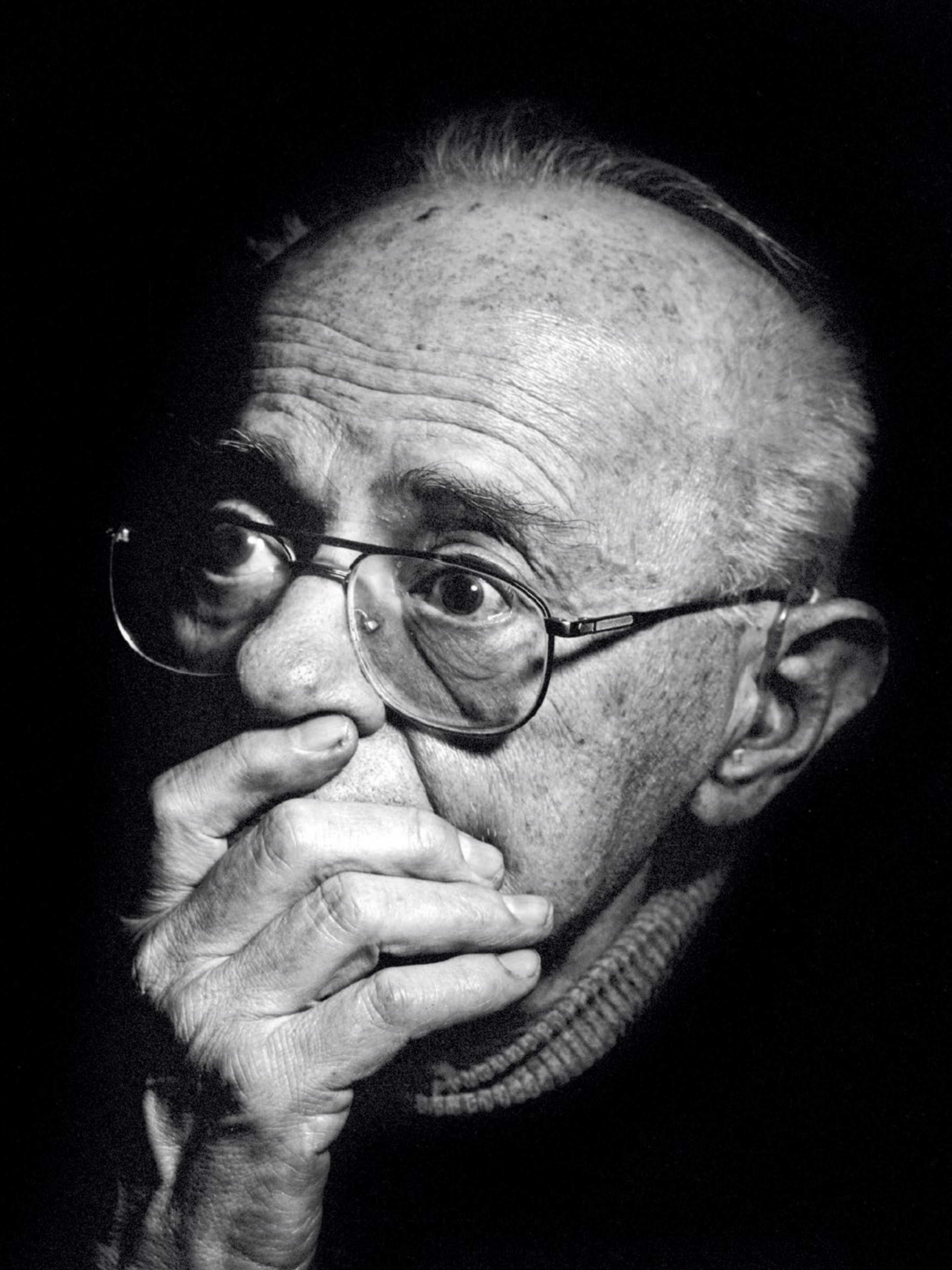
In 1784, wealthy Baltimore landowner Peter Carnes ascended from the yard of Philadelphia's New Work House. The balloon struck the prison wall, caught fire, and exploded. This was not the last explosion.

"THE INVENTION OF BALLOONS, THOUGH FAR-FAMED AND BRILLIANT, CANNOT BE CONSIDERED AS HAVING HITHERTO ADDED MUCH TO THE COMFORT OR UTILITY OF MAN." ***

*Excerpt from the 1785 poem "The Lunar Travelers," *South-Carolina Weekly Gazette*

***Samuel Miller

Source: Pethers, M. "Balloon madness": Politics, Public Entertainment, the Transatlantic Science of Flight, and Late Eighteenth-Century America. *History of Science* **48**, 181-226 (2010).



The Book No One Read

Why Stanislaw Lem's futurism deserves attention

BY LEE BILLINGS

FORUM/UIG/GETTY IMAGES

I **REMEMBER WELL THE FIRST** time my certainty of a bright future evaporated, when my confidence in the panacea of technological progress was shaken. It was in 2007, on a warm September evening in San Francisco, where I was relaxing in a cheap motel room after two days covering The Singularity Summit, an annual gathering of scientists, technologists, and entrepreneurs discussing the future obsolescence of human beings.

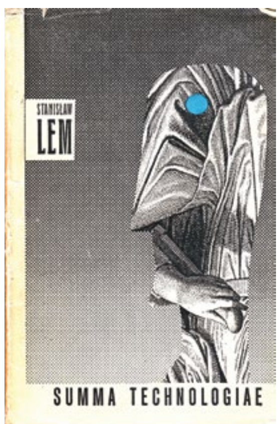
In math, a "singularity" is a function that takes on an infinite value, usually to the detriment of an equation's sense and sensibility. In physics, the term usually refers to a region of infinite density and infinitely curved space, something thought to exist inside black holes and at the very beginning of the Big Bang. In the rather different parlance of Silicon Valley, "The Singularity" is an inexorably-approaching event in which humans ride an accelerating wave of technological progress to somehow create superior artificial intellects—intellects which with predictable unpredictability then explosively make further disruptive innovations so powerful and profound that our civilization, our species, and perhaps even our entire planet are rapidly transformed into some scarcely imaginable state. Not long after The Singularity's arrival, argue its proponents, humanity's dominion over the Earth will come to an end.

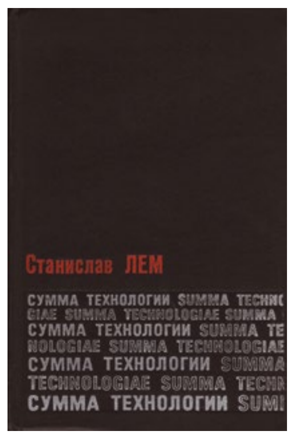
I had encountered a wide spectrum of thought in and around the conference. Some attendees overflowed with exuberance, awaiting the arrival of machines of loving grace to watch over them in a paradisiacal post-scarcity utopia, while others, more mindful of history, dreaded the possible demons new technologies could unleash. Even the self-professed skeptics in attendance sensed the world was poised on the cusp of some massive technology-driven transition. A typical conversation at the conference would refer at least once to some exotic concept like whole-brain emulation, cognitive enhancement, artificial life, virtual reality, or molecular nanotechnology, and many carried a cynical sheen of eschatological hucksterism: Climb aboard, don't delay, invest right now, and you, too, may be among the chosen who rise to power from the ashes of the former world!

Over vegetarian hors d'oeuvres and red wine at a Bay Area villa, I had chatted with the billionaire venture capitalist Peter Thiel, who planned to adopt an "aggressive" strategy for investing in a "positive" Singularity, which would be "the biggest boom ever," if it doesn't first "blow up the whole world." I had talked with the autodidactic artificial-intelligence researcher Eliezer Yudkowsky about his fears that artificial minds might, once created, rapidly destroy the planet. At one point, the inventor-turned-proselytizer Ray Kurzweil teleconferenced in to discuss, among other things, his plans for becoming transhuman, transcending his own biology to achieve some sort of eternal life. Kurzweil believes this is possible, even probable, provided he can just live to see The Singularity's dawn, which he has pegged at sometime in the middle of the 21st century. To this end, he reportedly consumes some 150 vitamin supplements a day.

Returning to my motel room exhausted each night, I unwound by reading excerpts from an old book, *Summa Technologiae*. The late Polish author Stanislaw Lem had written it in the early 1960s, setting himself the lofty goal of forging a secular counterpart to the 13th-century *Summa Theologica*, Thomas Aquinas's landmark compendium exploring the foundations and limits of Christian theology. Where Aquinas argued for the certainty of a Creator, an immortal soul, and eternal salvation as based on scripture, Lem concerned himself with the uncertain future of intelligence and technology throughout the universe, guided by the tenets of modern science.

To paraphrase Lem himself, the book was an investigation of the thorns of technological roses that had yet to bloom. And yet, despite Lem's later observation that "nothing ages as fast as the future," to my surprise most of the book's nearly half-century-old prognostications concerned the very same topics I had encountered during my days at the conference, and felt just as fresh. Most surprising of all, in subsequent conversations I confirmed my suspicions that among the masters of our technological universe gathered there in San Francisco to forge a transhuman future, very few were familiar with the book or, for that matter, with Lem. I felt like a passenger in a car who discovers a blindspot in the central focus of the driver's view.

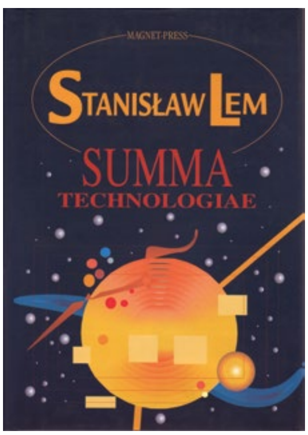




THE LEM ENCYCLOPEDIA (LEM.PL)

Such blindness was, perhaps, understandable. In 2007, only fragments of *Summa Technologiae* had appeared in English, via partial translations undertaken independently by the literary scholar Peter Swirski and a German software developer named Frank Prengel. These fragments were what I read in the motel. The first complete English translation, by the media researcher Joanna Zylinska, only appeared in 2013. By Lem's own admission, from the start the book was a commercial and a critical failure that "sank without a trace" upon its first appearance in print. Lem's terminology and dense, baroque style is partially to blame—many of his finest points were made in digressive parables, allegories, and footnotes, and he coined his own neologisms for what were, at the time, distinctly over-the-horizon fields. In Lem's lexicon, virtual reality was "phantomatics," molecular nanotechnology was "molectronics," cognitive enhancement was "cerebromatics," and biomimicry and the creation of artificial life was "imitology." He had even coined a term for search-engine optimization, a la Google: "ariadnology." The path to advanced artificial intelligence he called the "technoevolution" of "intellectronics."

Even now, if Lem is known at all to the vast majority of the English-speaking world, it is chiefly for his authorship of *Solaris*, a popular 1961 science-fiction novel that spawned two critically acclaimed film adaptations, one by Andrei Tarkovsky and another by Steven Soderbergh. Yet to say the prolific author only wrote science fiction would be foolishly dismissive. That so much of his output can be classified as such is because so many of his intellectual wanderings took him to the outer frontiers of knowledge.



If our technological civilization is to avoid falling into decay, human obsolescence in one form or another is unavoidable.

Lem was a polymath, a voracious reader who devoured not only the classic literary canon, but also a plethora of research journals, scientific periodicals, and popular books by leading researchers. His genius was in standing on the shoulders of scientific giants to distill the essence of their work, flavored with bittersweet insights and thought experiments that linked their mathematical abstractions to deep existential mysteries and the nature of the human condition. For this reason alone, reading Lem is an education, wherein one may learn the deep ramifications of breakthroughs such as Claude Shannon's development of information theory, Alan Turing's work on computation, and John von Neumann's exploration of game theory. Much of his best work entailed constructing analyses based on logic with which anyone would agree, then showing how these eminently reasonable premises lead to astonishing conclusions. And the fundamental urtext for all of it, the wellspring from which the remainder of his output flowed, is *Summa Technologiae*.

The core of the book is a heady mix of evolutionary biology, thermodynamics—the study of energy flowing through a system—and cybernetics, a diffuse field pioneered in the 1940s by Norbert Wiener studying how feedback loops can automatically regulate the behavior of machines and organisms. Considering a planetary civilization this way, Lem posits a set of feedbacks between the stability of a society and its degree of technological development. In its early stages, Lem writes, the development of technology is a self-reinforcing process that promotes homeostasis, the ability to maintain stability in the face of continual change and increasing disorder. That is, incremental advances

The result is a disconcerting paradox: To maintain control of our own fate, we must yield our agency to minds exponentially more powerful than our own.

in technology tend to progressively increase a society's resilience against disruptive environmental forces such as pandemics, famines, earthquakes, and asteroid strikes. More advances lead to more protection, which promotes more advances still.

And yet, Lem argues, that same technology-driven positive feedback loop is also an Achilles heel for planetary civilizations, at least for ours here on Earth. As advances in science and technology accrue and the pace of discovery continues its acceleration, our society will approach an "information barrier" beyond which our brains—organs blindly, stochastically shaped by evolution for vastly different purposes—can no longer efficiently interpret and act on the deluge of information.

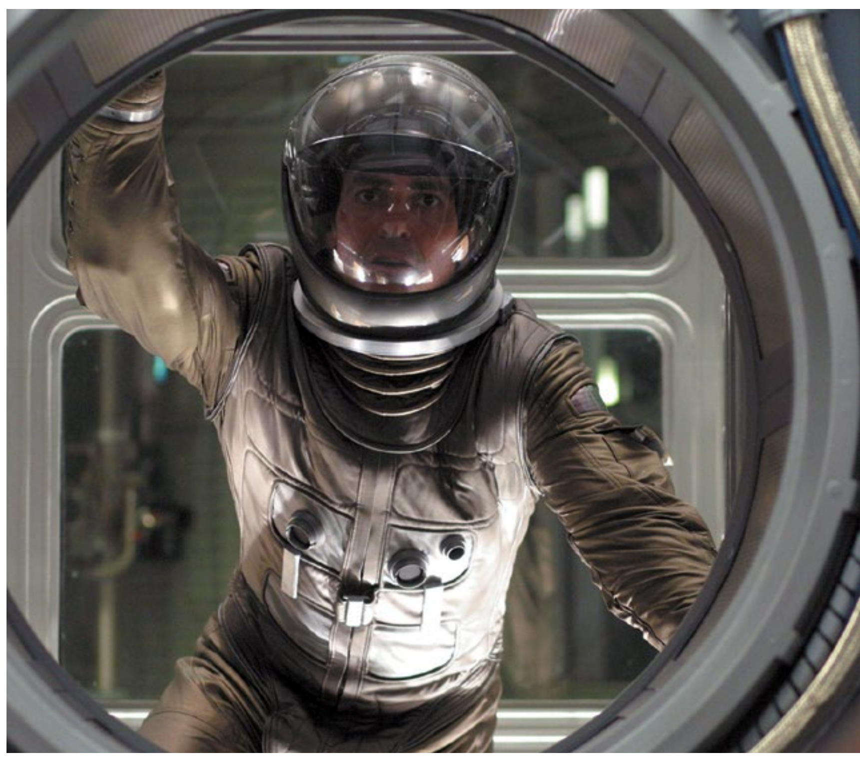
Past this point, our civilization should reach the end of what has been a period of exponential growth in science and technology. Homeostasis will break down, and without some major intervention, we will collapse into a "developmental crisis" from which we may never fully recover. Attempts to simply muddle through, Lem writes, would only lead to a vicious circle of boom-and-bust economic bubbles as society meanders blindly down a random, path-dependent route of scientific discovery and technological development. "Victories, that is, suddenly appearing domains of some new wonderful activity," he writes, "will engulf us in their sheer size, thus preventing us from noticing some other opportunities—which may turn out to be even more valuable in the long run."

Lem thus concludes that if our technological civilization is to avoid falling into decay, human obsolescence in one form or another is unavoidable. The sole remaining option for continued progress would then be the "automatization of cognitive processes" through development of algorithmic "information farms" and superhuman artificial intelligences. This would occur via a sophisticated plagiarism, the virtual simulation of the mindless, brute-force natural selection we see acting in biological evolution, which, Lem dryly notes, is the only technique known in the universe to construct philosophers, rather than mere philosophies.

The result is a disconcerting paradox, which Lem expresses early in the book: To maintain control of our own fate, we must yield our agency to minds exponentially more powerful than our own, created through processes we cannot entirely understand, and hence potentially unknowable to us. This is the basis for Lem's explorations of The Singularity, and in describing its consequences he reaches many conclusions that most of its present-day acolytes would share. But there is a difference between the typical modern approach and Lem's, not in degree, but in kind.

Unlike the commodified futurism now so common in the bubble-worlds of Silicon Valley billionaires, Lem's forecasts weren't really about seeking personal enrichment from market fluctuations, shiny new gadgets, or simplistic ideologies of "disruptive innovation." In *Summa Technologiae* and much of his subsequent work, Lem instead sought to map out the plausible answers to questions that today are too often passed over in silence, perhaps because they fail to neatly fit into any TED Talk or startup business plan: Does technology control humanity, or does humanity control technology? Where are the absolute limits for our knowledge and our achievement, and will these boundaries be formed by the fundamental laws of nature or by the inherent limitations of our psyche? If given the ability to satisfy nearly any material desire, what is it that we actually would want?

Lem's explorations of these questions are dominated by his obsession with chance, the probabilistic tension between chaos and order as an arbiter of human destiny. He had a deep appreciation for entropy, the capacity for disorder to naturally, spontaneously arise and spread, cursing some while sparing others. It was an appreciation born from his experience as a young man in Poland before, during, and after World War II, where he saw chance's role in the destruction of countless dreams, and where, perhaps by pure chance alone,



STAR POWER George Clooney plays the role of Dr. Chris Kelvin in the 2002 film adaptation of Lem's 1961 novel, *Solaris*.

his Jewish heritage did not result in his death. "We were like ants bustling in an anthill over which the heel of a boot is raised," he wrote in *Highcastle*, an autobiographical memoir. "Some saw its shadow, or thought they did, but everyone, the uneasy included, ran about their usual business until the very last minute, ran with enthusiasm, devotion—to secure, to appease, to tame the future." From the accumulated weight of those experiences, Lem wrote in the *New Yorker* in 1986, he had "come to understand the fragility that all systems have in common," and "how human beings behave under extreme conditions—how their behavior when they are under enormous pressure is almost impossible to predict."

To Lem (and, to their credit, a sizeable number of modern thinkers), the Singularity is less an opportunity than a question mark, a multidimensional crucible in which humanity's future will be forged.

I couldn't help thinking of Lem's question mark that summer in 2007. Within and around the gardens surrounding the neoclassical Palace of Fine Arts Theater where the Singularity Summit was taking place, dark and disruptive shadows seemed to loom over the plans and aspirations of the gathered well-to-do. But they had precious little to do with malevolent superintelligences or runaway nanotechnology. Between my motel and the venue, panhandlers rested along the sidewalk, or stood with empty cups at busy intersections, almost invisible to everyone. Walking outside during one break between sessions, I stumbled across a homeless man defecating between two well-manicured bushes. Even within the context of the conference, hints of desperation sometimes tinged the not-infrequent conversations about raising capital; the subprime mortgage crisis was already unfolding that would, a year later, spark the near-collapse of the world's financial system. While our society's titans of technology were angling for advantages to create what they hoped would be the best of all possible futures, the world outside reminded those who would listen that we are barely in control even today.

I attended two more Singularity Summits, in 2008 and 2009, and during that three-year period, all the much-vaunted performance gains in various technologies seemed paltry against a more obvious yet less-discussed pattern of accelerating change: the rapid, incessant growth in global ecological degradation, economic inequality, and societal instability. Here, forecasts tend to be far less rosy than those for our future capabilities in information technology. They suggest, with some confidence, that when and if we ever breathe souls into our machines, most of humanity will not be dreaming of transcending their biology, but of fresh water, a full belly, and a warm, safe bed. How useful would a superintelligent computer be if it was submerged by storm surges from rising seas or disconnected from a steady supply of electricity? Would biotech-boosted personal longevity be worthwhile in a world ravaged by armed, angry mobs of starving, displaced people? More than once I have wondered why so many high technologists are more concerned by as-yet-nonexistent threats than the much more mundane and all-too-real ones literally right before their eyes.

Lem was able to speak to my experience of the world outside the windows of the Singularity conference. A thread of humanistic humility runs through his work, a hard-gained certainty that technological development too often takes place only in service of our most primal urges, rewarding individual greed over the common good. He saw our world as exceedingly fragile, contingent upon a truly astronomical number of coincidences, where the vagaries of the human spirit had become the most volatile variables of all.

It is here that we find Lem's key strength as a futurist. He refused to discount human nature's influence on transhuman possibilities, and believed that the still-incomplete task of understanding our strengths and weaknesses as human beings was a crucial prerequisite for all speculative pathways to any post-Singularity future. Yet this strength also leads to what may be Lem's great weakness, one which he shares with today's hopeful transhumanists: an all-too-human optimism that shines through an otherwise-dispassionate darkness, a fervent faith that, when faced with the challenge of a transhuman future, we will heroically plunge headlong into its depths. In Lem's view, humans, as imperfect as we are, shall always strive to progress and improve, seeking out all that is beautiful and possible rather than what may be merely convenient and profitable, and through this we may find salvation. That we might instead succumb to complacency, stagnation, regression, and extinction is something he acknowledges but can scarcely countenance. In the end, Lem, too, was seduced—though not by quasi-religious notions of personal immortality, endless growth, or cosmic teleology, but instead by the notion of an indomitable human spirit.

Like many other ideas from *Summa Technologiae*, this one finds its best expression in one of Lem's works of fiction, his 1981 novella *Golem XIV*, in which a self-programming military supercomputer that has bootstrapped itself into sentience delivers a series of lectures critiquing evolution and humanity. Some would say it is foolish to seek truth in fiction, or to draw equivalence between an imaginary character's thoughts and an author's genuine beliefs, but for me the conclusion is inescapable. When the novella's artificial philosopher makes its pronouncements through a connected vocoder, it is the human voice of Lem that emerges, uttering a prophecy of transcendence that is at once his most hopeful—and perhaps, in light of trends today, his most erroneous:

"I feel that you are entering an age of metamorphosis; that you will decide to cast aside your entire history, your entire heritage and all that remains of natural humanity—whose image, magnified into beautiful tragedy, is the focus of the mirrors of your beliefs; that you will advance (for there is no other way), and in this, which for you is now only a leap into the abyss, you will find a challenge, if not a beauty; and that you will proceed in your own way after all, since in casting off man, man will save himself."

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


f(x)
x
y
$e^{i\pi}+1=0$
dx
f(x)
$\vec{F}=m\vec{a}$

How I Rewired My Brain to Become Fluent in Math

Sorry, education reformers, we still need memorization and repetition.

BY BARBARA OAKLEY

I **WAS A WAYWARD KID** who grew up on the literary side of life, treating math and science as if they were pustules from the plague. So it's a little strange how I've ended up now—someone who dances daily with triple integrals, Fourier transforms, and that crown jewel of mathematics, Euler's equation. It's hard to believe I've flipped from a virtually congenital math-phobe to a professor of engineering.

One day, one of my students asked me how I did it—how I changed my brain. I wanted to answer *Hell—with lots of difficulty!* After all, I'd flunked my way through elementary, middle, and high school math and science. In fact, I didn't start studying remedial math until I left the Army at age 26. If there were a textbook example of the potential for adult neural plasticity, I'd be Exhibit A.

Learning math and then science as an adult gave me passage into the empowering world of engineering. But these hard-won, adult-age changes in my brain have also given me an insider's perspective on the neuroplasticity that underlies adult learning. Fortunately, my doctoral training in systems engineering—tying together the big picture of different STEM (Science, Technology, Engineering, Math) disciplines—and then my later research and writing focusing on how humans think have helped me make sense of recent advances in neuroscience and cognitive psychology related to learning.

In the years since I received my doctorate, thousands of students have swept through my classrooms—students who have been reared in elementary school and high school to believe that understanding math through active discussion is the talisman of learning. If you can explain what you've learned to others, perhaps drawing them a picture, the thinking goes, you must understand it.

Japan has become seen as a much-admired and emulated exemplar of these active, "understanding-centered" teaching methods. But what's often missing from the discussion is the rest of the story: Japan is also home of the Kumon method of teaching mathematics, which emphasizes memorization, repetition,

ILLUSTRATION BY SAM FALCONER

and rote learning hand-in-hand with developing the child's mastery over the material. This intense after-school program, and others like it, is embraced by millions of parents in Japan and around the world who supplement their child's participatory education with plenty of practice, repetition, and yes, intelligently designed rote learning, to allow them to gain hard-won fluency with the material.

In the United States, the emphasis on understanding sometimes seems to have replaced rather than complemented older teaching methods that scientists are—and have been—telling us work with the brain's natural process to learn complex subjects like math and science.

The latest wave in educational reform in mathematics involves the Common Core—an attempt to set strong, uniform standards across the U.S., although critics are weighing in to say the standards fail by comparison with high-achieving countries. At least superficially, the standards seem to show a sensible perspective. They propose that in mathematics, students should gain equal facility in conceptual understanding, procedural skills and fluency, and application.

The devil, of course, lies in the details of implementation. In the current educational climate, memorization and repetition in the STEM disciplines (as opposed to in the study of language or music), are often seen as demeaning and a waste of time for students and teachers alike. Many teachers have long been taught that conceptual understanding in STEM trumps everything else. And indeed, it's easier for teachers to induce students to discuss a mathematical subject (which, if done properly, can do much to help promote understanding) than it is for that teacher to tediously grade math homework. What this all means is that, despite the fact that procedural skills and fluency, along with application, are supposed to be given equal emphasis with conceptual understanding, all too often it doesn't happen. Imparting a conceptual understanding reigns supreme—especially during precious class time.

The problem with focusing relentlessly on understanding is that math and science students can often grasp essentials of an important idea, but this understanding can quickly slip away without consolidation through practice and repetition. Worse, students often

Teachers can inadvertently set their students up for failure as those students blunder in illusions of competence.

believe they understand something when, in fact, they don't. By championing the importance of understanding, teachers can inadvertently set their students up for failure as those students blunder in illusions of competence. As one (failing) engineering student recently told me: "I just don't see how I could have done so poorly. I understood it when you taught it in class." My student may have thought he'd understood it at the time, and perhaps he did, but he'd never practiced using the concept to truly internalize it. He had not developed any kind of procedural fluency or ability to apply what he thought he understood.

There is an interesting connection between learning math and science, and learning a sport. When you learn how to swing a golf club, you perfect that swing from lots of repetition over a period of years. Your body knows what to do from a single thought—one chunk—instead of having to recall all the complex steps involved in hitting a ball.

In the same way, once you understand why you do something in math and science, you don't have to keep re-explaining the how to yourself every time you do it. It's not necessary to go around with 25 marbles in your pocket and lay out 5 rows of 5 marbles again and again so that you get that $5 \times 5 = 25$. At some point, you just know it fluently from memory. You memorize the idea that you simply add exponents—those little superscript numbers—when multiplying numbers that have the same base ($10^4 \times 10^5 = 10^9$). If you use the procedure a lot, by doing many different types of problems, you will find that you understand both the why and the how behind the procedure very well indeed. The greater understanding results from the fact that your mind constructed the patterns of meaning. Continually focusing on understanding itself actually gets in the way.

I LEARNED THESE THINGS about math and the process of learning not in the K-12 classroom but in the course of my life, as a kid who grew up reading Madeleine L'Engle and Dostoyevsky, who went on to study language at one of the world's leading language institutes, and then to make the dramatic shift to become a professor of engineering.

As a young woman with a yen for learning language and no money or skills to speak of, I couldn't afford to go to college (college loans weren't then in the picture). So I launched directly from high school into the Army. I had loved learning new languages in high school, and the Army seemed to be a place where people could actually get paid for their language study, even as they attended the top-ranked Defense Language Institute—a place that had made language-learning a science. I chose Russian because it was very different from English, but not so difficult that I could study it for a lifetime only to perhaps gain the fluency of a 4-year-old. Besides, the Iron Curtain was mysteriously appealing—could I somehow use my knowledge of Russian to peer behind it?

After leaving the service, I became a translator for the Russians on Soviet trawlers on the Bering Sea. Working for the Russians was fun and engrossing—but it was also a superficially glamorous form of migrant work. You go to sea during fishing season, make a decent salary while getting drunk all the time, then go back to port when the season's over and hope they'll rehire you next year. There was pretty much only one other alternative for a Russian language speaker—working for the National Security Agency. (My Army contacts kept pointing me that way, but it wasn't for me.)

I began to realize that while knowing another language was nice, it was also a skill with limited opportunities and potential. People weren't pounding down my door looking for my Russian declension abilities. Unless, that is, I was willing to put up with seasickness and sporadic malnutrition out on stinking trawlers in the middle of the Bering Sea. I couldn't help but reflect back on the West Point-trained engineers I'd worked with in the Army. Their mathematically and scientifically based approach to problem-solving was clearly useful for the real world—far more useful than my youthful misadventures with math had been able to imagine.

So, at age 26, as I was leaving the Army and casting about for fresh opportunities, it occurred to me: If I really wanted to try something new, why not tackle something that could open a whole world of new perspectives for me? Something like engineering? That meant I would be trying to learn another very different language—the language of calculus.

With my poor understanding of even the simplest math, my post-Army retraining efforts began with not-for-credit remedial algebra and trigonometry. This was way below mathematical ground zero for most college students. Trying to reprogram my brain sometimes seemed like a ridiculous idea—especially when I looked at the fresh young faces of my younger classmates and realized that many of them had already dropped their hard math and science classes—and here I was heading right for them. But in my case, from my experience becoming fluent in Russian as an adult, I suspected—or maybe I just hoped—that there might be aspects to language learning that I might apply to learning in math and science.

You go to sea during fishing season, make a decent salary while getting drunk all the time, then go back to port when the season's over.

What I had done in learning Russian was to emphasize not just understanding of the language, but fluency. Fluency of something whole like a language requires a kind of familiarity that only repeated and varied interaction with the parts can develop. Where my language classmates had often been content to concentrate on simply understanding Russian they heard or read, I instead tried to gain an internalized, deep-rooted fluency with the words and language structure. I wouldn't just be satisfied to know that понимать meant "to understand." I'd practice with the verb—putting it through its paces by conjugating it repeatedly with all sorts of tenses, and then moving on to putting it into sentences, and then finally to understanding not only when to use this form of the verb, but also when not to use it. I practiced recalling all these aspects and variations quickly. After all, through practice, you can understand and translate dozens—even thousands—of words in another language. But if you aren't fluent, when someone throws a bunch of words at you quickly, as with normal speaking (which always sounds horrifically fast when you're learning a new language), you have no idea what they're actually saying, even though technically you understand all the component words and structure. And you certainly can't speak quickly enough yourself for native speakers to find it enjoyable to listen to you.

This approach—which focused on fluency instead of simple understanding—put me at the top of the class. And I didn't realize it then, but this approach to learning language had given me an intuitive understanding of a fundamental core of learning and the development of expertise—chunking.

Chunking was originally conceptualized in the groundbreaking work of Herbert Simon in his analysis of chess—chunks were envisioned as the varying neural counterparts of different chess patterns. Gradually, neuroscientists came to realize that experts such as chess grand masters are experts because they have stored thousands of chunks of knowledge about their area of expertise in their long-term memory. Chess masters, for example, can recall tens of thousands of different chess patterns. Whatever the discipline, experts can call up to consciousness one or several of these well-knit-together, chunked neural subroutines to analyze and react to a new learning situation. This level of true understanding, and ability to use that understanding in new situations, comes only with the kind of rigor and familiarity that repetition, memorization, and practice can foster.

As studies of chess masters, emergency room physicians, and fighter pilots have shown, in times of critical stress, conscious analysis of a situation is replaced by quick, subconscious processing as these experts rapidly draw on their deeply ingrained repertoire of neural subroutines—chunks. At some point, self-consciously "understanding" why you do what you do just slows you down and interrupts flow, resulting in worse decisions.

When I felt intuitively that there might be a connection between learning a new language and learning mathematics, I was right. Day-by-day, sustained practice of Russian fired and wired together my neural circuits, and I gradually began to knit together chunks of Slavic insight that I could call into working memory with ease. By interleaving my learning—in other words, practicing so that I knew not only when to use that word, but when not to use it, or to use a different variant of it—I was actually using the same approaches that expert practitioners use to learn in math and science.

Self-consciously "understanding" why you do what you do just slows you down and interrupts flow, resulting in worse decisions.

When learning math and engineering as an adult, I began by using the same strategy I'd used to learn language. I'd look at an equation, to take a very simple example, Newton's second law of $f = ma$. I practiced feeling what each of the letters meant—f for force was a push, m for mass was a kind of weighty resistance to my push, and a was the exhilarating feeling of acceleration. (The equivalent in Russian was learning to physically sound out the letters of the Cyrillic alphabet.) I memorized the equation so I could carry it around with me in my head and play with it. If m and a were big numbers, what did that do to f when I pushed it through the equation? If f was big and a was small, what did that do to m? How did the units match on each side? Playing with the equation was like conjugating a verb. I was beginning to intuit that the sparse outlines of the equation were like a metaphorical poem, with all sorts of beautiful symbolic representations embedded within it. Although I wouldn't have put it that way at the time, the truth was that to learn math and science well, I had to slowly, day by day, build solid neural "chunked" subroutines—such as surrounding the simple equation $f = ma$—that I could easily call to mind from long term memory, much as I'd done with Russian.

Time after time, professors in mathematics and the sciences have told me that building well-ingrained chunks of expertise through practice and repetition was absolutely vital to their success. Understanding doesn't build fluency; instead, fluency builds understanding. In fact, I believe that true understanding of a complex subject comes only from fluency.

In other words, in science and math education in particular, it's easy to slip into teaching methods that emphasize understanding and that avoid the sometimes painful repetition and practice that underlie fluency. I learned Russian not just by understanding it—understanding, after all, is facile, and can easily slip away. (What did that word понимать mean?) I learned Russian by gaining fluency through practice, repetition, and rote learning—but rote learning that emphasized the ability to think flexibly and quickly. I learned math and science by applying precisely those same ideas. Language, math, and science, as with almost all areas of human expertise, draw on the same reservoir of brain mechanisms.

AS I FORAYED INTO a new life, becoming an electrical engineer and, eventually, a professor of engineering, I left the Russian language behind. But 25 years after I'd last raised an inebriated glass on the Soviet trawlers, my family and I decided to take the trans-Siberian railway across Russia. Although I was excited to take the long-dreamed-of trip, I was also worried. I'd barely uttered a word of Russian in all that time. What if I'd lost it all? What had those years of gaining fluency really bought me?

Sure enough, when we first got on the train, I spoke Russian like a 2-year-old. I'd grasp for words, my declensions and conjugations were all wrong, and my formerly near-perfect accent sounded dreadful. But the foundation was there, and day by day, my Russian improved. And even with my rudimentary Russian, I could handle the day-to-day needs of our traveling. Soon, tour guides were coming to me for help translating for the other passengers. When we finally arrived in Moscow, we hopped in a taxi. The driver, I soon discovered, was intent on ripping us off—heading directly the wrong way and trapping us in a logjam of cars, where he expected us ignorant foreigners to quietly acquiesce to an unnecessary extra hour of meter time. Suddenly, Russian words I hadn't spoken for decades flew from my mouth. I hadn't even consciously known I knew those words.

Underneath it all, when it was needed, the fluency was there—and it quickly got us out of trouble (and into another taxi). Fluency allows understanding to become embedded, emerging when needed.

As I look today at the shortage of science and math majors in this country, and our current trend in how we teach people to learn, and as I reflect on my own pathway, knowing what I know now about the brain, it occurs to me that we can do better. As parents and teachers, we can use simple, accessible methods for deepening understanding and making it useful and flexible. We can encourage others and ourselves to try new disciplines that we thought were too hard—math, dance, physics, language, chemistry, music—opening new worlds for ourselves and others.

As I discovered, having a basic, deep-seated fluency in math and science—not just an "understanding," is critical. It opens doors for many of life's most intriguing jobs. Looking back, I realize that I didn't have to just blindly follow my initial inclinations and passions. The "fluency" part of me that loved literature and language was also the same part of me that ultimately fell in love with math and science—and transformed and enriched my life.

BARBARA OAKLEY is a professor of engineering at Oakland University, Rochester, Michigan, and the author of, most recently, *A Mind for Numbers: How to Excel at Math and Science (Even If You Flunked Algebra)*. She is also co-instructor, with Terrence Sejnowski, the Francis Crick Professor at the Salk Institute, of one of the world's largest online courses, "Learning How to Learn," with Coursera.

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SOME HALF A BILLION years ago, the first animals with bilateral symmetry appeared on Earth. Rather than being shapeless or spherical, they had long axes with a "left" and "right." Their mouths separated from their anuses, allowing their gut to run down the length of their body. Movements became more directed, and nervous systems more complex.

The new layout gave the animals a significant advantage, and is today apparent in most of the animals around us, from worms to humans. Life had enshrined a new, potent form of order.

Symmetry, on first glance a mere detail of arrangement, has unexpected powers, aesthetic, practical—even moral (think of the Golden Rule). We find it in physics, families, and the brain. As shorthand, it heightens our powers of observation, helping us recognize faces and calculate particle interactions. As organizing principle, it steers genes and galaxies. Scientists, long ago convinced that it is mixed into the truth of things, flock to it.

Which leaves us asking—is symmetry the realest thing there is?

Welcome to "Symmetry."

—MS

"When marked with black ink on various parts of their bodies, the dolphins flipped and wriggled in an attempt to see it, convincing the researchers and many others that they recognized themselves."

CHELSEA WALD

"What Do Animals See in a Mirror?" p.78

SYMMETRY

STRUCTURE TAKES WING

When the Earth Had Two Moons

A new model—"The Big Splat"—explains the strange asymmetry of the moon

BY COREY S. POWELL

F**OR MORE THAN HALF** a century, the moon had been mocking the best minds in science, and for Erik Asphaug enough was enough.

The taunting began three years before Asphaug was born. On Oct. 7, 1959, the Soviet Luna 3 spacecraft looped behind the moon, snapping off a series of grainy but distinct photos and then radioing them home. Because the moon's rotation is perfectly synchronized with its revolution, one hemisphere always points toward Earth while the other always points away, unseen. Luna 3's first-ever images of the lunar far side revealed an expanse of rugged, blandly gray highlands—a vista utterly unlike the near side's charismatic, Man-in-the-Moon markings. It didn't take a planetary scientist to recognize the weirdness of that split personality. "I remember as a boy seeing one of the news programs showing the far side of the moon, and thinking it was incredible that a planet could be so different on each side," Asphaug says.

Now it was 2010 and here Asphaug was, a professor of earth and planetary sciences at the University of California, Santa Cruz, attending a colloquium, still waiting for an explanation for the moon's aggressive asymmetry. He listened, increasingly antsy, as his colleague Ian Garrick-Bethell sketched out his proposed answer. In this latest theory, Earth's gravity raised powerful tides on the moon billions of years ago, while it was young and molten. The bulges then froze in place, giving rise to the thicker crust and distinctive geology of the far side. The concept made no sense to Asphaug. "You'd get a bulge on both the far side and the near side, just like when you have high tide on Earth," he says. But the whole point of the theory was to put a bulge on the far side only. "So the answer has to be that some miracle happens to erase the other half. It makes the problem even worse than before."

Asphaug was not only annoyed; he was inspired. For years he has been working to develop models of low-velocity impacts in the early solar system. "People have been biased, looking at impacts and thinking only

ILLUSTRATION BY WEBUYYOURKIDS

about hypervelocity events," he says. "People forgot that things can hit at lower velocities." These kinds of events are constructive rather than destructive: If two objects collide slowly enough they bump and stick together, "like throwing mud at the wall of a house or throwing snowballs at each other." Asphaug had been thinking that low-velocity impacts, what he liked to call "splats," could explain how comets formed. Suddenly he realized he might have the solution to the moon problem sitting right in front of him. He grabbed one of his post-docs, Martin Jutzi (now at the University of Bern), and spelled out his idea. What if Earth originally had two moons, which only later merged into the one we know?

"We went to the lab right after that seminar and Martin coded up the moon being hit by a companion moon," Asphaug says. The result of those computations was a novel interpretation of lunar asymmetry. In Asphaug's view, the jumbled lunar highlands are the wreckage of a second moon that once orbited the Earth, pasted onto the surface of the moon. Small wonder that the far side looks like a different world; it *is* a different world. The new model provides an integrated description of the moon's ancient origin and its modern appearance, but to Asphaug the concept goes deeper than that. It showcases a broader, and largely overlooked, process in planetary formation: the gentle collision, in which two bodies come together in a kiss.

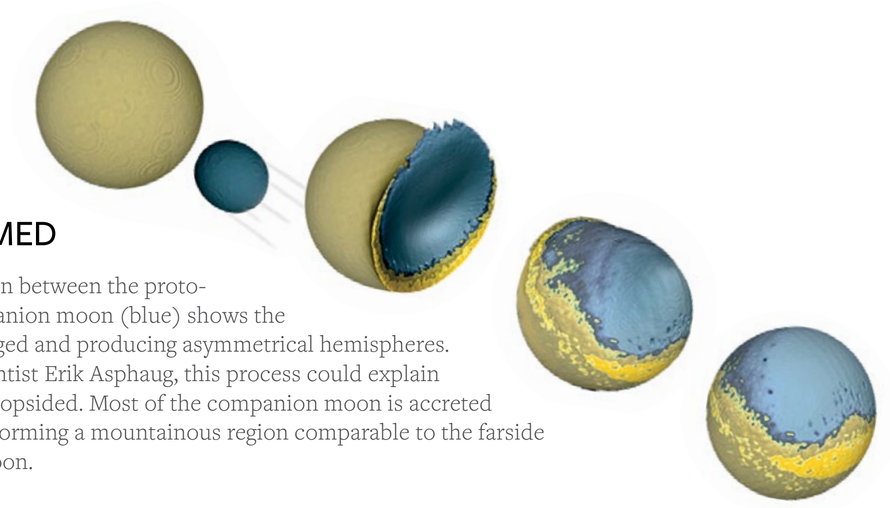
LIKE MOST THEORIES IN science, Asphaug's Big Splat model is sculpted from the marble of previous research. In fact, the first truly scientific description of the origin of the moon is also centered on the interaction between two worlds, but it envisioned a separation rather than a joining. In 1878 George H. Darwin, son of Charles, proposed that the moon was flung off from the fast-spinning newborn Earth, like a wayward child falling off a merry-go-round. The missing chunk of our planet is still evident, he speculated, as the basin of the Pacific Ocean.

That "fission hypothesis" stuck around a long time. I remember reading about it as a child, in the dreamy pre-Apollo science books I inherited from my older brothers—books that predated Luna 3 by a few years. But from a dynamics perspective, it doesn't work. There is no plausible way to get the Earth spinning quickly enough to cast away part of its surface, and even if there were, there is then no way to siphon off enough angular momentum to match the current physical state of the Earth and moon. As for the Pacific Ocean, it is a transient feature associated only with the modern arrangement of the continents. When the moon formed, about 4.4 billion years ago, the Pacific did not exist. (Go easy on Darwin; his theory predated the concept of plate tectonics by nearly 90 years.)

Other lunar origin stories followed, each positing a different relationship between Earth and moon, and each suffering from its own fatal flaw. American astronomer T.J.J. See proposed that the moon formed as an independent planet and was then captured into orbital servitude by the Earth. Flaw: Our planet's gravity is not strong enough to have set the snare. A number of other researchers, most volubly French mathematician Edouard Roche, argued that the moon and Earth coalesced side by side in the early solar system. Flaw: When geochemists started digging into the 842 pounds of rocks returned by the Apollo astronauts, they found that the moon's overall composition is distinct from Earth's, deficient in easily vaporized compounds known as volatiles. A parallel world should be a much closer match.

Not one moon but two? A celestial impact that produces a landslide instead of a catastrophe? Yeah, let us get back to you on that.

Yet in many other ways the moon's chemistry is very similar to Earth's—strangely similar, in fact. The ratio of two different types of oxygen in those lunar rocks matches terrestrial rocks almost perfectly. The oxygen ratio is like an ID tag that tells you where an object formed. Meteorites have their own ratio. Mars has its own ratio. The moon just looks like a twin of the Earth. There you have it: The moon is nothing like the Earth, except that it is also exactly like the Earth. Another,



SPLAT! HOW THE MOON WAS FORMED

This simulation of a collision between the proto-moon (yellow) and a companion moon (blue) shows the lunar masses becoming lodged and producing asymmetrical hemispheres. According to planetary scientist Erik Asphaug, this process could explain how Earth's moon became lopsided. Most of the companion moon is accreted as a pancake-shaped layer, forming a mountainous region comparable to the farside highlands on the Earth's moon.

MARTIN JUTZI & ERIK ASPHAUG

more subtle asymmetry needing to be explained.

Planetary scientists digested all the convoluted evidence and settled on a new creation narrative, the Giant Impact theory, inspired by two groundbreaking 1975 papers. In this model, Earth was born moonless. Then shortly after its formation it collided violently with a Mars-size body, commonly referred to as Theia (the mother of the moon goddess Selene in Greek mythology). The resulting inferno vaporized Theia along with a substantial part of Earth's outer layers. Some of the material was blasted to kingdom come, but much of it settled into a disk around the bruised Earth. Within a very short period of time—perhaps as little as a decade!—the disk had condensed to form the moon.

The Giant Impact theory handily accounts for most of the broad chemical and dynamical attributes of the Earth-moon system. Despite lingering uncertainties, it is almost universally regarded as the best explanation for why the moon exists at all. What it does not do is answer the big, shining question hanging in front of us: Why the hell does the moon *look like that*?

It is not just an issue of cosmetics. The Man-in-the-Moon markings are enormous plains of dark, frozen lava, known as *maria*. For some reason, almost all of the *maria* are on the near side. More generally, the early moon was much more volcanically active on the Earth-facing hemisphere. NASA's moon-orbiting GRAIL (Gravity Recovery and Interior Laboratory) mission measured the lunar crust and confirmed that it's thicker on the far side; the spacecraft also found that the near side (and the near side only) has a network of long, linear, buried features, which planetary geologists interpret as volcanic dikes. The obvious-seeming answer is that Earth's gravity is to blame for all this imbalance, but there is no physically plausible way to make the connection.

"People have been trying to explain the asymmetry for a long time. Ideas keep getting put forward, they get kicked around for a while, and they often don't fare very well," Asphaug says. More often, the issue of the moon's double identity gets swept aside entirely. Last fall, David Stevenson of Caltech co-hosted a major conference on lunar formation at the British Royal Society. He chuckles at the way many of his colleagues talked around the problem: "There's this elephant in the room, but people are sort of ignoring it and they're looking at the cat over in the corner."

IN MANY WAYS, ASPHAUG'S model is an organic extension of the prevailing ideas of lunar formation—in truth, of the whole current thinking about how planets form. The infant solar system gradually built up from dust to rocks to asteroids to planets, all within a swirling disk around the newborn sun, starting a little over 4.5 billion years ago. That story is well established by a library of evidence, from the analysis of meteorites to observations of similar disks around other infant stars. As the planets came together, increasingly large objects had to crash into each other. Some of those crashes had to happen gently enough that the two objects got pasted together into a single, larger one, Asphaug notes. Otherwise the planets would have stopped growing and our solar system would be a swarm of fractured rubble.

Asphaug has spent a career exploring the subtleties of the collision process, first at Santa Cruz and, since 2012, at his current home, Arizona State University. Over the years, he contributed significantly to the mainstream Giant Impact model, helping to refine the mainstream model of Theia as a Mars-size interloper. In the process, he says, "I woke up to the fact that accretion is imperfect and complicated." He became interested in what he calls "almost-accretion" events, ones in which two planets collide incompletely; he came to regard the Giant Impact as just one case in a larger set of possible encounters, ranging from sloppy mergers to hit-and-run impacts in which both planets survive, mostly intact.

"My big learning experience in grad school was realizing how little you had to do before you get to the limits of knowledge in planetary science. It's not like physics where there's 400 years of stuff you have to get through before you can find a problem that's novel and unsolved," Asphaug says. "In planetary science, there are a lot of fundamental questions with no good answers. You start to say, 'That's what you think? *Really?* OK, well I've got an idea, too.' "

His colloquium-room epiphany got Asphaug thinking about what happened right after the Giant Impact. Planetary scientists typically assumed that a single moon emerged from the conflagration, but that was not the only possibility. Asphaug's idea that two moons emerged dovetailed perfectly with his computer modeling for comets. "We had splats on the mind. It was kind of a coincidence," he says.

Matija Cuk at Harvard University had already surmised where a second moon might have come from, filling in a second part of the picture. When the giant impact created a huge, Earth-circling ring of vaporized rock, Cuk noted, there were two points of stability, located 60 degrees ahead of the moon and 60 degrees behind in the same orbit. Those spots were like gravitational tidal pools, calm locations where a second, smaller object could have formed. Cuk did not give this companion moon a name, but for the sake of clarity I'll call it Endymion, after Selene's lover in Greek mythology.

At first, the moon and Endymion coexisted peacefully, but (as often happens in romantic relationships) things changed over time. Gravitational interactions caused the main moon to spiral away from Earth, shifting the dynamics of the whole system. Endymion lost its steady perch and fell into its lover's arms. Cuk theorized that Endymion eventually broke up and rained down on the moon like a hailstorm of asteroids. Asphaug saw a quite different possibility.

"When things co-orbit they hit each other pretty slowly, at about the speed things would fall, so it doesn't create a shock or a lot of melt," Asphaug says. "Instead of thinking of this as a gargantuan impact, it's more like a cosmic landslide. It would be one of the largest landslides you can imagine." In the later stages, the remains of Endymion would be falling at a rate of a few hundred meters per second, just 1/100th the speed of the giant impact that got the process rolling in the first place.

"If you do the calculation you get a bulge where the impactor hits; it's a thickening crust made of slightly lower density material," Asphaug says. The shape of the bulge in his model matches the form of the actual crust on the lunar far side. He estimates that Endymion needed to be about 621 miles (1,000 kilometers) wide to account for the mass of that additional crust; that is a plausible size, about one-quarter the diameter of the modern moon. Such a small body would have cooled to solid rock within 100 million years, the approximate age at which Endymion would have become unstable. As it crumbled down onto the lunar surface, it would have created a hemisphere-wide rubble field, nicely accounting for the thicker crust on the moon's far side.

The Big Splat has additional intriguing consequences. The weight of all that rock landing on one hemisphere of the moon would compress molten material, rich in radioactive elements, and force it toward the other hemisphere, Asphaug notes, "so it creates not only a crustal asymmetry but also a thermal asymmetry." A concentration of heat on one side of the moon could also cause it to expand, creating the dikes seen by the GRAIL spacecraft. Voila: The thick crust of the far side, the volcanic activity of the near side, and the enigmatic lunar dikes, all explained in a single stroke.

Asphaug is less confident that the Big Splat can fully account for the egregious asymmetry that started this whole conversation, the concentration of dark markings solely on the moon's near side. "It's a bit of a stretch," he concedes, because the lava flows that created the lunar maria erupted much later, about a billion years after the formation of the moon. But by explaining the thicker crust on the far side and the greater internal heat on the near side, his model at least sets up the right conditions for the lava to prefer one hemisphere over the other.

The more I listen to Asphaug, the more convincing he sounds. Although the Big Splat can't account for all of the moon's off-kilter anomalies, it does cover an awful lot of them. But in the glacier-speed world of lunar science, Asphaug's ideas have received a lukewarm reaction so far. Not one moon but two? A celestial impact that produces a landslide instead of a catastrophe? Yeah, let us get back to you on that.

Jay Melosh, a veteran planetary scientist at Purdue University and a member of the GRAIL team, raises a concern that the density of the lunar crust is the same on the near side as the far side. It's possible that Endymion simply had the same density as the surface of the moon, but the lack of diversity "at least makes it more difficult to maintain Asphaug's Big Splat model," he says. Stevenson is similarly cautious. "I don't find it convincing but I would not exclude it," he says. "It doesn't emerge naturally from what we think happens after a giant impact." Dynamics experts like Cuk are much more supportive of the model. In the end, though, the primary critique is not that there's any evidence disproving the Big Splat—there isn't, really—but that there isn't enough uniquely supporting it.

Asphaug is sympathetic. "We may have a hypothesis that explains a lot of things but is relatively untestable," he says. "We're starved for data right now." One way forward would be to place a network of seismic stations on the moon, which would make it possible to read the complete history recorded by its internal structure. Whatever happened during the giant impact (if there was one) and the subsequent Big Splat (ditto) must have left its mark deep inside. In two years NASA will launch InSight, a high-precision seismic station for Mars, but every proposal to send an equivalent mission to the moon has been shot down. "It's a sad commentary about how America just put an end to landed lunar missions in the 1970s," Asphaug says. "I think it's going to be the Chinese who will finally get answers."

Fortunately, that glum note is not where the story ends, because there is another way—a whole set of ways—to test Asphaug's model and to learn how planets and moons formed and evolved. Evidence of "almost-accretion" events, he notes, may be all around us. Comets may preserve ancient layered splat structures; the European Space Agency's Rosetta mission, now on its way to Comet Churymov-Gerasimenko, will be able to take a look. Pluto and its large satellite Charon may have formed in a giant impact analogous to the one that formed Earth's moon. The New Horizons spacecraft will make a close flyby in 2015. Mars has its own peculiar north-south asymmetry, and the InSight probe will help investigate whether an impact might be to blame there, too.

As Asphaug continues to run his models, he keeps coming up with more places to investigate. In a paper published last year in *Icarus* he argues that Saturn's complex satellite system might be the result of multiple impacts and mergers, a more elaborate version of the process that made our own moon. His latest idea, now in press, is that the planet Mercury was the victim of one or more hit-and-run impacts as it formed, which would account for both its dense, iron-rich structure and for the improbable presence of water in its searing-hot crust.

The ultimate Man-in-the-Moon message, according to Asphaug, is that planet formation is sloppy and creative and wildly varied, in ways most of his colleagues have overlooked. He wants to make sure he is not missing any part of it. "With modern computer codes, we can explore a very large parameter space," he says with the same geek fervor that propelled him into the lab in 2010. "The fun never stops."

COREY S. POWELL is editor at large at *Discover* magazine, where he writes the Out There column and blog, and acting editor of *American Scientist*.

TWO-STROKE TOILETS

The trouble with time travel

BY JOHN GRANT

ILLUSTRATIONS BY MARCOS CHIN

WHAT'S THIS?" I SAID, looking down at the change the old woman had put down on the counter between us. There were bills of the wrong size and color, clunky-seeming coins that were too big and too dull. I stirred a finger in the little pile.

She glanced down herself, then put a hand to her mouth.

"Oh, I'm so sorry, Mr. Duggan. Blame it on age. I forgot. You're new around here. I—"

I smiled at her. Since Riane and I had moved here to Tarburton-on-the-Moor three or four months ago we'd found that some of the people were prickly and suspicious—"damn' Yanks"—and others tried to be ingratiating only in hopes of making a buck off us. Or a pound off us, I should say. Old Nettie, who owned the general store but nowadays left the business of actually selling the stuff to her sons and daughters and *their* sons and daughters, of whom there seemed to be an unlimited and uniformly stocky supply, wasn't one of the unfriendly ones. From the outset she'd welcomed us, although with the polite reserve of an earlier generation.

"Is it French?" I said, picking up one of the bills. "Ten Shillings," read the copperplate, dried-blood script.

So the money wasn't French. I knew enough about the country we'd come to live in, perhaps for the rest of our lives, that I was aware the Brits had once counted their money in pounds, shillings, and pence. What I'd picked up was a ten-bob note, as they'd once said. I'd never seen one before. It looked a bit like a ten-pound note that someone had shrunk in the laundry. The ten-bob note had disappeared when the currency went decimal—back in the 1970s, I guessed. Where once there'd been twenty shillings to the pound and twelve pennies to the shilling, now there were a hundred new pence to the pound… and the pound was a coin, not a green paper bill like the next one I picked up.

"These are amazing," I said, studying it closely. "Are they still legal tender?"

"It's a mistake, Mr. Duggan," Nettie said, trying to brush the money away from me with her hand. "A misunderstanding. Just some souvenirs of the past I keep in the cash register."

It was obvious the explanation was a lie. Nettie's face was as wrinkled and dark as a fig, and it didn't keep secrets well. But of course I couldn't tell her I knew she was lying to me. I pushed the coins and bills towards her—reluctantly, though, because they interested me.

"They look as if they should be in a museum," I said. "That's a half-crown, isn't it?"

Half a crown. Two shillings and sixpence. Twelve and a half pence in modern currency, except that the half-penny (not to be confused with the old ha'penny coin, which was half an *old* penny) had been abandoned a while ago. I couldn't help thinking the Brits could have made life easier for everyone if they'd called their new coins cents, like other countries did. A hundred cents to the pound. Then there'd be no confusion over pennies and pence.

"Some people still like the old money." Nettie was visibly relaxing a little. It was a Monday morning and there was no one else in the shop except her and me and the smell of shadows. "Money was worth more, back then."

I imagined it had been. In the days when there had been ten-bob notes, ten bob was worth something. Now they were asking you to put the equivalent, a fifty-pence piece, into parking meters.

Nettie still hadn't put the heap of old money away. She'd paused, her hand resting on it, and seemed to be having an internal conversation with herself.

"You and Mrs. Duggan," she said aloud at last, "you're not planning to be just fly-by-nights, are you? You've come to Tarburton to *live*, haven't you, Mr. Duggan?"

"For as long as you'll have us," I said, grinning. "We like it here. If we ever have kids, this is where we want them to grow up."

She drew her head back, looking at me through narrowed gray eyes. "It's about time you hurried up with the little ones, you two. That wife of yours isn't getting any younger."

"Don't let her hear you say that."

Nettie put her hand on mine. "Can I trust you?"

"Yes. Of course."

"Then let me tell you what everyone else around here knows. It's not something I ever do myself, you understand, but..."

RIANE'S PEOPLE HAD ORIGINALLY come from this part of the world, a couple of generations back, and she's always talked of Devon and Dartmoor with that curious form of nostalgia people show for places they've never in fact been to but with which they feel a sort of inherited familiarity. When we'd married eight years ago we'd planned to honeymoon here—"rediscover my roots," as Riane put it—but around that time ABC had unexpectedly not renewed *Alphonse and Claude* for a fifth season (two strongly accented Frenchmen living together in NYC and trying hilariously to pull girls when everybody assumes they're gay), and so I was suddenly out of a job. By the time my agent had sold the pilot of *Birgit and Piotr* (a German lesbian and a gay Russian man, both strongly accented, living in Chicago and trying hilariously to pull appropriate partners when everyone assumes they're an item), we'd had a honeymoon in Wyoming and liked it. Besides, as Riane pointed out to friends when in her cups, we'd only left the trailer twice.

Birgit and Piotr had enjoyed a better run than it deserved. By the time it wound down, to everyone's great relief, I was writing a children's show about a family of vampires—you've probably not seen it, but I think it's maybe the best thing I've done—and then there was *Humphrey the Pussycat*, and it seemed I'd struck gold. *Humphrey* was a quiet hit at home, but where it started breaking records was in the U.K. At last Nickelodeon called it a day, but there was a production company in Abingdon, near Oxford, that wanted to pick up the reins.

All this time Riane had been teaching at MIT. When she was offered a research fellowship at Exeter, it seemed obvious to both of us that we should grab the chance to go live where her grandfather was born. We'd had ideas of a grand old mansion in the middle of the moor, with creaking doors and ghosts and rusty suits of armor, but reality set in fairly fast and we bought a big red house on the fringe of Tarburton instead.

Tarburton was about an hour's drive from Exeter, which isn't too strenuous as commutes go. I had script conferences on *Humphrey* no more than once a month or so in Abingdon, which was a fairly easy journey from Newton Abbot, the nearest rail hub. We could drive to the moor in less than five minutes, walk to the nearest pub in three. And, despite the unfriendliness of some of the natives, we loved it here.

"I CAN'T BELIEVE I'm doing this," said Riane. "Correction. I can't believe I'm allowing *you* to do this."

I knew what she meant. There are things that the creator and scriptwriter for *Humphrey the Pussycat* can do that are taboo to researchers attempting to reconcile string theory with General Relativity, one of Riane's current bugbears. It wasn't so much that she knew that what Nettie had told me was a physical impossibility, more that she knew the physics was several orders of magnitude more complicated than I did.

It was a pleasant summer evening at the edge of Dartmoor. We were probably about a mile away from where, a few weeks after we'd arrived in Tarburton, Riane and I had spent a pleasant hour or so in the darkness of a warm night "testing Dartmoor to see if it worked," as Riane put it. It hadn't, luckily: Neither of us wanted kids, whatever Nettie might think.

I fetched out of the trunk of the car the big metal can that Nettie had lent us. It looked suspiciously rusty in all the wrong places, but the fact that the metal was painted brown made that seem somehow less worrying.

"5 GALLONS" was embossed on the side of it.

Those were five *British* gallons. The British gallon is twenty-five percent bigger than its U.S. counterpart. This sucker was going to be heavy by the time I'd filled it.

Far in the distance I could see a little posse of

> That's what we usually do with wonderful things, we humans. We take the marvels of quantum mechanics and use them to watch reality TV.

Dartmoor ponies feeding unconcernedly. Right beside where we were standing was an ugly aluminum gate with a big padlock on it. The gate was festooned with yellow tape and a couple of ugly big black-on-yellow metal signs saying:

DANGER
Keep Out!
Unexploded Ordnance!

The signs bore the marks of a few seasons' weathering by the elements, which would have been a bit of a giveaway if any tourist had paused to think about it, but presumably none of them had—they'd all been only too keen to put as much distance between them and the unexploded bomb as possible.

"Well, see you soon." I shrugged in a way that I hoped made me look nonchalant. In fact I was terrified—terrified of what was about to happen if Nettie had been telling the truth, possibly even more terrified that this might be her idea of a joke, that suddenly Riane and I would be surrounded by a derisive horde of the locals, jeering at the two dumb Yanks.

Riane crossed her arms under her breasts, hugging herself. She shivered, although the evening wasn't cold.

"Get going, will you?"

"Wish me good luck?"

"Good luck."

"A goodbye kiss?"

She pecked my cheek brusquely.

"A final message?"

"If you're not back here within ten minutes you're in trouble, mister."

So, using the key Nettie had given me, I undid the padlock. The gate opened on well-oiled hinges. The empty gas can clanking against my knees as it tried to trip me up, I shut the gate firmly behind me, leaving it to Riane to redo the padlock.

Then I took one small step forward, another to the left (*widdershins*), and let myself stumble into full daylight.

"SO THAT EXPLAINS WHY the Shell on Bratherton Street never does much business," said Riane. We were sitting in the White Lion with pints of Guinness and plates of shepherd's pie. The Shell was the only gas station between here and halfway to Newton, and most of the time it looked deserted. It survived on auto repairs and passing tourists.

Cheap gas. It seemed such a trivial way to use something so wonderful as what I'd just discovered, thanks to Nettie. And yet that's what we usually do with wonderful things, we humans. We take the marvels of quantum mechanics and use them to watch reality TV.

I'd tripped and landed face-down on spongy grass with the metal gas can half under me, bruising my stomach. Nettie had told me to hold it out to my side, and of course I'd forgotten.

I picked myself up, swearing softly at the pain, and looked around me.

I was standing next to a stretch of gray road that wound its way in slow curves across the moor. There were half a dozen small clouds in an otherwise flawless blue sky. As near as I could guess, the sun was directly overhead. Away in the distance I could see two black dots moving—a pair of hawks, circling for prey. About fifty yards from where I stood was a sleepy-looking gas station.

Clutching the rusty canister firmly, I began walking.

On the edge of the gas station's forecourt was a sign with big yellow-on-black capital letters that read:

TWO-STROKE
TOILETS

I grinned nervously. *Two-stroke toilets? What gives? Some kind of Congressional trysting place?*

It was the kind of silliness I needed right then. The scene was peaceful, and yet the very fact that I was here at all was so completely *wrong* that my back-brain was telling me I should be turning and running as far and fast as my legs would carry me. I was breathing in little short gasps, as if I'd just carried something heavy too quickly up a flight of stairs. But I made myself keep going until I was past the perplexing sign and crossing the cracked forecourt to the pumps.

Even then I think I might have turned tail if I hadn't seen Dr. Wallen, the older of Tarburton's two GPs, inside the little sales kiosk between the two pairs of pumps, talking amicably to the woman there as she sold him a couple of packets of cigarettes. Wallen suddenly noticed my arrival and glanced at me as if I'd caught him committing some guilty act—which of course I had. A doctor. Cigarettes. *Verboten*. Very, very *verboten* back at home in the 21st century, even in Tarburton.

Because this wasn't the 21st century I was in, not any longer. Even if Nettie hadn't warned me what to expect, I think I'd have known it the instant I fell through the gap between evening and daylight.

Dr. Wallen came out of the booth and nodded to me. "G'day." There was something different about him, but I couldn't immediately identify what it was. He picked up his own gas can and, carrying it with much more ease than I'd have expected, began to make his way along the side of the road in the direction from which I'd just come.

The woman he'd been speaking to emerged and walked towards me, wiping her hands together with a grimy cloth.

"Can I help you?"

She had bright rust-colored hair, lots of it, tied back from her face. A broad face with very pale skin and a thousand tiny orange freckles. She was wearing faded brown overalls. Later it'd occur to me that she was extremely pretty, but at the time I was too unsettled to notice.

I gestured at the big brown can I held.

"Of course," she said, taking it from me.

As she bent over filling it—I'd chosen the higher grade of gas (*petrol*) because the difference between four shillings and eightpence for the regular and four shillings and elevenpence for the super seemed trivial—I drifted into the booth. Besides the cigarettes (odd brands like Player's Weights and Park Drive that I only half-recognized), there was a selection of candies (Smarties, Mars Bars, Fry's Five Boys Chocolate) plus a couple of copies each of the *Daily Mirror* and the *News Chronicle*.

I didn't notice the headlines, just the date. Today was the 14th of June, 1958.

"All done," said the young woman, smiling. She'd come up behind me without me noticing. "That'll be twenty-four shillings and tenpence, please."

Even though I'd practiced with the old money Nettie had given me, the red-haired woman still had to help me before I got the exact amount sorted out. I wondered if I should give her a tip and then decided against—she was so friendly she might take offense if I tried to press a few of the clumsy old pennies into her hand.

"Do you do much business?" I said by way of conversation as my money vanished into the till.

"We don't do badly." She had an open smile and sparkling green eyes. "Dad keeps saying we should close the place down and go and run a pub somewhere, but we do all right. There's not so many cars, out here on the moor, although July and August get busy. But then there's the foot traffic, like yourself. Cigarettes?"

"I don't smoke, thank you."

"Wise man. It's a filthy habit. I keep trying to give it up, myself, but it's something to do in between customers." She gave a rueful shrug.

We talked a few minutes longer—it was clear that business was slow enough she was glad of the company—and then I was lurching back along the road. Dr. Wallen was obviously far fitter than I was, because he'd managed his burden with considerably more ease. I was overly conscious that Lin—as she'd told me her name was—must be watching me, perhaps putting a hand up to cover her smile.

There's an idea in the Koran that Allah recreates the universe in every single instant. There's no such thing as the passage of time, just an infinite succession of Nows.

Screenwriters don't get nearly as much exercise as they should, I thought. But, if I was going to make a habit of buying cheap gas here in 1958, I would surely start building up the muscles. I'd have to. The distance back to the gate seemed to get longer rather than shorter with every pace I took.

At last I was there, though.

You couldn't see the gate from this side, just a couple of worn old bricks in the grass that Nettie had told me to look out for.

I put the heavy canister down for a moment, bending over with my hands on my knees as I struggled to get my breath back.

Then I picked it up, stepped up onto the bricks, twisted toward my right, and found myself facing a worried-looking Riane on the other side of the gate.

"Back so soon?" Then she saw how heavy the can was, and nodded. "Tell me when we get home."


GAS

"Did you see Dr. Wallen?" I said.

A little line of puzzlement appeared on her forehead.

"No," she said. "Should I have?"

ERNIE BAINTON, A CANDIDATE for Tarburton's chief village idiot—although there was some fierce competition for the slot—was beginning to get rowdy at the bar, a sure sign that he was about to become pugnacious. Since one of the targets of his pugnacity could all too easily become the "damn' Yanks," we finished up our suppers and left. Outside on Church Street the night was quiet, with few cars about. Lights in upstairs windows indicated the kids were in bed, or getting there; there was a dimmer, flickering light in many of the downstairs ones. An orange moon hung ahead of us, low over the horizon. It was almost impossible for me to reconcile the mundane tranquility of the scene with the fact that, just a few hours ago, I'd been breathing the air of over fifty years ago.

"What are you going to tell them at the university?" I asked Riane as we ambled along arm-in-arm.

"Nothing," she said. "Not yet, anyway."

"But don't you feel it's your responsibility as a physicist to—?"

"I probably will, eventually. But for now I have responsibilities as a Tarburtoner, too."

She didn't have to say any more. The people around us—the kids in their beds and their parents slumped in front of the TV—weren't exactly our new family, but we did owe them some kind of loyalty. Nettie had trusted us not to broadcast the town's secret to the world. We couldn't ignore that trust.

"Do you have any explanations for it?" I said. "Wormholes? Folds in time? The contemporaneous intersection of higher-dimensional nexuses?"

She chuckled. "You borrowed that last from Humphrey."

"He borrowed it from me. If you think about it."

We walked on a few more moments in silence.

"I try not to start forming hypotheses until I have evidence," she said. "At the moment all I know is that, yes, if you step through a particular... *gateway*... if you step through a particular gateway *just right* you find yourself in 1958. It's an impossibility, of course. Except *you* did it, darling, and you came back with the fully leaded gasoline to prove it. And then I took a look for myself, and was even able to buy a tube of Smarties for threepence. So clearly the impossibility isn't impossible at all. But I can't even begin to start guessing what's going on..."

She kicked a loose stone into the gutter. It skittered with a noise like fleeing cockroaches.

"I'll probably not sleep at all tonight, Tommy. And if I do I'll have nightmares." She smiled wearily. "Oh, the joys of physics. This is at one and the same time the most exciting thing that's ever happened to me and the most frightening. There's a lot of stuff that's going to have to be rewritten, basic stuff. Stuff we all thought we knew but we obviously didn't."

I laughed. "You're right. I get it easy. All I need to know is that it happened, that it's real. Though I'd like to know what two-stroke toilets are."

She squeezed my arm. "If it's any consolation, I don't know either. We can look it up in Wikipedia when we get home."

"Wikipedia? Is that what we pay you fancy-dandy research physicists for?"

A few minutes after we'd gotten home, while I was digging out the glasses for us each to have a scotch, I heard Riane laughing hysterically. I went through to the living room to find her sitting in front of her laptop, the bright display lighting up her face.

"Okay," I said. "Break it to me gently."

"The toilets are a separate item."

"Come again?"

"The sign tells people the gas station has toilets, and also that they can buy two-stroke there."

I put the glasses down on the coffee table and then headed for the kitchen to fetch the bottle. When I got back with it I said, "So what's two-stroke?"

"It's the fuel you use in a two-stroke engine." She raised a hand to stop me asking the obvious question. "Most internal combustion engines have a four-stroke cycle. The piston goes twice up and twice down the cylinder for a complete cycle. In a two-stroke it's arranged so the whole cycle can be done with a single up-and-down movement. Look"—she pointed at the screen—"Wikipedia even has a natty little animated diagram."

I looked, then read a few lines. Two-stroke engines could be a lot lighter than four-stroke ones for the same energy yield, but their exhaust emissions were obscene. No wonder they'd largely been phased out of

> The past's just like the future—it's made up of an infinite number of possible courses.

this greenhouse-gas-aware world. Back in the 1950s, of course, no one except maybe a few climatologists had heard of global warming, so what did emissions matter? No one had thought too much, either, about what the lead in those emissions might be doing to people's brains. The more we learn, the more frightening the world becomes.

"Motorbikes, lawnmowers, that kind of thing," Riane was saying. "When the stuff's used today the gas is usually cut with vegetable or synthetic oil, so the environmental effects aren't so dire. Even so..."

I poured us each a couple of fingers of liquor, then added an extra finger to my own glass. Riane wasn't the only one who might have difficulty sleeping tonight.

THE NEXT DAY WAS a Saturday, so Riane was with me as I returned the key and the gas can to Nettie; she'd been expecting us, I supposed, which was why she was serving in the shop again. As always on a Saturday morning her store was quite busy, mainly with people picking up items they'd forgotten to buy more cheaply the night before at the big-box stores outside Newton and Exeter.

"How long has this been going on?" I asked Nettie in a low voice at a moment when the place had temporarily emptied out.

The can had vanished as if by magic. She'd left the little brass key on the counter.

"Years," she said. "Ten? Twenty? Who counts?"

"Can we go back there again?"

"Why not?" The old woman nodded in the direction of the window. "Ronnie Gibbs will cut you a copy of the key. And sell you a canister. Make sure he doesn't try to sell you one of they plastic ones. They didn't have they, back then."

Ronnie Gibbs owned the Tarburton hardware store. There was a sign in his window that read

You Won't Believe Our Prices!

and it was nothing but the truth. For obvious reasons, he was known locally as The Robber, or The Boy from Brazil, or just plain Biggsie.

"I'd better take out a second mortgage," I told Nettie.

She gave me a frosty smile. "Tell him I sent you."

If you hopped into a time machine and went back to the past, you could do anything there you wanted without creating rafts of paradoxes.

And, sure enough, a few minutes later we were getting discounts big enough that Ronnie's prices were only about twice what we'd have paid in Newton.

Once I'd returned the original of the key to Nettie, Riane and I trudged back along the High Street. We got the occasional curious look, but by now most people knew who we were. I was gratified that some of the looks Riane got were, as usual, not just curious but appreciative. Her grandfather, the one who'd come from one of the nearby villages, had been of Cornish blood, and had the small darkness of many of the Cornish people. His wife, Riane's grandmother, married after Gramps had moved to San Francisco to haul sacks of grain on the docks, had been a Thai. Their daughter, Bella, had married an African American with a dash of Irish. When I'd first met Riane I'd told her she was either an angel or a stranger from another world or just a top-quality mongrel. She'd chosen mongrel: As she'd pointed out, mongrels are always the best and most faithful and loving and intelligent of dogs.

"And you can pick them up at the pound," I'd added.

SOMETIMES WE WENT TOGETHER to buy Lin's cheap gas, more often I went on my own while Riane was in Exeter. Occasionally Riane gazed wistfully at the cigarettes and murmured to me, "Almost makes you wish you smoked, doesn't it?" We stocked up on cheap candies, too. Some of these were hard and sticky and dangerous to teeth; covered in sugar crystals, they were kept in big glass jars and sold by the quarter-pound in little white paper bags: pineapple chunks, which were bright yellow on the outside, pear drops, which were a dangerous-looking green, and my own personal favorite, acid drops, which were a sort of pearl gray and tasted like one of those rare cough medicines you actually like. We once bought a copy each of the *Mirror* and the *Chronicle*, but only once. It was always June 14th when we went to Two-Stroke Toilets, so why buy the same paper twice?

"I have a conundrum for you," said Riane one Friday night when I'd returned with a can of gas in back of Trudy, our little Smartcar. My favorite theoretical physicist had been drawing little diagrams in a notepad while waiting for a casserole to cook.

"You have?" I said warily.

"Let's take a conservative estimate and say that a thousand of our fellow-Tarburtoners are buying their gas—at least sometimes—from Lin."

"That seems reasonable."

"And let's say they're doing it on average every couple of days—in fact, let's say the average is about 1.825 days, just to make the math easier."

"Two hundred trips apiece each year," I said, sitting down opposite her at the kitchen table. I took a gulp of the warm beer she'd been drinking.

"Yep. So that's two hundred thousand visits to Two-Stroke Toilets every year from 21st-century Tarburton, all told. And everybody's going to June 14th, 1958. But people have been doing this for years—twenty years, maybe? Call it four million visits, or thereabouts. Four million people a day going to and fro along that little stretch of road. Where are they all? We hardly ever see anyone else there from our own time. How could Lin fill four million gas cans in a single day? And where would all the gas come from? Twenty millon gallons of the stuff? Why isn't the grass by the roadside trampled into oblivion? Why haven't those two bricks at the"—she looped her hand around in the air as she sought the right word—"those two bricks at the *portal*. Why haven't they been worn down to dust?"

"Maybe not everyone arrives on the same day?" I suggested. "It's always June 14th, 1958, for us. Perhaps for other people it's June 15th, or 1959, or who knows?"

People in Tarburton didn't talk much about their supply of cheap gas, so it was difficult to compare notes. I think the locals figured that, if they spoke about Two-Stroke Toilets among each other, sooner or later the news would leak to the outside world, and after that there'd be havoc. If it hadn't been for Nettie accidentally giving me change from the wrong drawer of her till and deciding Riane and I could be trusted, we could have lived for decades in the village and never known.

Riane shook her head irritatedly. "That would reduce the problem a bit, but only by a matter of degree. You're still looking at a major logistical problem—and one that should be getting worse all the time."

I went and fetched a beer for myself from the fridge, and a replacement for Riane, too. She nodded her thanks, took a pull, waited until I was sitting down again.

"But even that's not the strangest thing," I said.

"The strangest thing of all," she agreed, "is how come we never meet *ourselves*?"

I could see that half the figures with which she'd been filling up the pages of her notebook were diagrams with lots of arrows and question marks or equations that looked to me like untidy bundles of barbed wire. The other half were doodles of Snoopy. She only ever doodled Snoopy when she wasn't just baffled by a physics problem but profoundly worried by it.

"Maybe we eventually will?" I said. "I've only been there twenty times, maybe thirty. You've come along with me less than half that many. Each visit doesn't last more than ten, fifteen minutes…"

My voice trailed away. I always arrived not just on the same day but at about the same time. However I looked at my own math, I should have run into my own alter ego by now. Something else that had been bothering me came to the surface. Lin treated me like a new customer every time I appeared. Sometimes I thought I saw a flicker of recognition in Lin's eyes, but that was probably just me flattering myself. She was a pretty girl.

"It's as if there were millions of different June the 14ths, 1958," said Riane, recognizing my frustration.

"But that can't be, can it?"

"No. Yes. Perhaps. Maybe." She drew a vicious line through one of her equations, tearing the page with the point of her pencil. "It depends on what you mean by the past. Let's get some food inside us."

We didn't say much as we ladled steaming chicken stew onto a couple of plates. I cracked a bottle of the cheap Shiraz we both liked. Riane lit candles. All very domestic.

"Mary Cranston, one of the people I work with," she said eventually, holding out her glass for a refill, "believes we've got our ideas of the past all wrong. We think of the future as a sort of infinite fan of branching possibilities. Probabilities, rather. We can make guesses about which of them might be more likely than others, but we can't say for certain which if any of them will happen. The past's different, though. The past has *already happened*. So we think of there being just the one past—a single road that brought us to where we are."

My wife was silent a moment as she chewed, swallowed.

"Mary says that's a big mistake, and she has the math to prove it. She says the past's just like the future—it's made up of an infinite number of possible courses. We can guess at which one of them did happen, but we can't be sure. Her math's very beautiful. There's this lovely symmetry either side of the present."

Riane gestured with her two hands as if she were comparing the weights of two apples. "The past," she said, raising her left hand. "The future." She raised the other. "According to Mary, we should all become Now Chauvinists. The Now isn't just another instant in an endless succession. It's the constantly moving balance point, the center of symmetry, between the past and the future. If you go back to the past you can expect Two-Stroke Toilets to be in only a tiny fraction of a myriad June the 14ths, 1958. That still means a hell of a lot of... of..."

"Of Two-Stroke-Toilets-containing-June-the-14ths-1958," I said. "Sounds like something out of Dr. Seuss."

"Yes. Sooner or later we may very well meet ourselves. There's not so many matching locations that the chances of doing so are zero. And we can expect to keep on meeting other people from today's Tarburton when we're buying gas. I wouldn't be surprised if we met someone who's dead."

"Dead?"

"Dead in our time. The Tarburtoners who go to Two-Stroke Toilets to get their gas could be coming from any time after the gateway was discovered."

"Or any time in the future," I said. "I haven't noticed anyone with a jet pack, have you?"

She looked momentarily puzzled. Then I could see her pushing that to the side of her mind as a conundrum to be ignored for now, pulled out for re-examination later.

"All those different summer days," I said thoughtfully.

We grinned winily at each other.

I felt my grin fading. "But I don't see it," I said. "Not really. I can remember what happened yesterday. There was only one of it."

"Was there?" Riane's eyes were shining with amusement in the candlelight.

I thought for a few moments.

"You have a point," I said at last. Perhaps my recollection of yesterday was just the single story my mind had chosen to believe. "So you think that every time we go to Two-Stroke Toilets we're visiting a different possible past?"

"Something like that, yes."

"Only something like that?"

"There's an idea in the Koran," said Riane, "that Allah recreates the universe in every single instant. There's no such thing as the passage of time, just an infinite succession of Nows, each of them being a special creation."

"You're losing me."

"It could be that, each time we think we're going back to June the 14th, 1958, what's really happening is that we're creating a new universe."

"Do you really believe that?"

"What I believe or don't believe isn't relevant. But the math is even more beautiful than Mary Cranston's. And if you put both of our notions *together*—because there's no reason why they shouldn't both be true—the math gets yet more beautiful still."

She picked up her notebook and leafed back a few pages, then held it out to me. The paper was covered with what looked, in the uncertain light from the candles, like a plate of spaghetti as drawn by Jackson Pollock in a foul mood. With a Snoopy in the corner.

"That's beautiful?" I said.

Riane laughed. "It's all in the eye of the beholder."

TWO DAYS LATER IT was a Sunday. The papers had come whumping in through the letterbox in the usual way, and I'd gone and fetched them, pausing for a pee on the way back to bed before climbing in beside a still-snoring Riane. On the table by my bedside I had a copy of *Chambers' Dictionary* and a collection of pencils and pens. One of the olde worlde addictions we'd developed was the Azed crossword in the *Observer*.

I'd been sleeping poorly, the past couple of nights. After Riane had finished explaining to me how she thought the passage of time *really* worked, I'd drunk enough Shiraz to make sure I was three-quarters asleep before I fell into bed, luckily at the first attempt. But I'd awoken at two or three in the morning, watching the trees and the moonlight make dancing pageants on the bedroom wall while outside cats fought and foxes barked. For hours I just lay there, trying to persuade myself I was dreaming up creative ideas for the new season of *Humphrey* when in fact all I was doing was panicking, the same old dreary thoughts chasing around and around in my head like Ben Hur on his track, getting nowhere. Finally I'd gotten to sleep in the dawn.

Last night had been a repeat of Friday, although without the benefit of the Shiraz. Both nights, Riane had slept like a child. I supposed she was used to her own ideas.

This morning I got nowhere with the crosswords.

What Riane had tried to explain to me was that, rather than existing in a single universe, moving according to the dictates of a forward-pointing arrow of time, our existences were more a matter of sliding sideways through an infinite number of probabilistic universes, each one differing in slight detail from its neighbors. For convenience, our minds labeled these as moments of the past and future. Mary Cranston's notion of Now Chauvinism still held good, because in any instant there was just a single reality, condensed out of the vast probabilistic array.

I found myself wondering if I were living in some comforting delusion, if suddenly her skin would start blistering and blackening and peeling away from her bones.

I could get my head around these ideas so long as I kept them in the abstract. As soon as I started relating them to myself, though—that was when the panic started. Because what it meant, surely, was that there wasn't just one of me—just one Tommy Duggan—but an infinite number, one for every universe my consciousness slid through.

Riane didn't see this as an assault on her identity, but I was less sanguine. It made me feel vulnerable, threatened, and, in an odd way, horribly alone.

There was another consequence that she'd explained to me, assuming her own and Mary Cranston's "beautiful" mathematical workings were correct. If you hopped into a time machine—which was effectively what we were doing—and went back to the past, you could do anything there you wanted without creating rafts of paradoxes. You wouldn't come home to find yourself in a drastically altered version of the present, like in the old science fiction stories. All you'd have done was tweak one of countless possible pasts a little.

After a time Riane woke, and reached out for me. While I was holding her in my arms the fears receded. Surely this was the only reality that mattered. Her warmth.

Between phone calls, I never can decide if she's alive or dead.

WE HAD A SNACK lunch at the White Lion—a basket of scampi, tartar sauce out of a jar—and then pottered out of town in Trudy.

"Coming with me?" I said as we rolled to a halt by the padlocked gate.

"You bet." Riane gave an exaggerated shiver. It was a chilly day. On the other side of the gate, June 14th, 1958 would be pleasantly warm, as it always was.

"Come on, then." I fiddled with the key in the padlock, and a few moments later we were ambling along the road towards the familiar sight of Two-Stroke Toilets.

From somewhere we heard the sound of youthful and drunken voices raised in song: "She'll be coming 'round the mountain when she comes..." There was an atrocious gear change at the end of the line.

We smiled at each other nostalgically. It wasn't so many years since we'd been teenagers and the world was a place to fill with noise.

My shoelace broke. "Damn!"

Riane started laughing at me as I limped another pace or two.

"Here, dammit, woman." I passed her the empty gas canister. "Mock me, would you? You go on ahead and start filling her up. We'll talk about punishment later."

"Oo-er," she said, taking the can.

"And get me a bag of acid drops, why don't you?" I called after her.

I knelt down to try to repair the lace. Even as I did so, I think I had a sense of the inevitable sneaking up on me, but I shook the feeling away. It was too nice a day. There were birds singing and little white clouds scudding. There were kids in a car celebrating their hormones. The air was...

"She'll be wearing pink pajamas when she..."

Wait a moment. Kids in a car celebrating their hormones?

They'd never been here before. It was always roughly the same time of day when we came to Two-Stroke Toilets—always noonish. I squinted up at the sun, high in the sky. Nothing should ever be different.

This wasn't June the 14th, 1958. Couldn't be.

The car shot past me as I was pushing myself to my feet. It had an open top, and I saw a glimpse of three close-cropped heads and some bright clothing.

The driver made some attempt to slow as he reached Two-Stroke Toilets—I assume he wanted to stop for gas. Whether he got his foot caught between brake and accelerator or what I don't know, but the car must have been doing sixty or more when it hit the little row of bricks at the front of the forecourt and, tilted up at a crazy angle, careened straight into the front pair of pumps.

Where Lin and Riane were. Riane was bending down to unscrew the cap from the gas can while Lin was reaching to pluck the nozzle from its cradle. They looked up the instant before a couple of tons of screaming metal hit them.

I was screaming too. I'd kicked away the unlaced shoe and was running at a hobble towards the carnage when suddenly one of the pumps went up in a fireball. Lin must have tightened her grip on the nozzle in the instant of her dying.

Moments later, the other pumps erupted—one, two, three mushrooms of flame.

I tried to force myself closer, believing there was a chance I could pluck Riane from the inferno even at the same time I knew it was futile, that I'd just be killing myself as well. The heat took the decision away from me, beating me back no matter how hard I struggled against it. My throat was raw from the fumes and the airlessness and my own screams. The roar of the flames engulfed the world.

I collapsed into darkness.

QUITE HOW LONG IT was before I opened my eyes again I can't tell. I suspect it was no more than a few minutes. The conflagration that had once been Two Stroke-Toilets seemed to be a little less greedy, but that might just have been because I could hear nothing. A huge column of black smoke climbed into the sky, and must have been visible for miles around. Soon there would be other people here—tourists, cops, firemen.

Some instinct picked me up and forced me to walk back toward the portal. I don't know how I got there. There were small burns all over my jeans and sweatshirt. Some embers still smoldered; I could see them, register them, but didn't have the presence of mind to know how to slap them out.

Up onto the two bricks.

A small rightward turn.

Home.

My hand seemed to sizzle when I put it on the rough metal of the gate, and I shrieked like a child.

I HAVE VAGUE, STROBED recollections of driving back through Tarburton. I didn't see streets or people: just a darkening, twisting tunnel at whose other end was the big red house Riane and I had bought.

I couldn't find my front-door key. I knew it must be in one of my pockets but I couldn't locate it instantly and my hands were hurting too much to let me probe deeper.

Except—except, I abruptly noticed, my hands were pristine, unscathed. I'd thought they were scorched from the heat, burned where embers had landed on them.

It didn't matter. They were in anguish.

I threw myself against the door, yelling in pain, yelling though each cry was in itself a new agony. Someone came out of a house opposite to watch. I didn't care.

And then the door wasn't there any longer.

Someone had opened it.

Riane.

"Whatever's going on?" she said, wiping sleep from her eyes with the back of a hand. "Are you all right, darling? Where have you been?"

RIANE STILL LIVES IN Tarburton and works in the Physics Department of the University of Exeter, although she has a full professorship now. Her colleague Mary Cranston was tipped for a Nobel because of her theoretical work on the nature of time, but died unexpectedly; since the award is never given posthumously, it went to someone else. Riane's parallel work has remained far more controversial. Both hypotheses go a long way toward explaining dark matter and perhaps dark energy. Riane is still my favorite theoretical physicist and we have long and frequent phone calls full of laughter and sometimes tears, but I can't live with her, not after seeing what I saw.

I'm living in New York City these days. *Humphrey the Pussycat* finally came to the end of its useful life—it lasted about one season past that end, to be honest—but luckily *Rudolf the Magnificent* (about this superhero rabbit who's, like, fat and stupid) saved my bacon. Now I go to script conferences near Times Square rather than near Oxford.

Riane was disbelieving when I tried to tell her what had happened. She went whiter than I've ever seen her, clearly assuming I'd lost my wits, and sat heavily in one of the kitchen's upright wooden chairs, her hand splayed between her breasts as if to keep her heart in. I poured her a stiff scotch, then one for myself. My hands and face still hurt like hell, but the pain was ebbing. Somewhere I'd trodden on something sharp with my shoeless foot; focusing on the chore of cleaning and dressing that wound helped me tune out, or at least turn the volume down on, some of the far worse things that had happened.

Although I remembered clearly that Riane and I had gone together to fetch a can of gas, it seemed that this wasn't what happened at all. She'd felt drowsy after our pub lunch, so had decided to take a nap. The next she knew of me was when I was clamoring at the front door.

One thing she knew for certain was that my tales of time travel were impossible. She had no memory of those occasions she'd come with me. When I asked her where she'd thought the gas for the cars was coming from, because we certainly weren't buying it at the Shell, she grew sufficiently distressed by the contradiction between logic and her memory that I backed off.

"But time travel *just cannot be done*!" she kept repeating, eyes full of tears.

As she'd told me a couple of days—or a lifetime—ago, both her own and Mary Cranston's models of time's workings rely on the notion that there's a disconnect between past and future: There's a probabilistic symmetry around the one fixed point of certainty, the Now. Riane's death decades before she was born couldn't affect, except in the most trivial way—an afternoon nap rather than a shared excursion—what happened in the present.

I don't know why the portal took us back to a different day, just that once. Or maybe it wasn't a different day—maybe it was the right day but in a rogue timeline. I never tried to go back to Two-Stroke Toilets again, so I had no way of telling. Paying full rate for a tank of gas seemed cheap—even at British prices—if it meant I never had to risk reliving that horror.

But the worst thing I didn't know was if the "now" I'd come home to was the same "now" from which I'd departed. If the universe really does consist of an infinite array of parallel realities, are there other realities out there where Riane did in fact accompany me, and in which her death was permanent? It's surely just as likely an outcome.

For the first few weeks afterwards, it looked as if everything would work out all right between us. I took my nerves and agitation to Dr. Wallen, who insisted I undergo a course of counselling; however, since I couldn't tell the shrink—a Bovey Tracey man—the truth of what had happened, the effort was wasted. Even so, the nightmares started to be less soul-racking and to come less often.

But, as my mind became calmer, my unease at being around Riane increased. I found myself more and more often looking sidelong at her and wondering if I were living in the middle of some comforting delusion, if suddenly the picture would change and her skin would start blistering and blackening and peeling away from her bones...

I had new nightmares to replace the old ones, and far too often they were attacking me during the day, during my waking hours. I couldn't make love to Riane, in case she disintegrated in my arms. I couldn't even hold her. I began sleeping on the living-room couch. I couldn't watch her eat.

Finally I left her a message telling her that this was no use, that we had to live apart, that the quirks of time might have saved her life but they'd nevertheless taken pains to ensure that, one way or the other, I lost my wife.

I think in the end it was a relief for her to see me go. Her nutty screenwriter husband.

It's still good to hear her voice on the phone and know she's alive and happy. There's a new guy in the picture now, although she's not entirely convinced he's a keeper. Her work gets steadily more absorbing to her, steadily more incomprehensible to me. She tells me her students seem to get stupider every year but, thank mercy, there's always a few brightly burning candles among them.

Me, all I have is the memory of Riane. Between phone calls, I never can decide if she's alive or dead. If

I went to visit her I'd know for sure, like opening the box on Schrödinger's cat, but this is something I'm not going to do.

I lack the courage.

ONE LAST THING I did before leaving Tarburton was to go down to Nettie's grocery store to give her back the key.

"It's not my key," she said sourly. The news was all over town that Riane and I were splitting up, and sympathy was heavily on Riane's side. Everyone knew as a stone-cold fact that I was running off with some floozy actress half my age whom I'd impregnated in a drunken, dope-fueled orgy in Oxford, everyone knows how these television people are, morals of alley cats the lot of them. "You bought it yourself from Biggsie."

"But I won't be needing it any longer, Nettie. Take it. You can give it to someone else. Save them the expense of having their own copy made."

Her cheeks seemed to warm a little at the prospect of doing Biggsie out of a sale. With a show of reluctance she spirited it away to some hidden compartment under the drawer of the till.

"One more thing," I dared to say, now that we were almost friends again.

I flattened out one of the store's paper bags on the counter.

L.A. MANGENS
General Stores
Fish and Game to Order

"Your name's not just Nettie, is it?" I said.

She grunted. She hadn't called on one of her beefy sons or grandsons to throw me out.

"You're Linnet, aren't you? That's *you* out at the gas station—the garage, I mean. That's why you're just about the only person in Tarburton who never goes there."

For a moment she looked over toward the far corner of the store as if gazing back over a vista of decades. Then she turned her piercing scrutiny in my direction once more.

"Have a good life, Mr. Duggan," she said. "Wherever that life may lead you."

JOHN GRANT is the author of some 70 books and the recipient of two Hugo Awards, a World Fantasy Award, and various others. His *A Comprehensive Encyclopedia of Film Noir* was published last fall; he's currently putting the final touches to *The Young Person's Guide to Bullshit* for fall 2014 publication. He writes about movies regularly at *Noirish*.

Math Shall Set You Free—From Envy

How to do divorce, divestment, and death properly

BY ERICA KLARREICH

MAEGAN AYERS AND HER then-boyfriend, Nathan Socha, faced a dilemma in the fall of 2009. They had found the perfect little condo for sale in the Boston neighborhood of Jamaica Plain: on the ground floor, just a mile from the nearest "T" train station, and close by Boston's Emerald Necklace, a seven-mile chain of parks and bike paths. Federal incentives, low prices, and high rents had made home-buying an unusually attractive proposition, and the pair was eager to snap up the condo.

But, as the couple's parents gently pointed out, Ayers and Socha were not yet married, or even engaged. If their relationship were to sour, they would have none of the protections that married homebuyers enjoy. As "tenants in common," one of them could legally rent out or even sell his or her share of the condo to a total stranger. In the event of a break-up, Ayers and Socha wondered, how could they avoid conflict over their jointly owned condo?

Many families are faced with some version of Ayers and Socha's quandary—how to fairly divide coveted goods. Some achieve a satisfying division, and are even strengthened in the process; others are ripped apart. Despite these high stakes, the methods families use to divide their assets tend to be very ad hoc.

Ayers and Socha did something different: They turned to mathematics.

PERHAPS THE OLDEST FAIR division method on the books—one which has been used by children from time immemorial—is the "I cut, you choose" method for dividing up, say, a cake between two people. One person cuts the cake into two pieces, and the other person gets to choose which piece to take. Abraham and Lot used this method to split up the land in which they would settle: Abraham divided the land, and Lot chose Jordan, leaving Canaan for Abraham.

"I cut, you choose" has one very appealing property:

ILLUSTRATION BY EMMANUEL POLANCO

It is envy-free, meaning that neither participant would willingly trade her share for the other share. The person who cuts the cake—or tract of land, or other divisible good—has an incentive to make the two shares as equal as possible from her perspective, since she doesn't know which she'll end up with. If she does a good cutting job, she will be content with either piece. The other participant gets to choose her favorite piece, so neither person will wish to trade.

But when the good being divided is not homogenous—when the cake has an assortment of different frostings, or the land has a mix of fertile valleys, mineral-rich mountains, and arid deserts—the "I cut, you choose" method falls short on other important measures of fairness and desirability.

In these settings, the chooser has a distinct advantage over the cutter. The cutter, to be safe, must divide the cake into two pieces that, to him, have equal value. But the chooser may have very different preferences from the cutter. Maybe from the chooser's vantage point, one of the pieces is worth 60 percent and the other is worth 40 percent If so, he will happily walk away with considerably more than what he considers half of the cake. In mathematical language, the "I cut, you choose" method is not equitable.

Not only is the method not equitable, it can also fail to give each person the share that will be most useful to him. For instance, suppose John and Jane are sharing a cake that is half vanilla and half chocolate. John likes vanilla best, while Jane prefers chocolate. The ideal split is obviously for John to get the vanilla half and Jane the chocolate half. But if John is the cutter, then unless he knows Jane's preferences, that ideal split will appear too risky to him: He could lose the entire vanilla half. So he will divide the cake into two identical pieces, with an equal amount of each flavor. This division is not "efficient": There are other divisions that can improve some or all participants' shares without making anyone worse off.

Mathematicians have proven that when two people are dividing a cake, there is always some division that is simultaneously envy-free, equitable, and efficient (to get a sense of why this is true, see Cakes Are Fair Game on page 61). But there's no simple algorithm for identifying this ideal split. And, in some other division problems, mathematicians have shown that no ideal split even exists. In its stead, mathematicians have, over the past 20 years, developed a rigorous framework for exploring the trade-offs required by different kinds of divisions, helping to bring clarity to the fallout from divorce, death, and divestment.

ONE STRAIGHTFORWARD APPROACH that Ayers and Socha might have taken is called "the shotgun clause," a close analogue to "I cut, you choose" that is common in business contracts. This clause stipulates that if, for example, two owners of a business want to part ways, one of them will propose a buyout price, and the other will choose either to buy or be bought out at that price. Like "I cut, you choose," this method is envy-free but not equitable: It's better to be the chooser than the proposer. As a result, arguments about who should propose and who should choose sometimes lead to years of litigation, says James Ring, lawyer and CEO of Fair Outcomes, a Boston company that provides division algorithms.

In some division problems, mathematicians have shown that no ideal split exists.

Instead, Ayers and Socha committed that in the event of a break-up, they would use a relatively new algorithm called Fair Buy-Sell to determine which of them would buy out the other's share, and at what price. Fair Buy-Sell was devised in 2007 by Ring and Steven Brams, a professor of politics at New York University, and requires each partner to simultaneously propose a buyout price. If John proposes $110,000 and Jane proposes $100,000 then John, the higher bidder, will buy out Jane for $105,000. Unlike the shotgun clause, this method is equitable: Each participant ends up with something—either money or the business—at a price that is better than his or her offer. "Both participants always get a solution that's better than what they proposed," Ring says. And the business always goes to the partner who values it more.

This algorithm joins a long list of others, with names like Adjusted Winner and Balanced Alternation. Just as important as prescriptions for fair division, though, is understanding when perfect fairness is impossible, or comes at the cost of social welfare (which measures the extent to which items are going to the people who value them most). In the January 2013 issue of *The American Mathematical Monthly*, Brams—together with Christian Klamler of the University of Graz and Michael Jones of Montclair State University—showed that when three people are dividing a cake, it is sometimes impossible to find a division that is simultaneously envy-free, equitable, and efficient. Similarly, when three people have to divide a collection of indivisible items, it is sometimes necessary to choose between an envy-free solution and an efficient solution (for a simple example in which this happens, see Envy vs. Efficiency on page 62).

"Mathematics sets limits on what is achievable," Brams says. "Then the question is, if you can't get everything, what properties do you want to give up on?"

HERE TOO, SERVICES ARE popping up to help. A new, free online service called Spliddit will allow users to decide for themselves just how much they want to relax the notion of fairness. Its division algorithms ask participants to choose a particular fairness criterion—either envy-freeness or one of two weaker criteria. The algorithm then looks for the division at the chosen fairness level that produces the highest social welfare,

Cakes Are Fair Game

When two people are sharing a cake, whatever their preferences are, there is always some division that is simultaneously envy-free, equitable, and efficient. To get a rough sense of why this is true, consider a simplified version in which Jane and Sally are dividing a cake whose flavors and frosting vary only along vertical stripes, and assume that Jane and Sally are only allowed to make one vertical cut to divide the cake.

There's some knife position that Jane would view as a 50-50 split, and another position that Sally would view as a 50-50 split. If those two positions are the same, just cut the cake there. Otherwise, imagine slowly moving Jane and Sally's knives toward each other, so that each person's value for her piece increases at the same speed. The spot where the two knives meet is a perfect division: It is envy-free, since each person likes her piece better than the other piece, and it is equitable, since Jane and Sally have the same value for their pieces. And it is efficient, at least compared to other single-cut divisions, since if you were to slide the knife to a different position, one of the players would be worse off.

If you were to allow more than one cut, this simple division might not be the most efficient—for example, if one of the players loves the two stripes on the edges of the cake, a division that makes two cuts would probably do a better job. In the broader setting where more than one cut is allowed, there is still a guaranteed envy-free, equitable, and efficient solution, but this is harder to prove. In a forthcoming paper in *The Mathematical Intelligencer*, Steven Brams, a professor of politics at New York University, and Julius Barbanel of Union College in Schenectady, New York, show a way to figure out how many cuts are needed, given the players' preferences.

which in this case is measured by the sum of all the participants' values for their winnings. The higher the fairness constraint the participants set, the lower the social welfare is likely to be, and vice versa.

The inner workings of the Spliddit algorithms are not as transparent as those of the Fair Buy-Sell algorithm. But Ariel Procaccia, a computer scientist at Carnegie Mellon University in Pittsburg whose research team created Spliddit, nevertheless believes that even math-phobic individuals will be able to use the site: The divisions the algorithms generate should speak for themselves, he says.

"People should be able to look at a proposal and see that it makes sense—that they like their share and don't want to switch with anyone," he says.

WHILE FAIR DIVISION ALGORITHMS have come a long way, their real-world use can be complex. For one thing, human beings can entertain equally compelling but mutually exclusive notions of fairness. When siblings are dividing their parents' estate, for example, should each sibling get an equal share, or should the sibling who nursed their father through his last illness get more? A fair division algorithm cannot make this determination for a family.

"Depending on how the algorithm plays out, it could offend either set of moral sensibilities," says Peter Ditto, a social psychologist at the University of California, Irvine. "It's hard to satisfy all our intuitions about fairness and justice, because they tend to mutually conflict." Our satisfaction is further complicated, says Ditto, because evolution has honed us to be injustice detectors, so that "we often feel we are being screwed even when we aren't." Throw in the intricacy of emotional responses to a settlement, and it becomes clear that our relationship with division algorithms will not always be a simple one.

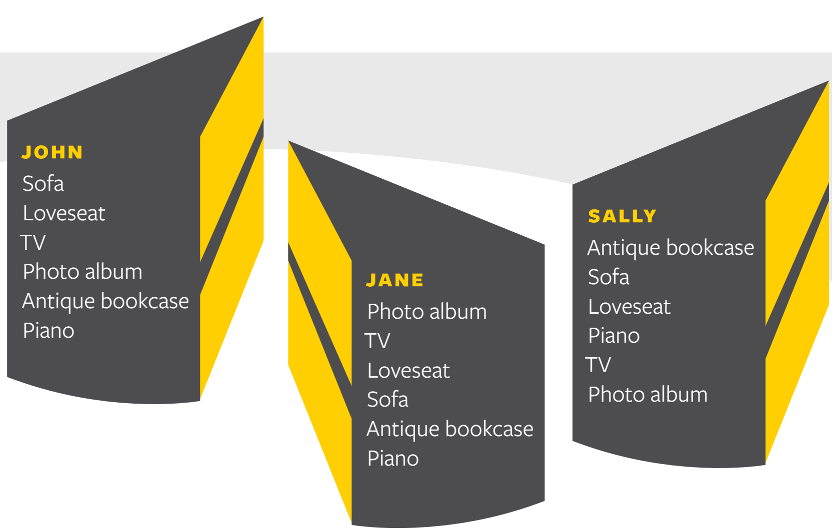
At the same time, the impartial nature of mathematical algorithms can help people tease out their own subconscious motivations and tame their hypersensitive unfairness radars. That's what happened when Fair Buy-Sell was used to resolve an ugly feud that had dragged on for years between siblings who had inherited a family business empire and couldn't agree about who would buy out whom.

"Each side claimed the other side was offering too little," Ring says. "That's how people behave in a conflict if they don't trust each other—maybe I'll say that I will buy you out for $100,000, but if you want to buy me out, you have to pay me $200,000. It's human nature."

When one sibling's lawyer challenged him to use the Fair Buy-Sell algorithm, the process of choosing a price to plug into the system led the sibling to an epiphany: He didn't actually want the business. His previous intransigence, he realized, had been an attempt to unfairly profit at his sibling's expense. The fair division

ENVY VS. EFFICIENCY

Sometimes it's necessary to choose between the fairest and the most socially useful division of a collection of items. For example, suppose John, Jane, and Sally are dividing their grandmother's furniture and effects, and they each list the items in order of preference as shown on the right.



algorithms offer "a very powerful and positive thing," Ring says. "To get what I want, I don't have to lie to you and brutalize you and pretend I care about things for years."

Division services like Fair Outcomes and Spliddit offer a mathematical lens through which users can view their own motivations. Will they choose to emphasize envy-freeness or social welfare? If even an envy-free division feels unacceptable to them, are they motivated by vindictiveness? As Marc Kilgour, professor and Chair of Mathematics at Wilfrid Laurier University in Waterloo, Ontario, puts it, the mathematical approach to fair division "throws a light on all kinds of behavior that has been around for a long time."

As for Ayers and Socha, they never did end up invoking the Fair Buy-Sell algorithm. Instead, Maegan Ayers became Maegan Socha, and the married couple eventually sold their condo and moved to Rhode Island, where they are expecting their first child in July. Looking back, Maegan sees their condo purchase and fairness contract as the young couple's leap into adulthood. "At the time I thought that part of being adult was being old enough to make those kinds of decisions, and I'm pleased by how we handled it," she recalls. "It was a sign of faith and confidence in each other to know that if things didn't work out, we wouldn't be unfair or hurtful to each other. We'd preserve something, even if the relationship didn't work."

ERICA KLARREICH is a mathematics and science writer based in Berkeley, California. Her work has appeared in the 2010 and 2011 volumes of *The Best Writing on Mathematics.*

There's only one way to divide these items that is guaranteed to produce no envy:

John: Sofa and TV
Jane: Loveseat and photo album
Sally: Antique bookcase and piano

With this division, each person likes his or her share better than anyone else's. But this division is not efficient. John and Jane will both be happier if they trade the TV and the loveseat, producing the division:

John: Sofa and loveseat
Jane: TV and photo album
Sally: Antique bookcase and piano

This new division is efficient—there's no way to make further improvements without making at least one person worse off. And John and Jane's trade seems harmless enough, since it doesn't make Sally's share any worse. But it may make Sally envious: The sofa and loveseat are high up on her preference list, and if she thinks they make a great pair, she might covet John's share over her own bookcase and piano. There is no division that is simultaneously envy-free and efficient. Which division makes the most sense for John, Jane, and Sally depends on their particular relationships and values.

Half Male, Half Female, Total Animal

Mixed-sex animals teach us about our own multifarious nature

BY FERRIS JABR

A**S THEY OFTEN DO** after a rainstorm, butterflies had gathered around puddles on Pigeon Mountain in northwest Georgia. Nets in hand, James Adams and his friend Irving Finkelstein watched the insects lapping up salts and proteins dissolved in the muddy water, their folded wings yawning apart now and then. There were silvery-blue *Celastrinas* and Skippers the color of cinnamon and ash. Largest of all were the Tiger Swallowtails—pastel lemon males with black, dagger-like stripes and midnight-dark females with a dusting of evening cerulean.

Suddenly a very odd creature flitted past Adams and Finkelstein—a swallowtail unlike any they had ever seen. Its left half was yellow; its right, black. It was as though someone had sliced up two different insects and seamlessly sewn them back together. Finkelstein yelped and took a swipe at the bizarre beauty, missing by quite a bit. Suppressing his excitement, lest it misguide his hand, Adams chased the butterfly a few steps, swung, and netted it. He could see immediately that he had caught a gynandromorph—an animal that was half-male and half-female.

Butterfly collectors love gynandromorphs for their rarity as much as their peculiarity. They are unpredictable hiccups in nature's symphony of symmetry. The creatures tantalize scientists, too, because they offer a unique opportunity: the chance to study typically male and female genes and anatomy in the same body.

For hundreds of years, naturalists have been documenting gynandromorphs among insects, spiders, lobsters, and birds. More recently, researchers—aided by increasingly sophisticated laboratory tools—have overturned reigning theories of sexual development by studying such hybrids. As has proven true time and again throughout the history of science, the creatures that seem strangest—those that are too odd, too asymmetrical to fit neatly into our presupposed categories—teach us the most about how all living things work. It turns out, for example, that the standard explanation of how a bird becomes male or female is wrong.

Scientists came to this realization not by investigating scores of typical birds, but rather by examining a few gynandromorphs. It all started with an odd zebra finch.

IN THE LATE 1990S, a lab animal caretaker at Rockefeller University kept finding eggs in a cage that supposedly contained only male zebra finches. To identify the culprit, she moved all the birds into individual enclosures. The eggs were coming from a bird that, as it grew older, looked increasingly different from the rest. On its right side it had all the typical features of a male: a blush of orange plumage on its cheek, a zebra-striped neck, and a handsome patch of brown feathers speckled with white dots near its wing. In contrast, its left side was almost entirely gray with a few black and white facial markings and an egg cream breast—characteristically female plumage. Realizing that this bird was a gynandromorph, Fernando Nottebohm, the Rockefeller neuroscientist who owned the finch colony, gave the bird to his former student, Art Arnold, at the University of California, Los Angeles. He suspected that Arnold, who studied gender differences, might learn something from the creature.

Scientists had long assumed that birds become male or female the same way mammals do: They start out as unsexed embryos that, depending on the sex chromosomes, grow either a pair of testes or ovaries, which in turn release wave after wave of hormones to masculinize or feminize the organism. Yet now and then studies had uncovered inklings that this story was too simple.

Following these clues, Arnold and his colleagues decided to take a close look at the cells in the gynandromorph finch's brain. Typical male zebra finch brains have a network of neural circuits dedicated to learning courtship songs, and the area containing these circuits is much larger than the corresponding region in the female brain. If sexual development was dependent primarily on hormones, then each half of the gynandromorph's brain should be architecturally identical. After all, every organ in the bird's body was bathed in the same androgynous cocktail of sex hormones released by its testis and ovary.

What Arnold and his team discovered, however, was that the singing region was 82 percent larger in the right half of the bird's brain than in the left. To investigate further, the researchers sliced up the brain and

***HELICONIUS* BUTTERFLY GYNANDROMORPH**
"Gynandromorphs are beautiful because they violate our expectation of symmetry, " says Nipam Patel, a developmental biologist at the University of California, Berkeley. "We're so used to looking at something that is just male or just female, but to see them both at once—wow."

FROM THE COLLECTION OF NIPAM PATEL

soaked the thin sections in a solution brimming with bits of radioactive RNA designed to bind to either the Z or W sex chromosomes, the avian correlates of our X and Y. Laying the soaked slices onto photographic plates revealed that the brain's right hemisphere was comprised mainly of male cells with two Z chromosomes, whereas most of the left-hand cells had the female combination of a Z and W. The sex chromosomes, not hormones, had dictated the brain's fate, cell by cell.[1] "That one gynandromorph changed my mind about some very fundamental scientific dogma," Arnold says. "Brain cells are not a tabula rasa on which hormones write sex. They come pre-described."

In the mid 2000s, Michael Clinton, a developmental biologist at Edinburgh University, began studying gynandromorph chickens collected from poultry farms around the United Kingdom. On one side, the birds looked like males: white and gold plumage, a big red wattle, and a long hornlike protrusion on the leg known as a spur. On the other side they had female features: brown and russet feathers, and a much smaller spur and wattle. When Clinton and his team analyzed DNA from blood, skin, and muscle cells around the fowls' bodies, they found that the chickens were not just superficially split. As with the unusual zebra finch brain, their entire bodies were more or less divided on a cellular level, with lots of female ZW cells on one side and mainly ZZ cells on the other—but there was a bit of cellular

MYSTERIOUS MORPHOLOGY Mocker Swallowtail (*Paplia dardanus*) butterflies. A male (top), female (middle), and gynandromorph (bottom) are shown.

scrambling, too. They were kind of like bisected jars filled with two different flavors of jellybeans that mostly kept to their own sides but sometimes crossed over.

These chimeras confirmed that a bird's sex is determined cell by cell throughout the body, rather than uniformly through hormones as in mammals.[2] What remains unclear is exactly how the sex chromosomes within each cell shepherd sexual development independent of sex hormones. Perhaps the Z and W chromosomes initiate certain epigenetic changes—that is, changes to the molecules surrounding DNA that increase or inhibit the activity of different genes—from the moment of fertilization. Supporting this hunch, Clinton and his colleagues discovered that typically developing male and female bird embryos have divergent patterns of genetic activity even before sex organs develop.

Arnold and his team now want to know whether what they discovered in birds applies to mammals, too. To tease out the distinct roles of hormones and chromosomes in mammalian sex development, he and his colleagues have been studying unique strains of mice that have, say, one too many X or Y chromosomes or churn out female sex hormones even though they are genetically male. He hopes that this line of investigation will eventually yield new treatments for human maladies. Multiple sclerosis, cancer, heart disease, and many other illnesses are much less common, or less deadly, in one sex or the other. "If we can figure out why one sex is protected we can figure out new therapies," Arnold says. "To understand that, we need a list of factors that make males and females different. It used to be all about the hormones."

Multiple sclerosis, for example—a devastating illness in which the immune system attacks and destroys the nervous system—is much more common in women but more rapidly debilitating in men. Arnold's studies on mice that are genetically male but produce female hormones suggest that something about the combination of an X and Y chromosome—not male hormones—make cells more vulnerable to a severe course of a similar disease.[3]

> Multiple sclerosis, cancer, heart disease, and many other illnesses are much less common, or less deadly, in one sex or the other.

THE ZEBRA FINCH and chicken studies astounded researchers beyond the bird community. They "really argued against some longstanding notions we had about how cells get their sexual identity in vertebrates," says Nipam Patel, a developmental biologist at the University of California, Berkeley. As those experiments were underway, his own research on unusually sexed butterflies was overturning entrenched ideas as well. After more than a decade of obsessive study, Patel has concluded that in some cases, rather than a single animal with male and female parts, a gynandromorph is two different creatures fused together.

When Patel was about 8 years old, he came upon a dead male two-tail swallowtail butterfly lying in the grass in his backyard. He was entranced by its beauty: the way those yellow birdlike wings swooped out from the insect's body, only to arc in return, ripple and drip into a parenthesis. Patel carried the swallowtail inside and mounted it in a cigar box. He convinced his mother to sew him his first butterfly net. Since then, Patel has amassed a library of around 30,000 insects. And he has spent the past 16 years curating a second collection: not of physical specimens, but rather of photographs. Patel is the world's foremost collector of gynandromorph butterfly pictures.

Gynandromorphs appeal to Patel because they are naturally occurring experiments that allow him to study how animals develop. Many scientists have attributed the existence of gynandromorph butterflies to a cell division error. Like birds, male butterflies have two Z chromosomes in every cell, whereas female cells are ZW. When a caterpillar begins metamorphosis, the standard story goes, the dividing cell that will eventually produce the wings multiplies its chromosomes as usual, but fails to properly divvy up the sex chromosomes in its two daughter cells. One of the new cells gets a Z and W and becomes female; the other gets one or two Z chromosomes and becomes male. Each of those cells is the progenitor for either the left or right wing, so the butterfly looks half male and half female—split down the middle.

Scientists have clearly shown this to be the case, but some of Patel's photos have made him think that gynandromorphs form via other routes as well. Every now and then he has encountered specimens such as the *Heliconius* butterfly pictured on page 65. It's a member of a colorful tribe in which males and females look nearly identical. Patel identified this butterfly as a gynandromorph because the two halves of its abdomen differed subtly in size and structure, one having male genitalia and the other female. Its wings should have been the same, but they weren't.

Patel realized that, in addition to being doubly sexed, this particular insect might have a mixed identity. The patterns on its wings betrayed underlying genetics that could not be explained solely by a medley of female and male cells. A gene named *optix*, for example, determines where red rays grace the hindwings; another gene called *WntA* acts like a black Sharpie that darkens the wing here and there. Neither of these genes lie on the Z or W chromosomes—the only source of genetic variation between a gynandromorph's two halves, according to the standard origin story.[4] Yet the two wings had clearly activated different color pattern genes, indicating two entirely different genomes. When gynandromorphs differ in more than their sex characteristics, Patel thinks you could be looking at two animals in one.

How could that happen? An insect egg cell harbors a smaller sister cell known as a polar body—a leftover from the cell division that created the egg cell. Sometimes two sperm manage to slip inside the egg and fertilize the egg's nucleus as well as the polar body, creating two embryos that develop more or less like conjoined twins. The two animals' cells may not always keep to their own sides, however, which could explain why sometimes a gynandromorph has bilateral asymmetry and sometimes ends up a mosaic, with a splattering of opposite cells across a center line. Although other scientists have previously suggested that double fertilization accounts for some gynandromorphs, Patel has uncovered some of the clearest evidence to date.

Gynandromorphs' duality calls to mind Plato's *Symposium*, in which Aristophanes explains the origin of the sexes with a unique creation myth: In the beginning, he says, there were double-bodied primal humans—man and man, woman and woman, and man and woman—until, angered by their hubris, Zeus split them with bolts of lightning. But such duality is not just the stuff of myth. The more scientists fingerprint the genetic components of living things, the more they realize that we are all multifarious creatures. Every one of our cells essentially has two genomes: the human one in our nucleus and a non-human one tucked inside mitochondria that were once free-living microorganisms. Trillions of bacteria cover our skin and dwell inside our intestines, turning our bodies into a kaleidoscope of microbial genomes. And quite a few foreign genes have infiltrated our genome with the help of viruses and various parasites. Gynandromorphs catch our eye because their striking variegation seems so exceptional. In truth, they are mirrors reflecting the tessellations within us all.

FERRIS JABR is a writer based in New York. He has written for *The New York Times, Scientific American, Wired, New Scientist, Popular Mechanics, NOVA Next,* and *The Awl.*

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“JAMES DOTY’S HELPER’S HIGH”
BY EMMANUEL POLANCO

The Sacred, Spherical Cows of Physics

Theoretical physics milks symmetry to power its newest tool

BY DAVID KAISER

EARLY IN THEIR TRAINING, many physics students come across the idea of spherical cows. Cows in the real world—even at their most plump and well-fed—are hardly spherical, and this makes it tricky to calculate things like, say, how their volume or surface area scales with their height. But students learn that these numbers are easy to calculate if they assume the cow is a perfect sphere, or in other words, that it has spherical symmetry. The lesson: Hard problems become easier when certain underlying (though approximate) symmetries are enforced.*

The lessons of the spherical cow don't end with the undergraduate classroom, though. They extend to the very forefront of physics. The theoretical physics community of the 1980s and 1990s was split by debates over the reality of symmetries similar to, but much more complex than, the spherical cow. String theorists argued for a single, unified mathematical description of reality that relied on certain symmetries, but had almost no experimental support. Other physicists argued that the role of a theory was to predict and explain experiment, and not to pursue mathematical structures for their own sake—no matter how beautiful they might be. The warring factions began to reconcile in the last decade with the realization that some of the sophisticated tools that string theorists had built could be applied in unexpected ways to other problems, and could even help make sense of real data.

Late in 2013, the latest chapter in the history of symmetry in physics began to unfold, when two theoretical physicists unveiled a new calculation tool called the "amplituhedron." The amplituhedron is an exotic, flat-faceted geometric object that lives in an abstract, mathematical space of many dimensions. It

* One of the best discussions of physicists' spherical-cow joke is on pages 3-8 of Lawrence Krauss' *Fear of Physics*.

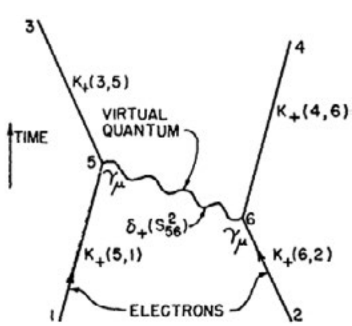
ILLUSTRATION BY MARCOS CHIN

can quickly yield answers that have up until now taken hundreds of pages of calculation. Most intriguingly, its power derives not just from making some symmetries apparent, but also from *abandoning* old symmetries. In doing so, it may point the way to changing how we think about space and time.

Diagrammatic Fables

Beginning in the late 1920s, great architects of quantum theory like Werner Heisenberg, Wolfgang Pauli, and Paul Dirac recognized that physical forces arise from the exchange of certain force-carrying particles. For example, photons—individual particles of light—are the force-carriers of electromagnetism. Charged particles like electrons exert an electromagnetic force on each other by trading photons back and forth. Over the course of the 1930s, physicists figured out ways to approximate the "amplitudes" for such processes, which tell them how likely they are to occur.

In the simplest approximation, two electrons interact with each other by trading a single photon. The resulting approximate calculations are in reasonable agreement with experiments. Yet quantum theory suggests that the electrons could trade any number of photons back and forth: two photons, three photons, 9 million photons, and so on. Each byzantine variation should contribute a modest numerical correction to the overall amplitude, since electrons and photons interact weakly with each other. The problem is that even the next-simplest case—trading two photons instead of one—is ferociously difficult to calculate. One of Heisenberg's intrepid students attempted such a calculation in 1936; his published equation spilled over several pages.



FEYNMAN'S FIRST Richard Feynman published this diagram in 1949. It depicts the scattering of two electrons (straight lines) by exchanging one photon (wavy line, labeled "virtual quantum"). Feynman associated each component of the diagram with part of the calculation of the amplitude for the scattering process.[1]

After World War II, a young Richard Feynman took up the challenge. He began to doodle as he imagined a sequence of events (see Feynman's First). On the left and right are lines representing electrons traveling through space and time (in the upward direction). They interact with each other by emitting and absorbing a photon, which carries enough oomph—energy and momentum—to change each electron's motion. The electrons thereby exert a force on each other, pushing each other apart. With this framework, Feynman could easily tackle more complicated interactions between two electrons, sketching, for example, all the ways that two electrons could trade two photons back and forth.

Feynman's diagrams served as fables, each element geared to convey a specific message. An electron had a certain likelihood of emitting or absorbing a photon, just as a photon had a certain likelihood to travel, unimpeded, from point *A* to point *B*. Feynman identified each element of his drawings with a corresponding mathematical expression. With those simple translation rules in hand, he could dispatch in half an hour the kind of calculations that had stymied the world's best theoretical physicists for decades.

Physicists have since tackled ever more complicated calculations using Feynman diagrams. Toichiro Kinoshita of Cornell University, for example, has spearheaded efforts to calculate the effects of electrons exchanging four photons, a calculation involving nearly 900 distinct Feynman diagrams. The theoretical results match experimental measurements to better than one part in a trillion, by far the most precise agreement between theory and experiment in the history of science. Feynman diagrams in hand, physicists learned to calculate things that few had even dreamed of before the war.[2]

Symmetries and Improvisations

Feynman had created his diagrams to help calculate interactions among electrons and photons. But soon after he introduced them, physicists began to apply them to a rather different set of interactions: nuclear forces. The transfer wasn't always easy. For one thing, nuclear particles like pions and other "mesons" * seemed to interact strongly with each other, quite unlike the weak coupling between electrons and photons. This meant that the more complicated diagrams, with more force-carrying particles in the mix, could no longer be treated as small corrections to the simpler diagrams, as they could with photons and electrons. Instead, these more complicated diagrams were weighted more than simpler diagrams when calculating amplitudes—and there were infinitely many such diagrams to consider. Feynman grew suspicious, writing to Enrico Fermi late in 1951, "Don't believe any calculation in meson theory which uses a Feynman diagram!"

Despite Feynman's misgivings, others plowed on. Among the earliest to adopt Feynman diagrams were the young theorists C.N. Yang and Robert Mills, working at the new Brookhaven National Laboratory in Long Island, New York. Brookhaven had one of the most powerful particle accelerators at the time, and Yang and Mills were eager to make sense of the dizzying variety of nuclear particles and interactions that the accelerator revealed.

In 1954, Yang and Mills returned to an idea that Heisenberg had floated in the early 1930s: When it comes to nuclear reactions, neutrons and protons appeared to act indistinguishably. They were certainly different particles—protons carried one unit of electric charge, while neutrons had no charge—and yet neutrons and protons seemed to interact with other nuclear particles, such as pions, in a symmetrical way. Exchanging protons for neutrons, and vice versa, appeared to make no impact at all. Physicists had a term for such differences that made no difference: "gauge invariance."

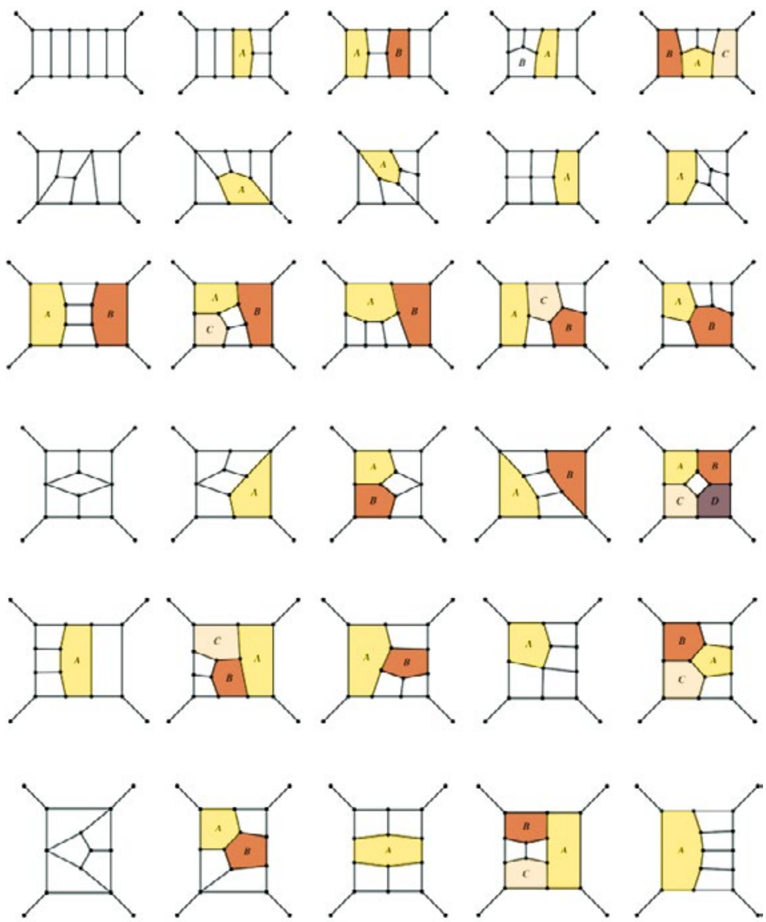
The young theorists built a new model of nuclear forces by elevating this dimly-glimpsed symmetry into a founding principle. What if all nuclear interactions *had* to respect the symmetry between neutrons and protons? Such a symmetry could only be upheld, they found, if they included a new type of particle. The sole purpose of the hypothetical "gauge particle"—at least in Yang's and Mills' calculations—was to scatter (or bump) off other nuclear particles in just such a way as to compensate for any possible differences in outcomes involving protons versus neutrons. All those scatterings, meanwhile, meant that the gauge particle would transmit forces: It was the force-carrier of the nuclear force, a cousin to the photon of electromagnetism.

> The amplituhedron approach makes the older, Feynman-diagram tools look as helplessly outdated as room-filling, jerry-built, vacuum-tube computers.

Here was symmetry with a vengeance. Yang and Mills made a leap from Heisenberg's intuition and scattered experimental evidence to suggest that the neutron-proton symmetry held exactly. To protect that symmetry, they had to dream up a whole new type of matter, which generated the very interactions among nuclear particles that Yang and Mills had set out to try to understand.

By the mid-1970s, particle physicists had pieced together a complicated collection of nuclear forces known as the "Standard Model," involving several different types of gauge particles. Within a few years, they began to accumulate experimental evidence for "gluons," the gauge particles that keep quarks bound inside protons, neutrons, and other nuclear particles. Large experimental teams at CERN first detected gauge particles of the "weak nuclear force"—the force that causes nuclear reactions like radioactive decay—in 1983. Once

* Mesons are subatomic particles composed of one quark and one antiquark.



FEYNMAN ZOO Applying Feynman diagrams to nuclear calculations results in a dizzying array of possibilities. Shown here is a subset of the diagrams used in the calculation of four-gluon scattering, as treated in a supersymmetric Yang-Mills model.[3]

imagined as a mere mathematical device, Yang-Mills gauge particles have become part of our world, physical instantiations of underlying symmetries.

Having established that gauge particles are real, physicists needed to calculate their behavior, including detailed scattering amplitudes. This proved to be difficult. Yang and Mills had made a modest-looking tweak to Feynman's rules for calculating with his diagrams, allowing direct scattering of gauge particles off each other, as required by their role in protecting gauge symmetries. While this looked simple, it produced enormous headaches. Feynman diagrams now needed to include closed loops formed just from gauge particles, a complication that never arose when applying the diagrams to electron-photon interactions.

Feynman himself demonstrated in 1963 that such closed loops would spoil the very symmetry that the gauge particles had been invented to enforce. So physicists had to insert still more strange mathematical machinery into their calculations, including "ghosts": fictitious particles whose sole purpose is to chase gauge particles around in certain types of Feynman diagrams, ultimately cancelling out of the calculations when different diagrams are added together. Unlike the gauge particles themselves, the "ghosts" (as their name implies) were not supposed to represent genuine particles. They were a mathematical fiction, a kludge invoked so that Feynman diagrams—a tool invented for other purposes—could be applied to models with Yang-Mills symmetry.

As a result, physicists have doggedly spent the last decades using this work-around, filling blackboards and journal articles with hundreds of Feynman diagrams littered with distinct squiggles for gauge particles and ghosts, wrestling with the fact that the symmetries that Yang and Mills introduced seem to have gummed up the works (see Feynman Zoo).

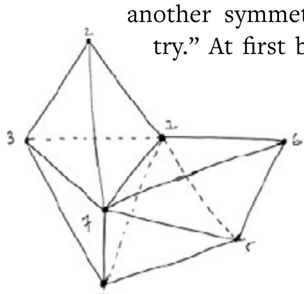
They have found a modest reprieve by invoking yet another symmetry, known as "supersymmetry." At first blush, supersymmetry sounds outlandish: a doubling of all known types of matter, so that every particle gains a "superpartner" which is almost identical to itself, differing only in the amount of intrinsic angular momentum, or "spin," that it carries. All those twinned particles lead to exact cancellations among whole classes of Feynman diagrams, greatly reducing the complexity of any given calculation.

Yet even with supersymmetry, any effort to calculate scattering amplitudes involving quarks and gluons has left physicists mired in an ungainly diagrammatic mess. Following Donald Rumsfeld, Feynman diagrams depict at least three types of beasts. There are the known knowns: particles like quarks and gluons that surely exist in our world. Others are the known unknowns: gauge-artifact "ghosts" that exist only in physicists' imaginations, and are not meant to represent real stuff in the world. And then there are all those superpartners, the unknown unknowns.

Despite decades of concerted searching—even in grand machines like the Large Hadron Collider at CERN—absolutely no empirical evidence has surfaced that superpartner particles exist. But as Rumsfeld famously declared, absence of evidence is not necessarily evidence of absence. Our universe might indeed be governed by supersymmetry, and all those superpartners might one day be discovered. Or they might be nothing more than a convenient mathematical fiction, a souped-up version of ghosts. What seems clear is that supersymmetry remains too convenient to discard: a beloved spherical cow of the microworld.

A New Tool for New Tasks

Nima Arkani-Hamed, a professor at the Institute for Advanced Study in Princeton, is among the most-cited physicists in the history of the universe. Still in his early 40s, he has already accumulated more than twice the number of citations that Richard Feynman collected over a lifetime. Together with his former student and co-author, Jaroslav Trnka, Arkani-Hamed is taking aim



THE AMPLITUHEDRON An example amplituhedron for the case of eight interacting gauge particles. This diagram is a projection of a three-dimensional face of the full amplituhedron, which in this case lives in four (abstract) dimensions.[4]

at the baroque complexity which physicists have had to face when calculating particle interactions.

On Dec. 6, 2013, Arkani-Hamed and Trnka uploaded a paper describing the amplituhedron onto the preprint server, arXiv.[4] Their claim is bold: Here, they write, is a replacement for the venerable Feynman diagram, at least for treating the types of interactions—like the nuclear forces—in which force-carrying particles can scatter directly off each other. When comparing apples to apples (restricting themselves to models that incorporate supersymmetry), their new method can reproduce in just a few lines of algebra the scattering amplitudes that others have painstakingly calculated from hundreds (even thousands) of Feynman diagrams.

To perform their new kind of calculation, Arkani-Hamed and Trnka use their exquisitely simple-looking geometrical constructions, the amplituhedra. Unlike Feynman's doodles, the new objects are not depicted in space and time; rather, they live in an imaginary, multidimensional mathematical space (see The Amplituhedron on page 75). The anchoring points in the new diagrams are coordinates that represent the particles' momenta, spin, and other variables, rather than locations in space where the particles actually meet.

Total momentum and spin must be conserved in any scattering, and hence each amplituhedron is built from closed polygons—essentially, generalizations of a simple triangle. Almost like magic, Arkani-Hamed and Trnka have demonstrated—at least in several tough test cases—that they arrive at the same value for the amplitude of various particle scatterings by calculating the volume of the corresponding amplituhedron, thereby doing an end-run around all those closed-loop, ghost-filled Feynman diagrams.

The result is a breathtaking economy. Physicists like Andrew Hodges at Oxford University and Jacob Bourjaily at Harvard University have marveled at the extraordinary compression and simplification that the amplituhedron approach promises. "The degree of efficiency is mind-boggling," Bourjaily exclaimed to a journalist recently—an uncanny echo of physicists' responses to witnessing Richard Feynman first calculate with his diagrams 65 years ago.[5]

The amplituhedron's power derives from promoting one kind of symmetry over another. The symmetries that it promotes are those of the amplitudes themselves, governed by very general principles and constraints like conservation of momentum. Swapping an outgoing particle for an incoming one corresponds to rotating the amplituhedron. Some rotations leave the object's appearance unchanged, just as one can rotate a dodecahedron by certain angles along various directions and not notice any change. To Arkani-Hamed and Trnka, these global symmetries—rotations of the entire amplituhedron that leave its structure unchanged—trump local gauge symmetries. This means that they discard some types of local symmetries. In fact, they discard—or at least demote—the very idea of "locality" itself. Feynman designed his diagrams assuming that all physical effects arise locally, when one little chunk of matter bumps into another one, at some location x and time t. Feynman didn't need to know the exact spot where each collision occurred—he integrated over all the possible locations when evaluating his amplitudes—but he nevertheless assumed that each interaction happened at some local position in space and time.

Arkani-Hamed, on the other hand, has a different view of locality. For him, the ultimate prize, the looming mountain in the distance, is a theory of quantum gravity. The amplituhedron is simply a base camp. And because a theory of quantum gravity would presumably explain the emergence of space and time from some deeper substrate or structure, he is eager to sidestep any assumptions about locality—since the notion of locality, after all, presupposes that space and time already exist. While his amplituhedra don't assume locality, the *solutions* it produces respect it: Locality is an emergent feature of Arkani-Hamed's framework, rather than a starting assumption.*

* In a similar way, Arkani-Hamed and Trnka show that the solutions they calculate obey "unitarity," even though they do not assume unitarity from the start—another conceptual break from the usual approach. Unitarity concerns the behavior of the probabilities calculated from all those amplitudes: The total probability for anything to happen must add up to one.

The Future

I can imagine a fractal pattern unfolding. Some time down the road, there could be so many amplituhedra cluttering young physicists' blackboards (or iPads), that they will feel the need to invent still another device, standing in for hundreds of amplituhedra just as a single amplituhedron stands in for hundreds of Feynman diagrams—and as each Feynman diagram, in turn, represents dozens of lines of algebra. Each new generation tends to reassess the symmetries that had previously been taken for granted. One physicist's sacred spherical cow becomes another's inefficient accounting scheme.

For now, though, the amplituhedron and the supersymmetry on which it relies remain unproven ideas. What we do know is that by avoiding local symmetries and enforcing global ones, the amplituhedron allows physicists to calculate complicated interactions with astonishing ease. Even if supersymmetry proves not to be an accurate description of our universe, the success of the amplituhedron suggests that the most basic forces of nature might be governed by a deeper, simpler mathematical structure than what Feynman diagrams have been able to reveal.

On that score, the amplituhedron approach makes the older, Feynman-diagram tools look as helplessly outdated as the room-filling, jerry-built, vacuum-tube computers that, like Feynman's diagrams themselves, date from the late 1940s. Whether the amplituhedron proves to be exact, or simply a good symmetry-based approximation—the latest spherical cow—will become clear over the coming years, as physicists continue to wrestle with which symmetries should count, and how.

DAVID KAISER is Germeshausen Professor and Department Head of MIT's Program in Science, Technology, and Society, and also Senior Lecturer in MIT's Department of Physics.

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What Do Animals See in a Mirror?

A controversial test for self-awareness is dividing the animal kingdom

BY CHELSEA WALD

T**HE IDEA FOR A TOOL** to probe the basis of consciousness came to Gordon G. Gallup, Jr. while shaving. "It just occurred to me," he says, "wouldn't it be interesting to see if other creatures could recognize themselves in mirrors?"

Showing chimpanzees their reflections seemed like a fascinating little experiment when he first tried it in the summer of 1969. He didn't imagine that this would become one of the most influential—and most controversial—tests in comparative psychology, ushering the mind into the realm of experimental science and foreshadowing questions on the depth of animal suffering. "It's not the ability to recognize yourself in a mirror that is important," he would come to believe. "It's what that says about your ability to conceive of yourself in the first place."

Gallup was a new professor at Tulane University in Louisiana, where he had access to the chimps and gorillas at what would later be known as the Tulane National Primate Research Center. The chimpanzees there had been caught as youngsters in Africa and shipped to America, where they were used mainly in biomedical research. By comparison, his experiment was far less invasive. He isolated two chimps in cages, and placed a mirror in each cage for eight hours at a time over 10 days. Through a hole in the wall, Gallup witnessed a shift in the chimps' behavior. First they treated the reflection like it was another chimp, with a combination of social, sexual, and aggressive gestures. But over time, they started using it to explore their own bodies. "They'd use the mirror to look at the inside of their mouths, to make faces at the mirror, to inspect their genitals, to remove mucous from the corner of their eyes," Gallup says.

Gallup was sure that the chimps had learned to recognize themselves in the mirror, but he didn't trust that other researchers would be convinced by his descriptions. So he moved to phase two of the experiment. He anesthetized the chimps, then painted one eyebrow ridge and the opposite ear tip with a red dye

ILLUSTRATION BY EMMANUEL POLANCO

that the chimps wouldn't be able to feel or smell. If they truly recognized themselves, he thought he knew what would happen: "It seemed pretty obvious that if I saw myself in a mirror with marks on my face, that I'd reach up and inspect those marks."

That's exactly what the chimps did. As far as Gallup was concerned, that was proof: "the first experimental demonstration of a self-concept in a subhuman form," he wrote in the resulting 1970 report in *Science*. "It was just clear as day," he remembers. "It didn't require any statistics. There it was. Bingo."

But the result that really blew Gallup's mind came when he tested monkeys and discovered that they did not do the same. The ability to recognize one's reflection seemed not to be a matter of learning abilities, with some species being slower than others. It was an issue of higher intellectual capacity. Gallup had obtained the first good evidence that our closest relatives share with us a kind of self-awareness or even consciousness, to the exclusion of other animals. Here, finally, was an experimental handle on a topic that had been the subject of speculation for millennia: What is the nature of human consciousness?

GALLUP WASN'T THE FIRST to come up with the notion that it might be significant if a person or animal recognizes itself in the mirror. He would only later learn that Charles Darwin had shown mirrors to orangutans, but they didn't figure the mirror out, at least while he was watching. Darwin had also noted that, for their first few years, his children couldn't recognize themselves in their reflections. In 1889, German researcher Wilhelm Preyer became the first to posit a connection between mirror self-recognition and an inner sense of self in people.

More than 50 years later, French psychoanalyst Jacques Lacan conceived of a childhood "mirror stage," in which mirrors contribute to the formation of the ego. By 1972, developmental psychologists started using mark tests similar to Gallup's to pin down the age at which children begin to recognize themselves in the mirror: 18 to 24 months.

Meanwhile Gallup, who moved to the University at Albany-SUNY, became interested in whether any nonprimates could pass. In the early 1990s, he took on a Ph.D. student, Lori Marino, who would explore the question. Working with Diana Reiss at Marine World Africa USA in California, Marino exposed two bottlenose dolphins to a mirror. Like the chimpanzees, the dolphins learned to use the mirror in a variety of ways, even "having sex in front of the mirror with each other, which we call our dolphin porno tapes," Marino says. The three researchers published the results, saying they were "suggestive" of mirror self-recognition.

Still, they were missing the crucial mark test for another decade. The biggest hurdle was anatomical: The dolphins didn't have hands to touch a mark. But Reiss and Marino, by then at the New York Aquarium, designed a modified test. When marked with black ink on various parts of their bodies, the dolphins flipped and wriggled in an attempt to see it, convincing the researchers and many others that they recognized themselves.

For Reiss and Marino, the dolphin study was not only convincing, it was a call to action. They and others now argue that passing the mirror test indicates a level of self-awareness that makes it unethical to keep a species in captivity. "These animals have at least some level of self-awareness, and if they do, they know where they are, they can be aware of the limitations of their physical environment," Marino says. She is now the science director for the Nonhuman Rights Project, which is attempting to gain legal rights for animals with higher-order cognitive abilities by getting courts to recognize them as "legal persons," and Reiss advocates for dolphin protection. Key to their arguments is the scientific evidence that chimps, elephants, cetaceans, and other animals are self-aware like humans. Not only can they suffer, but they can think to themselves, I am suffering.

Gallup, now in his 70s, mainly stays away from advocacy work, but he likes to philosophize about what exactly mirror self-recognition shows, and why that capability might have evolved. Clearly, it has little to do with mirrors since aside from the occasional still pond, our distant ancestors would never have encountered their reflections. He's come to the conclusion that a pass of the mirror test indicates a profound level of consciousness that includes animals' ability to contemplate their own thoughts and experiences as well as to imagine what others could be thinking and experiencing. This ability is called "theory of mind."

For support, he points to the fact that children start to demonstrate theory of mind around the same time that they start to recognize themselves in the mirror. "You have to be aware of yourself in the first place in order to begin to take into account what other people may know, want, or intend to do," he says. He notes that people with schizophrenia often cannot recognize themselves in the mirror, and they struggle with theory of mind as well. For example, compared to controls, schizophrenic individuals were less likely to understand a request hidden in a husband's statement to his wife: "I want to wear that blue shirt, but it's very creased."

Gallup suggests that a powerful sense of self may have evolved because it helped great apes deal with complex social situations. "Intellectual prowess supplanted physical prowess as a means of achieving dominance," he says. And, he suggests that strong self-awareness may also entail death-awareness. "The next step, it seems to me logically, is to confront and eventually grapple with the inevitability of your own individual demise," he says.

As for why dolphins and other non-primates recognize themselves in mirrors, Gallup isn't yet convinced they do. He suggests an alternative explanation for why his former student's dolphins wriggled in the mirror: to see marks on what they perceived as another dolphin peering back at them. And he asks for replication of recent studies finding that elephants use their trunks to touch white crosses on their foreheads, and that magpies dislodge stickers on their chests with their beaks.

Then there are researchers who discount whether the mirror test says anything about theory of mind in any animal, including humans. Most notably, Gallup's mentee, Daniel Povinelli. Like a son who witnesses his father's foibles and decides to become his opposite, Povinelli, now at the University of Louisiana-Lafayette, has become one of Gallup's most outspoken critics, even as they remain close on a personal level. He's come to believe that a chimp doesn't need to have an integrated sense of self in order to pass the mirror test. Instead, it needs only to notice that the body in the mirror looks and moves the same as its own body, and then make the connection that if there's a spot on the body in the mirror, there could also be a spot on its own body. That ability would still

DIY TEST

By the time a baby is 2 years old, it has undergone a cognitive shift in self-awareness, and can easily use a mirror to locate a sticker in its hair. Puppies and kittens aren't so impressed with stickers, but often play with their image in a mirror, which they do not recognize as their own reflection. Older dogs and cats tend to ignore their reflections, possibly because they have lost interest.

SHUTTERSTOCK

1
Place a big, colorful sticker in a baby's hair away from a mirror, making sure the baby doesn't notice or feel it.

2
Then take the baby to a mirror. The baby may point at the sticker, but they don't realize that it's on their own head.

3
When you remove it and show it to them, they'll be surprised.

Povinelli calls this reasoning "folk psychology"—unscientific inferences based on our own human experiences.

be pretty sophisticated, Povinelli adds, and it might reflect a keen awareness of the position of body parts that would likely be very helpful for swinging through trees. Indeed, he speculates that this physical self-awareness may have developed when our tree-dwelling ancestors increased in size and faced more challenges while navigating their branchy, leafy world.

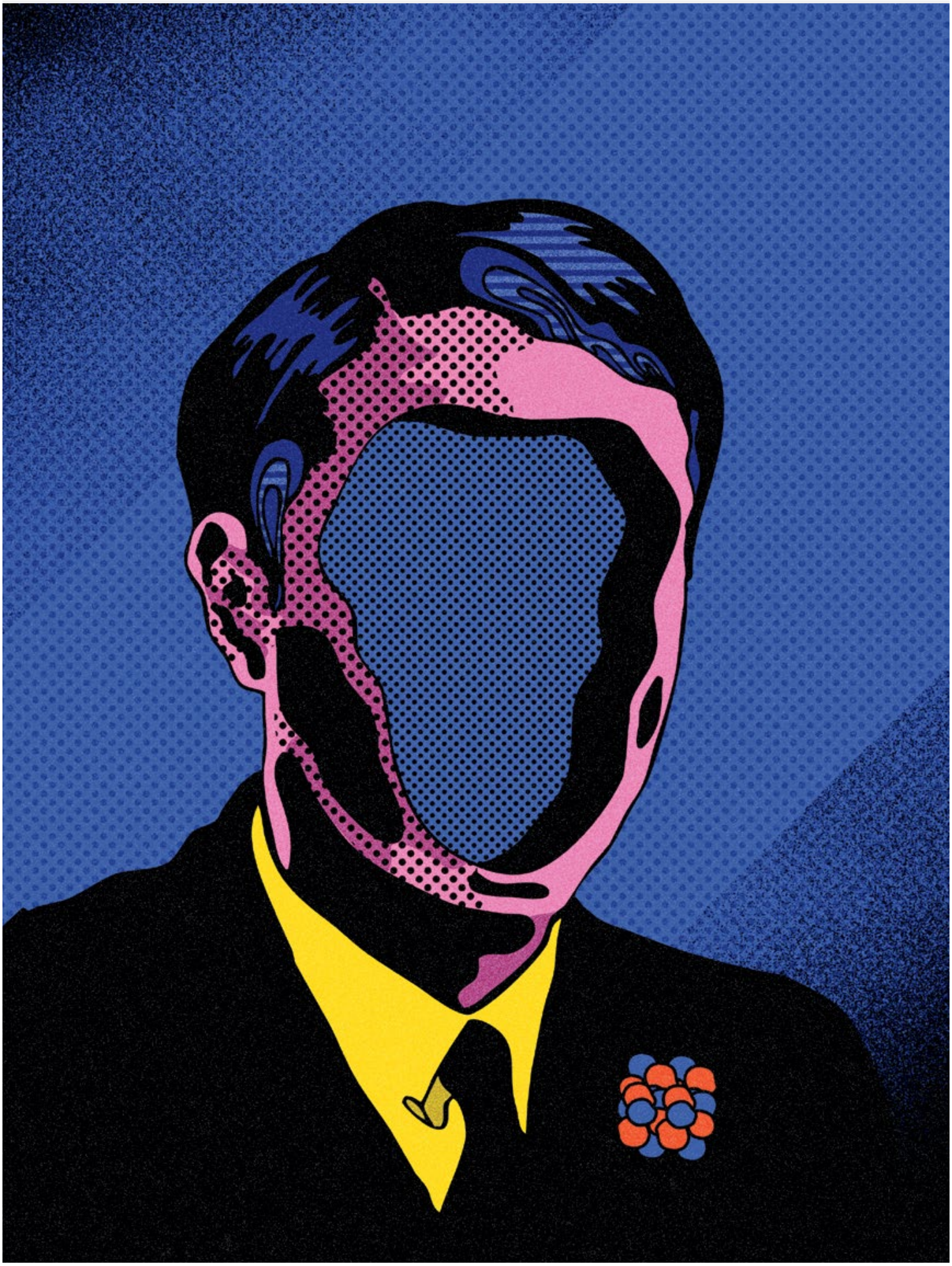
Povinelli's concerns stretch to other landmark studies on theory of mind in chimps, such as a series of reports that documented how a subordinate chimp refrained from hidden food when she watched a dominant chimp see researchers hide the food. The authors of this study argued that her reaction reflected her thoughts about what the dominant chimp had seen and what it would do. Combined with results from other experiments, they concluded that chimps can "understand both the goals and intentions of others as well as the perception and knowledge of others," and they can predict the action that will result.

But Povinelli calls this reasoning "folk psychology"—unscientific inferences based on our own human experiences. The subordinate chimp doesn't have to know the dominant's mind, he says, all she has to know is to avoid interfering with the dominant chimp.

To apply Povinelli's logic to humans, we may think deep, reflective thoughts when using a mirror to brush our teeth, but that doesn't mean that the part of the brain that's using the mirror to direct our toothbrush is the same part of the brain that's contemplating the self. Those two abilities may develop at the same time in children, but that does not mean that they're related, much less one and the same.

Povinelli's critiques aside, most comparative psychologists say there's something to mirror recognition, not least because it's only been observed in intellectually superior animals. Neuroscientists are now trying to shed light on the matter by searching for a physical basis for the ability in the brain. Although they haven't found a clear signal yet, Gallup remains undeterred. After nearly 45 years of fending off challengers, he is not likely to wake up in the morning, look in the mirror, and change his mind.

CHELSEA WALD is a freelance science writer who contributes to *Science* and *Nature*. She lives with her reflection in Vienna, Austria.



“THE DISAPPEARING PHYSICIST AND HIS ELUSIVE PARTICLE”
BY WEBUYYOURKIDS

14

WHILE MANY GENES ARE famous, one in particular has been prominent recently. In the early 1990s, scientists discovered that single-letter mutations in a gene named *BRCA1* led to a higher risk of breast cancer. On June 1 of this year, a new report in *Nature Genetics* implicated mutations in a closely related gene, *BRCA2,* for lung cancer.

The genes' function is to produce proteins that suppress tumors—so it's perfectly reasonable to assume a mutation in the gene is harmful. But in fact that's only half the story: Some scientists have argued that *BRCA* mutations can be beneficial, and an earlier *Nature Genetics* paper reported evidence that the gene *BRCA1* was involved in human adaptive evolution.

Mutations, we learn, make us what we are, so that ideas of "harm" and "help" become blurred and linked. Even the most intricate biological mechanisms, with the most important functions, are already slipping into the future to do something else.

In this issue, we trace the outlines of a world that is continually abandoning and inventing itself—often with our help.

Welcome to "Mutation."

—MS

"Although it is the most numerous massive particle in the universe, it is so slippery that it can pass through a light-year of lead as if it wasn't there."

MAGGIE MCKEE
"This Shape-Shifter Could Tell Us Why Matter Exists" p.130

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ENGINES OF CHANGE

America's Getting the Science of Sun Exposure Wrong

Why U.S. dermatologists won't base recommendations on skin color

BY JESSICA SEIGEL

HER MUM FROWNS ON IT. Cancer experts once all warned against it. But these days you'll find Vandana Verma, a 29-year-old secretary in Melbourne, Australia, sitting outside at lunch wearing no hat, no sunscreen, her arms and legs exposed because her doctor told her to. Her physician prescribed daily sunshine (along with vitamin D supplements) after a blood test in her first trimester came back highly deficient for vitamin D, the crucial hormone that the body creates when ultraviolet (UV) light hits the skin. "I was told if it didn't improve, it would affect mine and my baby's bones," says Verma.

This winter—June and July in Australia—the Cancer Council Australia is urging many people to dump the sunscreen and hat to catch some rays, after years spent advising the opposite. The about-face—exposing both sides of the body is advised—especially targets darker residents like Verma and those who live in seasonally low-light southern cities including Adelaide, Sydney, and Melbourne, where the UV index averages below 3 in their coldest months.* Regional alerts will remind schools that children should remove their legionnaires-style hats that are required the rest of the year. One public service posting from the partially government-supported SunSmart program on Facebook even shows a shirtless, pasty white man with arms outstretched, soaking up golden rays. The image would appall United States dermatologists, today expanding their campaign against any unprotected exposure to the sun.

Australia has the highest melanoma rate on Earth, which motivated the nation's famed "Slip! Slop! Slap!" campaign. Launched in 1980, it advised Australians to slip on a shirt, slop on the sunscreen, and slap on a hat. The slogan, promoted by Sid the Seagull—Australia's

* The UV index is an international scale, ranging from 0 to 11+, that measures the strength of UV radiation from the sun. A reading below 3 indicates there is little danger from the sun's rays for the average person.

ILLUSTRATION BY DANIEL ZENDER

equivalent of Smokey the Bear—was created to battle skyrocketing skin cancer. The southern hemisphere tilts toward the sun in Australian summer, so the sun beats down more directly below the equator than above. It is a harsh fit for the pale, blonde, and red-headed English, Irish, and Scottish immigrants and their descendants who settled on this continent far from the penumbra of their ancestral lands.

People regularly exposed to daily sun have a lower risk of getting melanoma and also have a higher survival rate if they do.

Today, some 70 percent of Australians will develop skin cancer at some point in their lives, including basal cell and squamous cell carcinomas—the less dangerous variety of skin lesions that mostly appear on sun-exposed body parts such as the face, neck, and hands. The scabby, pearly, rough-edged bumps, indents, and patches are rarely deadly if treated in a timely manner. Though also mostly curable if caught early—but deadly if not—malignant melanoma often morphs from moles or even a small dot, then metastasizes to other organs, like the lung and brain. Obituaries for young people are a regular feature of Australian newspapers—melanoma will afflict 1 in 18 Australians before they reach age 85. That's more than double America's rate.

But the melanoma capital of the world is welcoming back the sun after a half-century on the outs. The move follows a new understanding of skin cancer and vitamin D. By the early 2000s, research began to suggest a link between vitamin D and lower disease rates for cancers including breast, prostate, and non-Hodgkin's lymphoma, along with autoimmune diseases such as multiple sclerosis.[1] The need for sun especially affects darkly colored people since the skin pigment melanin, which protects against damaging ultraviolet solar radiation, also slows vitamin D production. Vitamin D deficiencies leach calcium from muscles and bones, causing pain, weakness, fractures, osteoporosis, and osteomalacia. Called rickets in babies and children, the bone-deforming illness not seen since Victorian times began cropping up from Britain to Australia—and the U.S. too—in darker populations, many of them recent migrants from equatorial zones.

At the same time, new research on who gets melanoma and why began changing beliefs about the sun. In 2003, a landmark eight-year study of 106,379 Scandinavian women published in the (American) *Journal of the National Cancer Institute* by an international team linked melanoma to sunburns (not tanning), blonde or red hair, and numbers of moles on the legs.[2] A second article in the *Journal of the National Cancer Institute* solidified what had long been reported, but not quite believed: People regularly exposed to daily sun have a lower risk of getting melanoma and also have a higher survival rate if they do,[3] because regular sun exposure protects against burning, a finding later confirmed by a landmark 2008 World Health Organization (WHO) International Agency for Research on Cancer report.[4]

This is the outdoor worker effect, when a chronic tan naturally waxes and wanes with the sun, growing darker with summer as the UV index intensifies, then fading with winter light.[5] In the ancient pattern of life, human appearance would track the seasons, as it does for other animals, like the bear and its winter coat. The modern indoor worker—especially in wealthier classes—grows pale inside offices, homes, and malls, then plunges into irregular bouts of excessive sunlight on beach vacations or long weekends. This sudden, intense, intermittent pattern of sun exposure heightens melanoma risk, says Bruce Armstrong, internationally-known Australian epidemiologist and former Deputy Director of the International Agency for Research on Cancer, a co-author on the landmark sunburn and melanoma research.

So in the "sunburnt" country, the public began accusing Slip, Slop, Slap mania with going overboard, based on prominent media coverage of the latest skin cancer and vitamin D findings. In 2004, Craig Sinclair, then director of the Cancer Prevention Centre at Cancer Council Victoria, called a meeting of the country's health and medical leaders to revise sun exposure guidelines. As a result, medical doctors and cancer authorities in Australia, New Zealand, and later Britain adopted nuanced new policies based on skin color and the sun's strength at different times of the year. Verma, too, used to slip on a shirt, slop on the sunscreen, and slap on a hat to protect her luminous olive complexion, prized for its relative pallor in her native India—now she is following the new guidelines to get several hours of sun a week all year and ditch protection altogether in Melbourne's winter.

"We're very active telling people when not to use protection" in winter, says Sinclair, who also heads the WHO's Collaborative Centre for UV Radiation and has published research on the revamped Australian policy in the journal *Progress in Biophysics and Molecular Biology*. Then he adds, "This is certainly unusual compared to the U.S."

CATCHING SOME RAYS On August 12, 2013, during the Australian winter, the Australian SunSmart Facebook page posted this photo of a white man basking in the sun.

AT THE TIME THAT these Commonwealth nations were revising sun recommendations, the U.S. proceeded in the opposite direction. In 2004, when pioneering vitamin D researcher Michael Holick advised five to 10 minutes of direct sunshine two to three times weekly in his book, *The UV Advantage: The Medical Breakthrough That Shows How to Harness the Power of the Sun for Your Health*, it cost him his position at the dermatology department of the Boston University School of Medicine. As a graduate student back in the 1970s, Holick helped identify and isolate the circulating form of vitamin D, called 25-hydroxyvitamin D3, which varies with intake before being processed in the kidneys into an active hormone, which he also identified. He found that the darkest skin takes six to 10 times longer than the lightest skin to create the same quantity of vitamin D.

Boston University School of Medicine dermatology chair Barbara Gilchrest asked Holick to either retract his recommendation for regular, direct sunlight and controlled use of tanning bed artificial UV lights, or resign. He stepped down, while retaining his primary professorship in medicine, physiology, and biophysics. Dubbed "Doctor Sunshine" in the ensuing media fracas, Holick still advocates a few minutes of direct sun a day as a "totally meaningless" danger for even the palest people—although he does wear sunscreen on his face in summer for longer outdoor activities like tennis.

So who is right—the Yankees or the Aussies and Brits? The answer lies in the details of how ultraviolet radiation works on the body. How the sun affects you depends on the shade of your complexion, which is determined by melanin, a pigment derived from amino acids older than life on earth. The anti-oxidizing molecule is so versatile at protecting and repairing DNA from the damage caused by UV solar radiation that creatures from humans to fungi deploy it in diverse ways, creating what is, in effect, nature's box of crayons.

Rising up inside the epidermis, the melanin sits atop cellular DNA like tiny umbrellas pointed one way—out, in order to shield from incoming rays. And here's the hitch—the same ultraviolet wavelengths in the 290 to 400 nanometers range that trigger melanin production also spark vitamin D creation. You cannot make one without the other. As humans fanned out from the equator into lower light zones, the *MC1R* gene evolved to produce two kinds of melanin. The *MC1R* gene[6] determines the type of melanin the body produces. In the mid-zone, such as the Mediterranean region, people developed the ability to tan deeply and lighten, tracking what can be dramatic shifts from winter to summer. They produce eumelanin, the pigment responsible for brown or black hair and for dark skin that tans easily. To survive in far northern Europe, humans paled, adapting to lower light and changing seasons with a different type of melanin, called pheomelanin, associated with fair skin and blonde and red

> "We're very active telling people when not to use protection" in winter, says Sinclair. "This is certainly unusual compared to the U.S."

hair with minimal protective value, but allowing more UV to penetrate to make vitamin D. The exterior of an Irish lass with her porcelain complexion would be rated a sun protection factor, or SPF, about 10 times lower than a sub-Saharan African. If she had red hair and freckles, linked to the *MC1R* gene, then she'd have a much higher risk of UV-related melanoma in sunnier regions. "People's skin adapted to the place where they live," says Nina Jablonski, distinguished professor of anthropology at Pennsylvania State University and author of *Living Color: The Biological and Social Meaning of Skin Color*.

Her research, cited in the landmark 2008 WHO report on vitamin D and cancer, used NASA satellite maps to show how gradients of skin color from darkest at the equator to lightest at the poles correlates with solar strength from zero to 90 degrees latitude. "We evolved under the sun," she says. "Our pattern of lack of sun exposure as a result of being indoors—even the concept of being indoors—is a recent concept in our history."

But in the U.S., the American Academy of Dermatology, representing 17,000 skin specialists, is issuing recommendations that do not take skin color into account. Earlier this year, leading ethnic dermatologists—an industry term used to describe dermatologists focusing on people with darker skin—published an article in the academy journal titled "Skin cancer and photoprotection in people of color: A review and recommendations for physicians and the public."[7] Promoted at the academy's 2014 meeting in Denver, the article advises all "people of color," even the darkest, to seek the shade and wear sunscreen, then take supplements to make up for any vitamin D shortfall. Recommendations like these have a direct effect on national healthcare policy. The academy sets medical guidelines for U.S. skin doctors, who influence policy through national organizations ranging from the Skin Cancer Foundation to the American Cancer Society and the U.S. Surgeon General. "They're extremely influential," says Holick.

While the Academy of Dermatology declines to tailor its recommendations by skin color, the data reveal very different realities for different races. For example, the academy often emphasizes that skin cancer is on the rise. There has indeed been a 17 percent jump in melanoma rates for Caucasians, from 22.9 to 26.8 cases in 100,000 people, between the years 2000 and 2010. But the incidence for African Americans has not changed over this same time period, flatlining at 1 case in 100,000—26 times lower, according to the U.S. CDC National Cancer Registry. Melanoma is mostly a white person's disease affecting "Caucasian populations residing in highly resourced, westernized countries," according to a WHO 2012 report. In the U.S., melanoma is the sixth most common cancer for Caucasians, but does not make the top 10 for African Americans.

When black people do get melanoma, it is often more deadly, in part because of later detection related to lack of awareness, less visible lesions, unequal health care access, and possibly distinct carcinoma biology, says Ophelia E. Dadzie, M.D., a British-Ghanaian dermatologist, dermatopathologist, and co-editor of the textbook *Ethnic Dermatology: Principles and Practice.* It is also often a different kind of melanoma, called acral lentiginous or subungual, which typically appears on the soles of the feet, and in finger and toe nail beds—parts of the body not exposed to the sun. "It may have nothing to do with sun exposure at all, but we can't say that's the case based on limited studies that have been done," says Armstrong, the Australian epidemiologist.

The American Academy of Dermatology's article about skin cancer and photoprotection acknowledges that for "blacks and Asians, UV radiation does not appear to be a major risk factor" in malignant melanoma. It also states that the effectiveness and impact of sunscreen for black people is unknown since SPF sunscreens are tested only on light-skinned individuals. But the report still goes on to recommend sunscreen for all people of color regardless of skin shade. For Henry W. Lim, M.D., a leader of the Skin Cancer Foundation's photobiology committee and chair of the Henry Ford Hospital dermatology department in Detroit, the missing information is irrelevant. "We don't need data on that," he said, because supplements would treat any D-shortfall, whatever that might be. "We want to make it simple as a public health message—as to what the public should reasonably be able to absorb and understand," says Lim. "To fine tune it is just too complicated, we feel."

The Skin Cancer Foundation echoes the American Academy of Dermatology in its colorblind sun protection advice. The blanket sunscreen recommendation incenses anthropologist Jablonski, who signed on to a letter to the academy's journal editor decrying unscientific conclusions and conflicts of interest from cosmetic company influence. Stated conflicts of interest in the photoprotection academy article include one of the study authors, Susan Taylor, M.D., who sits on the advisory boards of several corporations including Unilever, and founded a skincare line called "RX for Brown Skin," involving specialized sunblock. According to market research firm Euromonitor Inc., "ethnic" consumers are the subject of new products and marketing by the $8.2 billion global sunscreen industry.

"It's scientific issues mixed with the race card," says Jablonski. "Americans have a serious problem with skin color. When you think of the history of slavery in the United States, that is the problem," she says. "So many doctors feel extremely uncomfortable talking about it. What they see in skin color is a social barrier, not a physical phenomenon."

Even doctors who do want to talk about it face powerful opposition. Robert Gagel, president of the National Osteoporosis Foundation and internal medicine and endocrinology professor at The University of Texas MD Anderson Cancer Center in Houston, says that bone, muscle, and hormone physicians may often privately advise controlled sunlight to patients, but decline to officially say so in published clinical guidelines. "We choose not to provoke a 'fight' over this issue," says Gagel. "Rather than fighting a battle that we probably can't win we've focused on vitamin D supplements."

In fact, says Gilchrest of Boston University School of Medicine, the American Academy of Dermatology has debated, but rejected adjusting its universal no-sun stance. "They don't like to have recommendations that target one racial group or another," says Gilchrest, who is also the editor of the *Journal of Investigative Dermatology*. "They like to have one single recommendation for fear of insulting someone, I guess." She was unaware that Australia, which she described as a world leader on sun research, revamped their policy nearly a decade ago. In the U.S., she says, the skin color topic is "such a can of worms."

But down under, osteoporosis doctors, dermatologists, and national cancer leaders dealt with it, unanimously signing off on their "Risks and Benefits of Sun Exposure Position Statement" in 2005, later updated in 2007. The policy refers to the Fitzpatrick Scale of skin tone, which ranks skin color from lightest to darkest on a scale of 1 to 6. The scale was devised by Harvard dermatologist Thomas Fitzpatrick in 1975. Type 1 is "very fair, pale white skin that always burns, never tans," meaning Northern European. Type 6 is "deeply pigmented, dark brown to black skin that never burns," meaning sub-Saharan Africans, such as Nigerians. As the Australians state, darker people—Fitzpatrick 5 and 6 types—need more sun and are "relatively protected from skin cancer by the pigment of their skin."

Australian experts recommend vitamin D pills only for at-risk groups, such as darker-skinned people, pregnant women, babies of deficient mothers, the institutionalized, and the elderly. "There wasn't and there still isn't absolute evidence" that supplements are bioequivalent to sunshine, says Stephen Shumack, M.D., president of the Australasian College of Dermatologists. "We've always been pragmatic in Australia," he says. "The pragmatism leads us away from one size fits all." Sun exposure, instead, can be considered another facet of the emerging practice of personalized medicine. There are even apps for that. With 100,000 users, the official Cancer Council Victoria's mobile program, SunSmart, tracks the user's UV exposure and vitamin D intake. An American-made app, DMinder, created by California entrepreneur Rob Williams of Ontometrics, can be used worldwide.

For Dadzie, the sun is a personal issue. She lives in foggy London at a latitude of 50 degrees north. Though vitamin D deficiencies plague her dark-skinned patients, she never made the connection to her own low energy and sharp pains in her feet and hands until her office nurse suggested a blood test, which revealed extremely deficient vitamin D levels. Raised the daughter of a Ghanaian United Nations official, she grew up in Africa never thinking about her skin color or the ubiquitous sun. No one there wears sunscreen, yet skin cancers are rare, she explains. "Your mum will say to you the sun is really strong now, go into the shade. It's sensible. They're not deliberately tanning themselves. They're just being careful," says Dadzie, who was the lead author on the critical letter to the academy journal. Since all things western—and especially American—are so admired back in Africa, she worries that the American Academy of Dermatology message might influence black Africans. Her advice to people of all colors is simple: "Get to know your skin type."

JESSICA SEIGEL is an award-winning journalist, New York University adjunct journalism professor, and former *Chicago Tribune* national correspondent. Her work has appeared in *The New York Times, National Public Radio, Salon*, and other publications.

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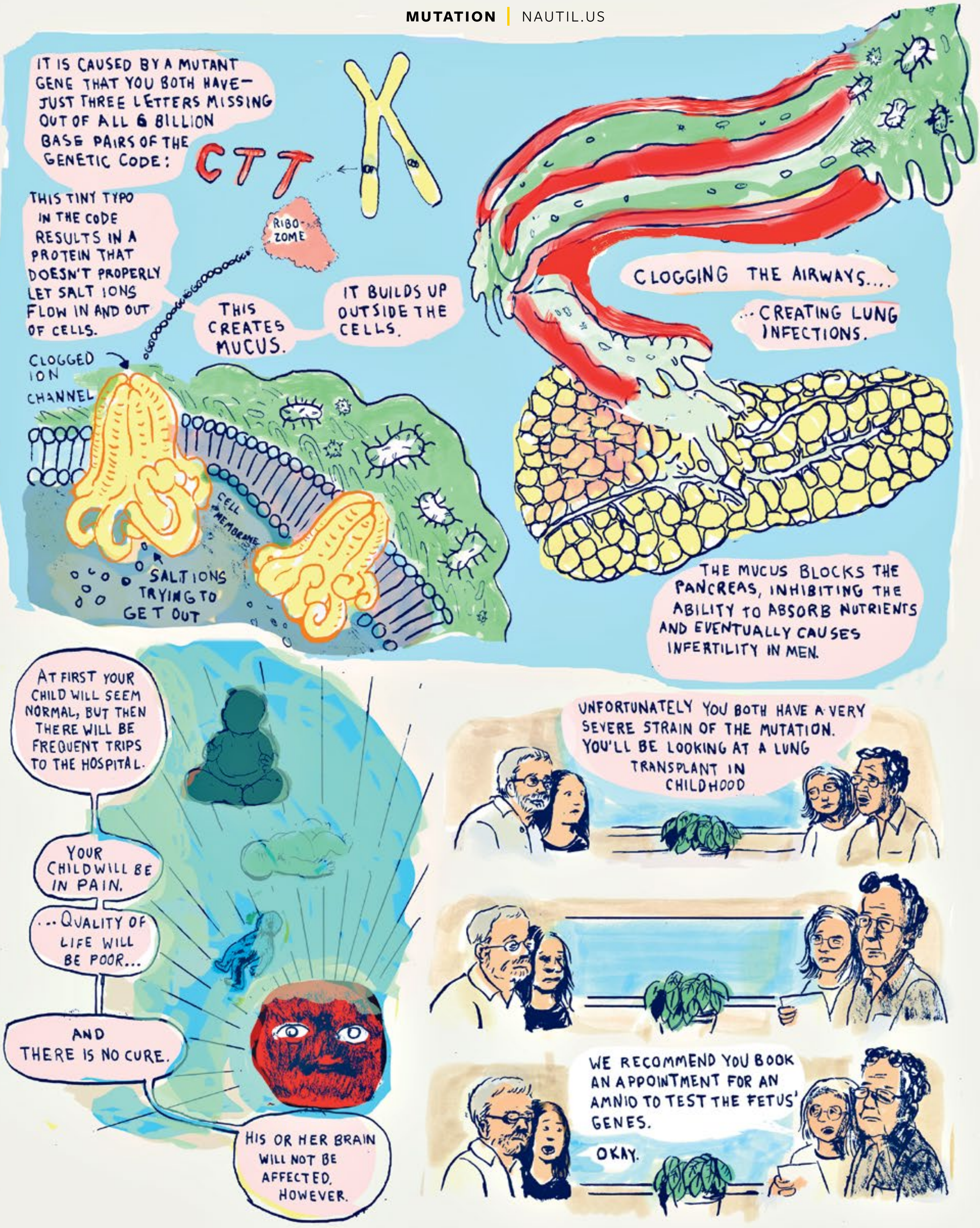
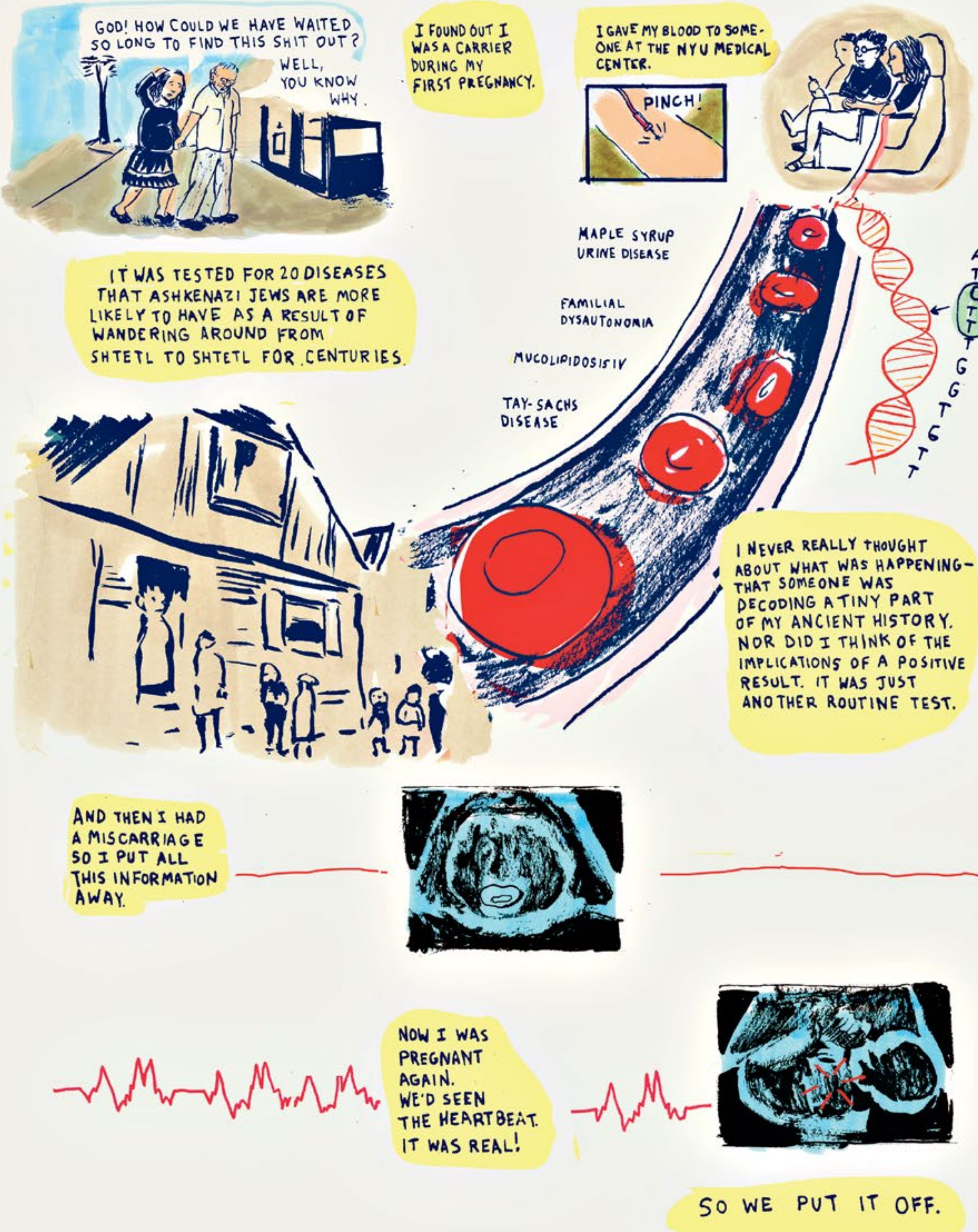
"CAN YOU DIE FROM A BROKEN HEART?"
BY KATHERINE STREETER

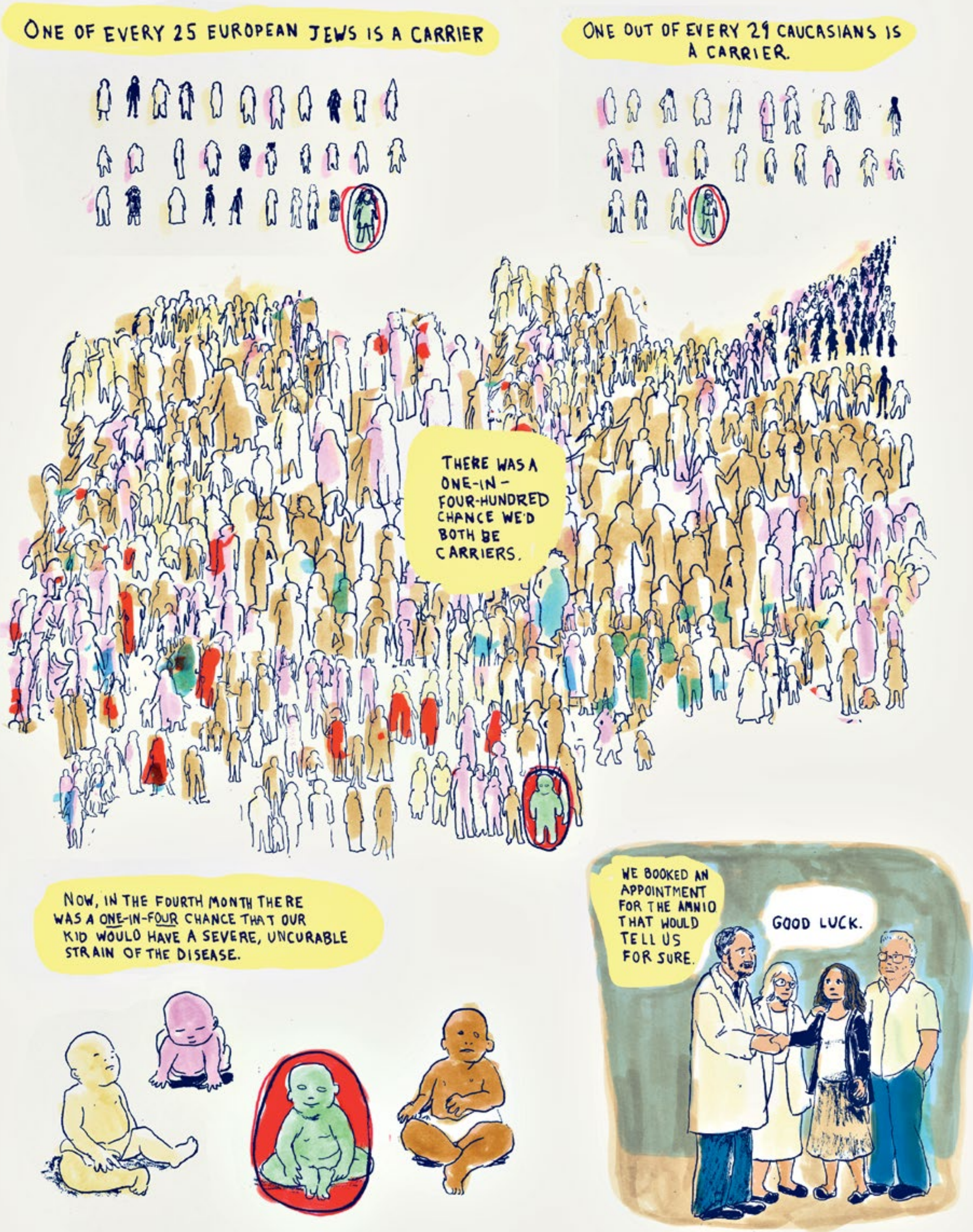
Carriers

My husband and I both carried the gene for cystic fibrosis—and I was pregnant

BY LAUREN R. WEINSTEIN


IT IS CAUSED BY A MUTANT GENE THAT YOU BOTH HAVE— JUST THREE LETTERS MISSING OUT OF ALL 6 BILLION BASE PAIRS OF THE GENETIC CODE:
CTT
THIS TINY TYPO IN THE CODE RESULTS IN A PROTEIN THAT DOESN'T PROPERLY LET SALT IONS FLOW IN AND OUT OF CELLS.
RIBO-ZOME
THIS CREATES MUCUS.
IT BUILDS UP OUTSIDE THE CELLS.
CLOGGED ION CHANNEL
CELL MEMBRANE
SALT IONS TRYING TO GET OUT
CLOGGING THE AIRWAYS....
...CREATING LUNG INFECTIONS.
THE MUCUS BLOCKS THE PANCREAS, INHIBITING THE ABILITY TO ABSORB NUTRIENTS AND EVENTUALLY CAUSES INFERTILITY IN MEN.
AT FIRST YOUR CHILD WILL SEEM NORMAL, BUT THEN THERE WILL BE FREQUENT TRIPS TO THE HOSPITAL.
YOUR CHILD WILL BE IN PAIN.
...QUALITY OF LIFE WILL BE POOR...
AND THERE IS NO CURE.
HIS OR HER BRAIN WILL NOT BE AFFECTED, HOWEVER.
UNFORTUNATELY YOU BOTH HAVE A VERY SEVERE STRAIN OF THE MUTATION. YOU'LL BE LOOKING AT A LUNG TRANSPLANT IN CHILDHOOD
WE RECOMMEND YOU BOOK AN APPOINTMENT FOR AN AMNIO TO TEST THE FETUS' GENES.
OKAY.


GOD! HOW COULD WE HAVE WAITED SO LONG TO FIND THIS SHIT OUT?
WELL, YOU KNOW WHY.
I FOUND OUT I WAS A CARRIER DURING MY FIRST PREGNANCY.
I GAVE MY BLOOD TO SOMEONE AT THE NYU MEDICAL CENTER.
PINCH!
IT WAS TESTED FOR 20 DISEASES THAT ASHKENAZI JEWS ARE MORE LIKELY TO HAVE AS A RESULT OF WANDERING AROUND FROM SHTETL TO SHTETL FOR CENTURIES.
MAPLE SYRUP URINE DISEASE
FAMILIAL DYSAUTONOMIA
MUCOLIPIDOSIS IV
TAY-SACHS DISEASE
A T C T T T G G T G T T
I NEVER REALLY THOUGHT ABOUT WHAT WAS HAPPENING— THAT SOMEONE WAS DECODING A TINY PART OF MY ANCIENT HISTORY. NOR DID I THINK OF THE IMPLICATIONS OF A POSITIVE RESULT. IT WAS JUST ANOTHER ROUTINE TEST.
AND THEN I HAD A MISCARRIAGE SO I PUT ALL THIS INFORMATION AWAY.
NOW I WAS PREGNANT AGAIN. WE'D SEEN THE HEARTBEAT. IT WAS REAL!
SO WE PUT IT OFF.


ONE OF EVERY 25 EUROPEAN JEWS IS A CARRIER
ONE OUT OF EVERY 29 CAUCASIANS IS A CARRIER.
THERE WAS A ONE-IN-FOUR-HUNDRED CHANCE WE'D BOTH BE CARRIERS.
NOW, IN THE FOURTH MONTH THERE WAS A ONE-IN-FOUR CHANCE THAT OUR KID WOULD HAVE A SEVERE, UNCURABLE STRAIN OF THE DISEASE.
WE BOOKED AN APPOINTMENT FOR THE AMNIO THAT WOULD TELL US FOR SURE.
GOOD LUCK.


MY HUSBAND AND I HAVE AN AMNIOCENTESIS TO FIGURE OUT IF OUR CHILD-TO-BE WILL HAVE CYSTIC FIBROSIS.
THE NEEDLE GOES IN. IT FEELS LIKE NOTHING.
I TRY NOT TO LISTEN.
TWO ARMS.
TWO LEGS.
ONE, TWO, THREE, FOUR, FIVE FINGERS ON LEFT HAND. ONE, TWO, THREE, FOUR... FIVE...
NO, NOT YET.
I DO NOT FOCUS ON THE SCREEN ABOVE ME.
I TRY TO FOCUS ON TIM'S HAND AND THAT LINE THAT EXTENDS DOWN TO MY BELLY.
MY PULSE AND HIS PULSE AND THE LINE THAT GOES BACK BACK INTO HISTORY WHERE SOMEWHERE, OUR ANCESTORS GOT THIS GENE MUTATION.
WHY IS THE CF MUTATION SO COMMON?
3.5% OF ALL CAUCASIANS ARE CARRIERS.


YOU'D THINK THAT HUMANITY WOULD HAVE NATURALLY SELECTED IT OUT OF THE GENE POOL, AS MOST PEOPLE WITH CYSTIC FIBROSIS DIE BEFORE THEY CAN HAVE KIDS.
COULD THERE HAVE BEEN SOME SELECTIVE ADVANTAGE FOR BEING A CARRIER?
THE CF GENE, F-508, HAS BEEN TRACED BACK 52,000 YEARS AGO TO THE PALEOLITHIC ERA, WHEN TIM'S AND MY FOREBEARERS WERE SPREADING ACROSS THE PLANET.
BECAUSE CARRIERS HAVE ONLY ONE CF ALLELE, THEY RETAIN SALTS AND FLUIDS IN SOME OF THEIR CELLS. SO, IT'S HARDER FOR THEM TO BECOME DEHYDRATED.
WHICH COULD HAVE GIVEN THEM RESISTANCE TO A SLEW OF GASTROINTESTINAL INFECTIONS.
THEY MAY HAVE BEEN MORE RESISTANT TO CHOLERA, TYPHOID, TUBERCULOSIS AND EVEN LACTOSE INTOLERANCE.
COULD THE THING THAT MADE OUR ANCESTORS NOT DIE IN THEIR OWN FILTH EVENTUALLY HAVE BROUGHT US TOGETHER?
HOW ROMANTIC!
NOTHING HAS BEEN PROVEN. I JUST WANT SOME SILVER LINING.
WE'LL LET YOU KNOW THE RESULTS IN THREE WEEKS.

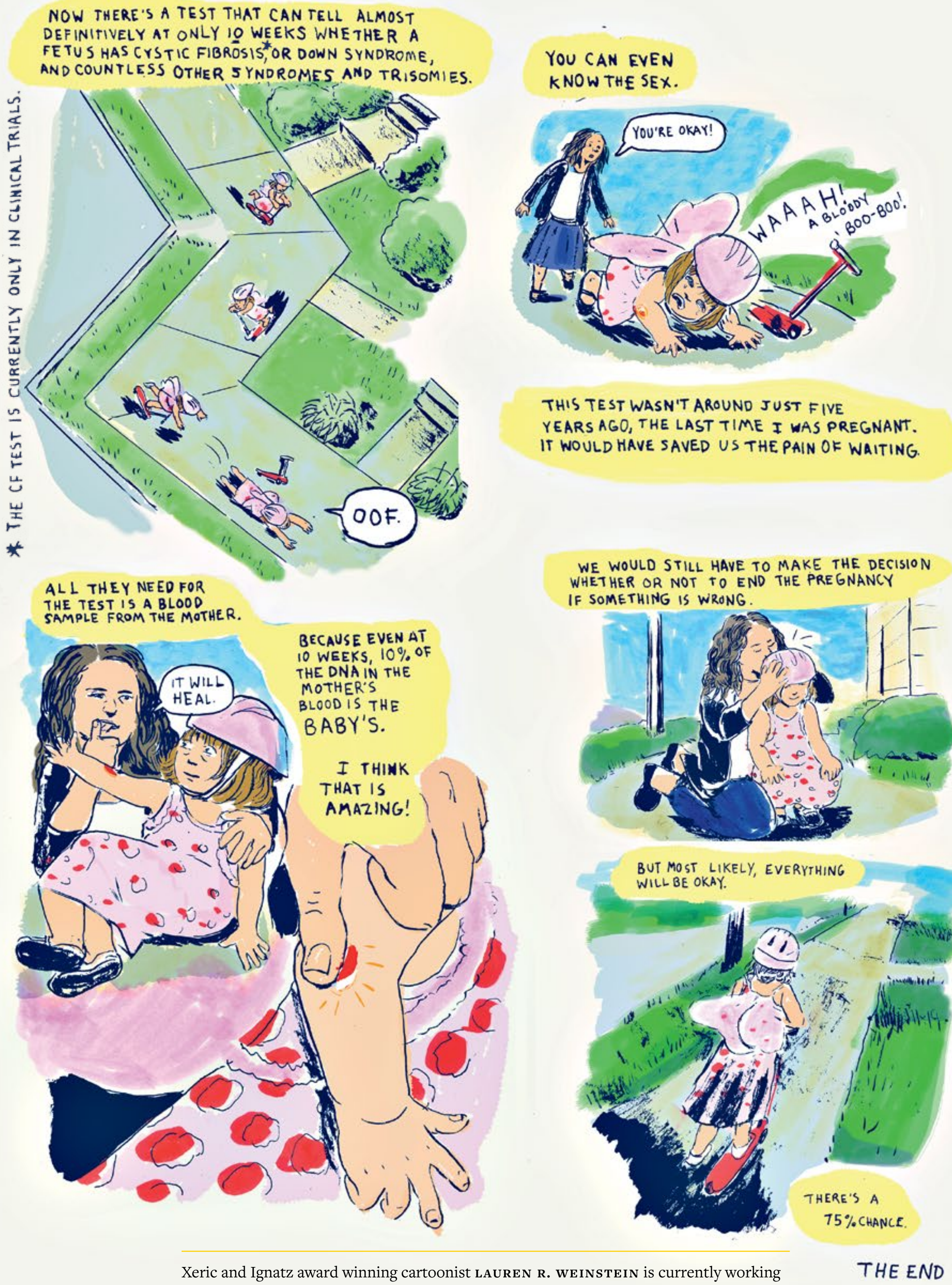

WE WAITED FOR THE TEST RESULTS TO SEE IF OUR FETUS HAD THE TWO GENES THAT MEANT IT WOULD DEVELOP CYSTIC FIBROSIS. THE THING I HATED MOST ABOUT WAITING WAS THAT THERE WAS NOTHING I COULD DO EXCEPT NOT STRESS.
75% GOOD
25% BAD
I'M A DO-ER, BUT I'M ALSO A WALLOWER.
YOU KNOW, IF THE TEST IS POSITIVE, WE DON'T HAVE TO "TERMINATE".
YEAH... OF COURSE.
BUT IF WE BROUGHT THIS CHILD IN TO THE WORLD WE'RE BASICALLY GUARANTEEING IT A LIFE OF PAIN.
YEAH. AND THE KID WOULD BE TOTALLY AWARE OF IT.
HOW DO YOU MAKE THE DECISION TO DENY SOMEONE A LIFE?
75% IS STILL REALLY GOOD ODDS. I'D PLAY THOSE ODDS ANYWHERE.
BUT KNOWING WHAT WE DO, HOW COULD "TERMINATION" NOT BE THE MOST HUMANE CHOICE?
MAYBE MY BODY THREW OUT THE BAD VERSION DURING THE MISCARRIAGE AND IS KEEPING THIS ONE BECAUSE IT'S GOOD?
FOR THE FIRST TIME IN MY LIFE THE MOST RATIONAL THING TO DO WAS TO HOPE.
I HOPE
I HOPE
I HOPE


AND THEN TWO WEEKS BEFORE WE WERE SUPPOSED TO GET THE RESULTS, I WAS LUCKY ENOUGH TO GO TO SWEDEN FOR A COMICS CONVENTION
EVERY MORNING MY ROOMMATES AND I WOULD EAT AT THIS PASTRY SHOP.
KONDITORI
EVERYONE COULD SEE I WAS PREGNANT, BUT I DIDN'T TELL ANYONE ABOUT THE TEST.
WE WALKED ALL OVER STOCKHOLM.
I DIDN'T BUY THE SCANDINAVIAN-DESIGNED, GENDER NEUTRAL BABY TOY.
I DID BECOME PARTIAL TO THIS STATUE OF ST. GEORGE SLAYING THE DRAGON.
AND ME AND "IT" WOULD HAVE CONVERSATIONS...
YOU CAN'T KNOW RIGHT NOW SO WHY NOT JUST ENJOY OUR TIME TOGETHER
OKAY.


FOR THREE WEEKS WE WAITED FOR THE RESULTS OF THE TEST THAT WOULD SAY FOR SURE WHETHER OUR BABY WOULD HAVE CYSTIC FIBROSIS.
I'M IN CREST HARDWARE LOOKING AT BUG SPRAY.
BUZZ BUZZ
HELLO?
IT'S REGINA, YOUR GENETIC COUNSELOR...
HI.
I HAVE GOOD NEWS.
YES!?
YOUR BABY DOES NOT HAVE CYSTIC FIBROSIS!
YES!!
HE OR SHE IS NOT EVEN A CARRIER!
WOULD YOU LIKE TO KNOW THE SEX OF THE CHILD?
YES!!!


SHE'S A GIRL!
A GIRL!
AND ALSO SHE DOESN'T HAVE TRISOMIES 21, 18 OR 13, OR FRAGILE X.
I DIDN'T KNOW I SHOULD HAVE BEEN WORRIED ABOUT THOSE!
A GIRL...
I'M SO GLAD I COULD GIVE YOU THIS HAPPY NEWS! I HAVEN'T GOTTEN THE BEST RESULTS IN THE LAST COUPLE OF WEEKS.
I'M SO SORRY.
THANKS SO MUCH.
CLICK!
I NEVER SPOKE TO HER AGAIN.
IT WAS AS IF THE WHOLE THING HADN'T HAPPENED.
BECAUSE REALLY, NOTHING HAD CHANGED PHYSICALLY INSIDE ME.
MY DAUGHTER HAD ALWAYS BEEN FINE.
HA! HA! HA!
THE HYPOTHETICALS WERE THE PROBLEM, AND THE PROBLEM SOLVED ITSELF.
XX xX xX XX
CAN YOU BELIEVE IT? MY BABY IS GOING TO BE HEALTHY AND ISN'T GOING TO BE BORN WITH A FATAL DISEASE AND SHE'S A GIRL!
THAT'S NICE SWEETIE, CONGRATS! THAT'LL BE $7.29.
WAS ALL THIS STRESS OVER NOTHING?


FIVE YEARS AFTER THE CYSTIC FIBROSIS TEST, MY DAUGHTER AND I ARE WALKING TO THE PARK. (WE MOVED OUT TO THE 'BURBS.)
STOP AT THE CORNER!
OKAY MOMMEE!
UP AHEAD A MILLION THINGS COULD GO WRONG.
HOLD HANDS WHILE WE CROSS THE STREET!
KEEP YOUR EYES OPEN FOR CARS!
I'M OKAY MOMMEE!
CAR
RUSTY NAIL
BROKEN GLASS
POISON IVY
DEER TICK
POTENTIAL KIDNAPPER
DIRTY SYRINGE?
BUT MOST LIKELY EVERYTHING WILL BE FINE.
WE'RE THINKING OF HAVING ANOTHER BABY.
MY COUSIN TOLD ME ABOUT HER FRIENDS— A COUPLE WHO WERE BOTH CARRIERS. FOR THEIR FIRST TWO KIDS, THEY AGONIZED WHILE WAITING FOR THE RESULTS. FOR THEIR LAST CHILD, THEY DIDN'T EVEN TAKE THE TEST.
THEIR LAST CHILD WAS PERFECTLY HEALTHY.
WHY WORRY?
BUT I COULD NEVER LET GO LIKE THAT.
WATCH OUT!



Xeric and Ignatz award winning cartoonist LAUREN R. WEINSTEIN is currently working on a graphic novel tentatively entitled *How to Draw a Nose* to be published by Henry Holt. You can see her work at Laurenweinstein.com.

How the Mormons Conquered America

The success of the Mormon religion is a study in social adaptation

BY MICHAEL FITZGERALD

AT THE END OF the smash Broadway musical, *The Book of Mormon*, the protagonist, Elder Price, a zealous young Mormon missionary in Uganda, triumphantly sings, "We are still Latter-day Saints, all of us / Even if we change some things, or we break the rules."

The ribald musical, written by *South Park* creators Trey Parker and Matt Stone, mocks the Mormon religion and its visionary founder Joseph Smith. At one point Smith has sex with a frog to rid himself of AIDS. The musical gleefully incorporates how the real church will react to it, having an outraged Mormon leader, Mission President, declare, "You have all brought ridicule down onto the Latter Day Saints!"

If the real Mormons feel like Mission President, they aren't showing it. Instead the church has consistently bought ad space in cities where the musical has appeared to promote the Church of Jesus Christ of Latter-day Saints and the real Book of Mormon, its sacred foundation. The ads have appeared on a Times Square billboard, around London, and in *The Book of Mormon* playbills for touring companies, featuring the taglines, "You've seen the play... now read the book," and "The book is always better."

Clearly the Church of Jesus Christ of Latter-day Saints can take a joke—especially if it gets people talking about the faith. That the Mormon church appears to be good-natured about a scatological musical might surprise those who associate the church with the squeaky clean image of the Osmond family and Mitt Romney.

The truth is that the Mormon church has always changed with the times. Religions have to mutate "if they're going to survive," says J. Gordon Melton, a religious scholar who founded the Institute for the Study of American Religion. They survive by setting what the anthropologist Roy Rappaport has called "ultimate sacred postulates," ultimate truths, and then re-interpreting them over time. Scholars say the Church of Jesus Christ of Latter-day Saints provides a casebook

ILLUSTRATION BY CHLOÉ POIZAT

study of how a religion has thrived by folding its postulates into a social institution that adapts to changing environments.

The analogy, they say, can be stretched to science. Religions don't have literal DNA, of course, but they can parallel how species mutate. There are key properties of successful genetic mutations that religions must have to succeed, says Lucas Mix, a researcher at the Haig Lab at Harvard University, who is both an evolutionary biologist and an Episcopalian priest. The properties are inheritance, variation, and selection.

For religions, inheritance means the ability to transmit beliefs, behaviors, and a sense of belonging to new generations. Variation means having the ability to allow for innovations to take place, and selection means having a way to absorb converts and deal with bad mutations—in religion's case apostates or heretics. Because Mormonism emerged so recently, says Jan Shipps, a historian of Mormonism, we can see its changes and how they helped guarantee the church's survival and growth—in fact, its phenomenal growth. Sociologist Rodney Stark, co-director of Baylor University's Institute for Studies of Religion, has projected that 265 million Mormons will populate the world by 2080.

LATTER-DAY SATIRE Neil Patrick Harris performs with the cast of *The Book of Mormon* at the 2012 Tony Awards. The Mormon church was hardly offended by the scatological musical: It bought ad space in cities where the musical appeared to promote the real Book of Mormon.

ANDREW H. WALKER / STAFF

THE MORMON STORY IS quintessentially American. "It has all the features we associate with being American: patriotism, country, entrepreneurship, capitalism—all bound together," says Wade Clark Roof, professor of religious studies at the University of California, Santa Barbara.

Mormon founder Joseph Smith was born in Sharon, Vermont, in 1805. The Louisiana Purchase was barely two years old. The westernmost of the 18 U.S. states were Tennessee, Kentucky, and Ohio. Florida, what would become Texas, California, and Utah, were all Spanish possessions. The United States had thrown off its connection to English and European history. The nation whose population would triple during Smith's 39 years was pushing west into new territories. Smith's family would itself move to Palmyra in western New York by 1817, seeking economic opportunity as the Erie Canal was being built.

The Smiths moved into the heart of the Second Great Awakening, a period of intense evangelization that ran from about 1790 until the end of the 1830s. Western New York was dubbed the Burned-Over District because so many people, the saying goes, were burned by the fires of revivalism. It was here, in 1827, that Smith claimed to have been led by the angel Moroni (son of the prophet Mormon) to gold plates written in "Reformed Egyptian." He spent the next three years "translating" the plates through a series of visions, dictating what he was told to various scribes.

The Book of Mormon did not replace what Christians call the Old and New Testaments, but became "another testament of Jesus Christ," written as "a record of God's dealings with the ancient inhabitants of the Americas and contains, as does the Bible, the fullness of the everlasting gospel." Perhaps most pivotally, at least in connecting the new religion to the new nation, the Book of Mormon claimed that Jesus, shortly after his resurrection, descended from heaven into America to heal the sick, bless children, and teach disciples how to spread his gospel.

The Book of Mormon was published in 1830, and from six initial converts, Mormonism grew quickly, thanks in no small part to Smith's charisma, touting the Book of Mormon like a talisman. Soon he had to build a more formal structure for his religion, and his vision of a new heavenly society on Earth. He called the faithful to a central location, a trait of Smith's Mormonism that probably helped it in the beginning, notes Matthew Bowman in his 2012 book, *The Mormon People*. Smith sent out evangelists, including to England and Scandinavia, but encouraged converts to come to where he was, and settle a community that could be separate from those who disagreed with their radical new ideas.

Being able to change without having practitioners feel like they have changed is a powerful adaptive tool for religions.

It was not free from strife. Smith had to flee his base in Kirtland, Ohio, due to the crash of a bank he founded. He then headed to Missouri, where a successful Mormon outpost had been established. The Mormons' rapid growth upset the settlers there, and armed conflict broke out. Smith was jailed along with some other Mormon leaders, but released after the Mormon community had gone across the Mississippi River into southern Illinois. They established Nauvoo, which grew to 12,000 residents by 1844, becoming the largest settlement in Illinois—more than twice the size of Chicago. Troubles came there, as well, in part because it became public knowledge that Smith was practicing polygamy. Smith attempted to destroy a local newspaper that exposed the polygamy, caused a public riot, and was jailed. A mob stormed the jail and killed him and one of his brothers.

The death of the prophet shocked Mormonism. But it survived because Smith had put in place mechanisms to accept and reject innovations—mechanisms that allowed it to both adapt and wall off competition. Smith established multiple councils, like the First Presidency, the Quorum of Twelve, and the Seventy, to judge new ideas, and he himself was subject to the councils. This helped Smith, and Mormonism, to contain the excitement of other newly converted Mormons, who were prone to charismatic visions of their own. It also meant there was established leadership in place to guide the church after Smith was killed; though some groups of Mormons split off, most remained supporters of Brigham Young, the leader of the Quorum of Twelve eventually elected as Smith's successor. This leadership structure remains in place today.

Religions don't have literal DNA, but they can parallel how species mutate.

The church's prime mutation was the Book of Mormon itself. "A lot of religions tend to last as long as the prophet, and when the prophet dies, the religion itself begins to die out," says Shipps. "The important thing about Mormonism is that it has the Book of Mormon."

The stories within the Book of Mormon offered a new revelation about Christianity, one adapted specifically to America. Those who accepted the message could believe they were helping to restore the real church of Jesus Christ—a seductive message. Mormonism is built on "a narrative structure rather than a philosophical belief system," explains Kathleen Flake, professor of Mormon Studies at the University of Virginia. "That allows people to find meaning in it through narratives." It allows them to see God's impact on their own lives.

Flake explains the church has simplified its message as the church has spread, a subtle adaptation most Mormons may not notice. Sunday school lessons involve simply giving scriptures to read and having people discuss them in their local context, without theological takeaways. Borrowing from existing successes, the centralized structure for controlling doctrine resembles that of the Catholic Church. Mormon men are even designated priests, but don't take vows of celibacy or spend years in theological training. The Latter-day Saints do not have a seminary. At the local level, everyone is a volunteer, and every person has a role to play.

As the 19th century rolled on, the Mormons adapted their doctrines to ensure their survival multiple times after Brigham Young led them west into what was then

AMERICAN RELIGION Joseph Smith claimed to have received "golden plates" from the angel Moroni in western New York. Smith translated the sacred texts into the Book of Mormon, a key passage of which has Jesus, after his resurrection, visiting America to teach disciples how to spread his gospel.

WIKIPEDIA

Mexico. He went seeking a place to create a new Israel, a heavenly kingdom on Earth, with its own laws, an idea that attracted Mormon converts looking to be part of something important. But Utah was not very hospitable, and Young would seek federal money for his struggling flock, creating ongoing tensions between the Mormons and the American government, especially after the Mexican-American War ceded territory including Utah to the U.S.

The Mormons lived communally, until the railroad and non-Mormon settlers forced them out of isolation. While a minority of Mormons practiced polygamy, the leadership fought to keep it, arguing it was protected as freedom of religion, until the U.S. Supreme Court ruled against the practice. While the church was under public fire, it steeled itself with capitalist enterprises. Young set up department stores and a co-op mercantile institution. "A mercantile church and a missionary church move in the same holy direction, and the vector that points both forward is the energy of enterprise," wrote Adam Gopnik in a 2012 *New Yorker* essay on Mormonism, as Romney ran for the White House. "It was a victory of Gilded Age capitalism… over Great Awakening spiritualism." And one that would stretch into the 20th century. Some of the major companies started or run by Mormons include Marriott, the hotel chain, JetBlue and Skywest airlines, Bonneville Distribution, and Beneficial Life Insurance.

IT'S A HALLMARK OF RELIGIONS to claim they haven't changed significantly in their core beliefs. Yet being able to change without having practitioners feel like they have changed is a powerful adaptive tool for religions, says Richard Sosis, an evolutionary anthropologist at the University of Connecticut, and co-editor of the journal, *Religion, Brain & Behavior*. "Religion's sleight of hand is fascinating, how effective religions are at masking the change that takes place," he says. Scholars "often recognize these changes as a consequence of economics and politics and all the different sociopolitical factors we would anticipate religion adapting to. But within the religion, you don't experience them."

Religions stress continuity to avoid appearing expedient, Sosis says, and to preserve their connection to the sacred, to the things that made them important in the first place. They want to stay connected to the sacred aspects that infused their founding and development. Rituals tend to endure, while behaviors adapt to social norms; a choir may be accompanied by a five-piece band instead of an organ, playing a modern hymn, but it's still a hymn.

Mormonism, then, has adapted in part by adopting a structure that allows for local flexibility and requires local involvement. This allows the religion to mesh with many different cultures. It has a prophet who declared new core truths to an existing religion and published the basis for those. It has always encouraged missionaries to go out and spread word of its beliefs, drawing in new people.

The Mormons "are notoriously one of the most assertively proselytizing churches," Flake says. "Mormons fly whatever flag gives them the freedom they need to root that religion in their culture. They root it by observing the culture laws of that country."

But the Mormon structure, like those of many religions, looks backward, not forward. It is not a structure that allows for quick responses to social currents. As Flake notes, two of the three major social movements in America, and much of the world in the last 100 years, include equal status for women and gays and lesbians. The Mormons are among many religions that do not give full equality to groups of people.

Such stances make Mormonism seem regressive in the U.S., where, in a recent poll, 55 percent of Americans support gay marriage, and where women have gained full leadership roles in a number of churches, notably Protestant denominations.

Social pressure will not change the church. Outsiders and dissenting Mormons can feel anger about the church's practices, but there's little point to organizing protests. The President of the Church, in accord with the two other members of the office of the First Presidency and the 12-man Quorum of the Twelve Apostles, changes doctrine. Flake says this creates incredible stability and immunity from outside influences or charismatic mavericks. The Mormons "pay a price for it but they also get a benefit for it," says Flake. "The price and the benefit look remarkably alike. You constrain or stabilize the system. It also makes them a very structurally conservative institution. They have to move by agreement."

That need for concurrence makes Mormonism a religion that is not typically subject to disruptive innovations, to borrow a term from Clayton M. Christensen, a professor at Harvard Business School, an expert on innovation, and a Mormon. In an interview, Christensen, 62, says the church is different than the church of his youth—it ordains blacks and sends more women on missions. It's because "we remain open to questions," he says, as Mormon Tabernacle Choir music plays in his office. He argues that other religions prefer to say they have all the answers. Practitioners of other faiths might dispute this, but new prophecies tend to be viewed with skepticism. Mormonism considers itself a faith of continuous revelation, where God may give new prophecies to the church's leadership. That gives it a mechanism for doctrinal change, such as abandoning polygamy or opening the priesthood to non-whites.

Christensen tells a story from the Book of Mormon about the brother of Jared, an ancient prophet, who talked to God in the clouds. God instructed the brother of Jared to build a boat, and when he did, the brother asked God to imbue a host of white stones with light so the brother could place them in the dark hull of the boat to see. God agreed and the brother was "blown out of his socks with fear," says Christensen, when he saw the actual finger of God, who later appeared to him as a man. The story, Christensen says, shows that while God doesn't change, what people on earth can know about God can.

Christensen says this process is similar to what the church is going through on some social issues. "Our understanding of God, and our relation to him, and questions like same-sex attraction and marriage, we're somewhere between here and there." Christensen says he realizes that same-sex attraction and marriage can be seen as a disorder and a sin. (The church states "sexual relations are proper only between a man and a woman who are legally and lawfully wedded as husband and wife.") But even if his position were that church leaders were wrong, Christensen says, "I can't announce to mankind that I'm right and the church is wrong. The best I can do is to say, 'well, just like the brother of Jared, where the truth is on the other side of this boulder, I'm on this side, I'm learning and I can say to myself and to my friends, I think I'm farther along than the church is on this one.'"

The church may catch up to society in its own time. Shipps notes in her 1985 book *Mormonism* that 1980s Mormons put back into 1880s Utah would not have recognized much about their faith, and the same may well hold true 100 years from now. As Mormonism continues to grow more rapidly outside the U.S. than in it, the religion will inevitably change. Already, its Quorums of the Seventy (there are eight quorums in total) include numerous people born outside of the U.S., especially Latin Americans.

On a recent Sunday morning in Providence, Rhode Island, a new face of Mormonism, in tune with a changing America, is on display, underscoring the church's perpetual ability to mutate and adapt. Music throbs happily as women in colorful dresses and men in suits and ties filter into a Mormon church in a well-kept red brick former school building.

"*Buenos dias*!" says a man in a light-colored suit, his once black hair gone mostly gray. Behind him hangs a painting. Two robed gray-haired men, blatantly gringo, stand over a white boy who cowers on the ground before them. That boy is Joseph Smith. Smith did not speak Spanish. But his 1820 vision of God and Jesus telling him not to join any local church because religion had lost its way appears to mean as much to the members of this Spanish-speaking Mormon congregation as it did to him.

After Communion is served, Rich Hutchins, a Pfizer senior director, and volunteer Mormon stake president, stands at the church's lectern. He's tall, wearing an Organization Man gray suit and white shirt, his brown hair trim, his face clean-shaven, his back straight. He gives the sermon in fluent Spanish. His sermon is about splitting the congregation, sending those who live around Central Falls, a suburb north of Providence that is nearly half Latino, to worship in a different church.

"This is how to hasten the work of salvation in our stake," he says. "It will enable more to attend church and worship." As a young girl in a back row weeps, Hutchins exhorts the congregation to think of those they know who have stopped coming because it is difficult to get to this Providence church. "Invite back those who have gone away!" he tells them. "The Lord has given us an opportunity to save their lives."

MICHAEL FITZGERALD is a writer in Cambridge, Massachusetts, whose work has appeared in *The Economist, Fast Company,* and *The New York Times.*

If the World Began Again, Would Life as We Know It Exist?

Experiments in evolution are exploring what would happen if we rewound the tape of life

BY ZACH ZORICH

IN LESS THAN FIVE milliseconds, a *Hydromantes* salamander can launch its tongue—including the muscles, cartilage, and part of its skeleton—out of its mouth to snag a hapless insect mid-flight. Among amphibians, it is the quick draw champ. Frogs and chameleons are comparative slowpokes when it comes to their ballistic anatomies. "I've spent maybe 50 years studying the evolution of tongues in salamanders," says David Wake, an evolutionary biologist at the University of California, Berkeley. He says, "this is a particularly interesting case because salamanders, who don't do anything fast, have the fastest vertebrate movement I'm aware of."

Within their lineage, evolution found a better way to accomplish tongue-hunting. Their seemingly unique adaptation appears to have evolved independently in three other unrelated salamander species. It is a case of convergent evolution—where different species separately developed similar biological adaptations when faced with the same environmental pressures. Salamanders are Wake's go-to example when asked a decades-old question in evolutionary biology: If you could replay the "tape of life," would evolution repeat itself? In the salamanders, it appears it has: In other organisms, it may not have.

This question was famously posed by the late evolutionary biologist Stephen Jay Gould in his 1989 book, *Wonderful Life: The Burgess Shale and the Nature of History*, which was published at a time when people still listened to music recorded on cassette tapes.[1] The book discussed fossils left behind by myriad strange animals that inhabited the Earth's oceans about 520 million years ago during the Cambrian period, and were preserved in the Burgess Shale. Nearly all animals alive today can trace their lineages back to the creatures that lived in the Cambrian, but not every animal that lived in the Cambrian period has descendants that live today. Many Cambrian species have since died out because they weren't fit enough to compete, or because they were in the wrong place at the wrong time during volcanic eruptions, asteroid impacts, or other extinction events.

ILLUSTRATION BY DANIEL ZENDER

Gould saw the incredible diversity of the Burgess animals and theorized that life today would have been different had history unfurled in another way. Random mutations and chance extinctions—events Gould called "historical contingencies"—would build on each other, he suggested, driving the evolution of life down one path or another. In Gould's view, the existence of every animal, including humans, was a rare event that would have been unlikely to re-occur if the tape of life was rewound to the Cambrian period and played again. One of the paleontologists—Simon Conway Morris of Cambridge University—whose work on the Burgess fossils was heavily cited by Gould in his book, strongly disagrees with this viewpoint.

Conway Morris believes that, over time, natural selection leads organisms to evolve a limited number of adaptations to the finite number of ecological niches on Earth. This causes unrelated organisms to gradually converge on similar body designs. "Organisms have to configure themselves to the realities of the physical, chemical, and also biological world," he says. In Conway Morris's view, these constraints make it all but inevitable that if the tape of life was replayed, evolution would eventually reproduce organisms similar to what we have today. If humans' ape ancestors had not evolved big brains and the intelligence that goes with them, he believes that another branch of animals, such as dolphins or crows, might have, and filled the niche that we now occupy. Gould disagreed.

Both scholars recognized that convergence and contingency exist in evolution. Their debate instead revolved around how repeatable or unique key adaptations, like human intelligence, are. Meanwhile, other biologists have taken up the puzzle, and shown how convergence and contingency interact. Understanding the interplay of these two forces could reveal whether every living thing is the result of a several-billion-year-long chain of lucky chances, or whether we all—salamanders and humans alike—are as inevitable as death and taxes.

RATHER THAN ATTEMPT TO reconstruct history with fossils, Richard Lenski, an evolutionary biologist at Michigan State University, decided to watch

ANCIENT GRAZERS A recreation of *Aysheaia pedunculata* made from a fossil. These caterpillar-sized creatures are thought to have grazed on sea sponges.

convergence and contingency unfold in real time, in the controlled environment of his laboratory. In 1988, he separated a single population of *Escherichia coli* bacteria into 12 separate flasks containing liquid nutrients, and let them each evolve separately. Every few months for the past 26 years, he or one of his students has frozen a sample of the bacteria. This archive of frozen microbes gives Lenski the ability to replay *E. coli*'s tape of life from any point he wishes, simply by thawing out the samples. Along the way, he can examine how the bacteria change, both genetically and in ways that are visible under a microscope. Lenski says, "The whole experiment was set up to test how reproducible evolution was."

In Gould's view, the existence of animals, including humans, was a rare event that would be unlikely to re-occur if the tape of life was rewound.

In 11 of Lenski's flasks, the *E. coli* cells grew physically larger, but bacteria in one flask divided into separate lineages—one with large cells and the other with small cells. "We call them the smalls and the larges," says Lenski. "They have coexisted now for 50,000 generations." No other population in the experiment did the same; a historically contingent event seemed to have taken place. Even 26 years later, none of the other *E. coli* lineages evolved it. In this case, contingency seems to have won out over convergence.

In 2003, another contingent event took place. The number of *E. coli* in one of the flasks increased to the point where the normally translucent nutrient solution turned cloudy. At first Lenski thought that the flask had been contaminated, but it turned out that the *E. coli*, which normally just feed on glucose in the solution, had developed a way to consume a different chemical in the flasks, called citrate. After 15 years, or 31,500 generations, just one of the populations was able to consume the substance.[2] Its population size quickly expanded by a factor of five.

This "historical contingency" gave Lenski and his graduate student Zachary Blount a chance to examine the likelihood that it would happen again if they rewound the tape. Blount went to the archive of frozen *E. coli*, and selected 72 samples collected at different periods in the experiment from the population that later evolved citrate metabolism. He thawed them out, and let them grow. Eventually, four out of the 72 samples acquired the ability. What's more, the mutations only occurred in populations that had been frozen after 30,500 generations. Genetic analysis showed that several genes had undergone mutations that "potentiated" the evolution of citrate metabolism before that point. In other words, the ability to consume citrate was contingent upon other mutations that had come before it. Those formed a fork in the road, altering the path that generations after would be able to travel.

The Long-Term Evolution Experiment, as the *E. coli* project is known, has surpassed 60,000 generations now, giving Lenski a deep data set from which to draw inferences about the interplay of contingency and convergence in evolution. Subtle changes in the bacteria's DNA that make them larger and better able to proliferate in the flask have been relatively common across the groups. At the same time, Lenski has witnessed striking cases of contingency, in which one population did something completely different than the others. But as in convergence, he adds, these transformations weren't entirely random.

"Not everything is possible," no matter the process, Wake explains. "Organisms evolve within the framework of their inherited traits." They can't pass on mutations that kill them or prevent them from reproducing. In the case of *Hydromantes* salamanders, their ancestors had to overcome a serious limitation: To acquire their ballistic tongues they had to lose their lungs. That's because their tongue partly derives from muscles that their predecessors instead used to pump air into the lungs. Now, that formerly small and weak muscle is much larger and stronger. It wraps like a spring around a tapered bone at the back of the mouth, and when the muscle squeezes, the bone generates the force that fires the tongue along with its bones out of

NOBU TAMURA

the mouth. So, *Hydromantes*' ancestor did not simply acquire a mutation and evolve a fast ballistic tongue. Instead, the adaptation followed a series of mutations that first enabled the creature to overcome its reliance on lungs for oxygen and buoyancy control. Each change was contingent on the one before it.

Chameleons, on the other hand, retain their lungs. Instead of re-tooling their lung anatomy, they have evolved a piece of collagen that allows them to catapult their tongues at prey. On the surface, salamander and chameleon tongues converge, but not upon closer inspection. It takes a chameleon 20 milliseconds to shoot its tongue at its prey, a positively glacial pace when compared to the *Hydromantes*' five-millisecond firing time. Why are chameleons stuck hunting with such slow tongues? The answer is that they have encountered a kind of obstacle to convergent evolution. The chameleon's tongue is fast enough to ensure their survival, but they lack the "framework of inherited traits" to evolve the salamanders' deadlier ballistic anatomy. The chameleons have reached what biologists call an "adaptive peak."

IN EXPERIMENTS WITH VIRUSES that infect bacteria, called bacteriophages, Harvard biologist David Liu discovered adaptive peaks as well. These peaks limit the ability of organisms to converge on a single, optimal design. They help explain why contingencies aren't often repeated.

Liu wanted to know whether identical groups of bacteriophages could separately evolve a particular enzyme if he put the same pressures on them. He quickened the rate of protein evolution within the viruses, using a system he calls PACE.

During the course of the experiment, the viruses that could not make the enzyme Liu was looking for were removed from the study: Those that achieved the goal, remained. Of those, some had "better" enzymes than others.[3] (Specifically, the enzyme they made, a polymerase, recognizes a certain DNA sequence and helps turn it into RNA—some polymerases recognized that sequence very precisely and others less so.) Like the chameleons' relatively slow ballistic tongue, the adaptations gained by most of the remaining viruses evolved an adaptation that allowed them to survive, but also prevented them from gaining even better polymerases. These viruses were stuck on a lower peak, while a few had climbed to higher ones.

To understand what biologists mean by adaptive peaks, imagine a landscape in which the topography represents the highs and lows of reproductive potential. In the case of Liu's bacteriophages, different populations searched this landscape through the acquisition of various mutations. Some landed beside small mountains and a few beside Mt. Everest-like peaks. The higher they climbed up their respective mountains, the easier it was to survive. So, they ascended the slope before them. Once at the top of a small peak, viruses could not then move to a taller, more optimal, one. In order to get there, they would need to climb back down, reducing their ability to survive every step of the way. That is a serious challenge because survival of the fittest is a present concern. Which mutation occurs first—which adaptive peak an organism begins to climb—is an historical contingency that convergent evolution can have a very difficult, if not impossible, time overcoming.

The timing of mutations mattered. "Early random events that create differences in the gene pool can have profound effects in determining whether an ultimately beneficial mutation is allowed to effect the survival of an organism," Liu says. "That randomness erodes the reproducibility of evolution." In this experiment, contingency had won out over convergence. Past events prevented repeatability.

One way that life may overcome the limitations of adaptive peaks was revealed in studies of digital organisms conducted by Michigan State University computational biologists Chris Adami and Charles Ofria. The duo created a computer program called Avida in which digital organisms evolve under environmental conditions set by the experimenter. Avidians mutate by randomly gaining and losing pieces of code that may allow them to solve math problems, which increases their ability to reproduce.

In one experiment, the Avidians were set to the task of evolving the ability to solve a complex logic problem called "bitwise equals." Only four out of the 50 digital populations evolved the code necessary to complete the operation.[4] All of the successful populations were ones that initially carried a lot of mutations (random pieces of computer code) that made it harder for them

CREATURES OF THE DEEP An artist's rendering of *Opabinia*. Similar to an elephant's trunk, its long proboscis was likely used to scavenge the seafloor for food and pass it back to the creature's bizarre, backward-facing mouth.

to solve math problems and therefore reproduce. It seems counterintuitive, but Ofria found that the early, bad mutations were essential to improving the fitness of later generations, perhaps because they added to the genetic variation that later random mutations could act upon.

DOES THE RARITY OF any particular sequence of events imply that major shifts in evolution are unlikely to be repeated? The experiments suggest that's true, but Conway Morris firmly answers, no. "You'd be daft to say that there aren't accidents of one sort or another. The question is one of time scales," he says. Given enough years and enough mutating genomes, he believes that natural selection will drive life toward the inevitable adaptations that best fit the organisms' ecological niche, no matter the contingencies that occur along the way. He believes that one day, all of the *E. coli* in Lenski's experiment would evolve to consume citrate, and that all of Liu's viruses would eventually scale their adaptive Mount Everests. Further, those experiments were conducted in very simple and controlled environments that don't come close to matching the complex ecosystems that life must adapt to outside the lab. It's hard to say how real-world environmental pressures might have altered the results.

So far, the biggest shortcoming in all of the attempts to answer the "tape of life" question is that biologists can only draw conclusions based on just one biosphere—the Earth's. An encounter with extra-terrestrial life would undoubtedly tell us more. Even though alien organisms may not have DNA, they'd likely show similar patterns of evolution. They would need some material that would be passed down to their descendants, which would guide the development of organisms and change over time. As Lenski says, "What's true for *E. coli* is also true for some microbe anywhere in the universe."

Therefore, the same interactions between convergence and contingency might play out on other planets. And if extraterrestrial life faces similar evolutionary pressures as life does on Earth, future humans may discover aliens that have convergently evolved an intelligence like ours.[5] On the other hand, if contingent events build on one another, driving the development of life down unique paths as Gould suggested, extra-terrestrial life may be extraordinarily strange.

Gould believed that humans represented a "wildly improbable evolutionary event." As evidence, he pointed to the fact that human-like intelligence has only evolved once in more than 2.5 billion years of life on Earth. He saw the likelihood of another species evolving intelligence similar to our own as vanishingly rare. The idea that we may be the sole sentient species in the universe carries with it some important implications that go beyond biology. "Some find the prospect depressing," he wrote in *Wonderful Life*. "I have always regarded it as exhilarating, and a source of both freedom and consequent moral responsibility."

ZACH ZORICH is a freelance science journalist and contributing editor at *Archaeology* magazine.

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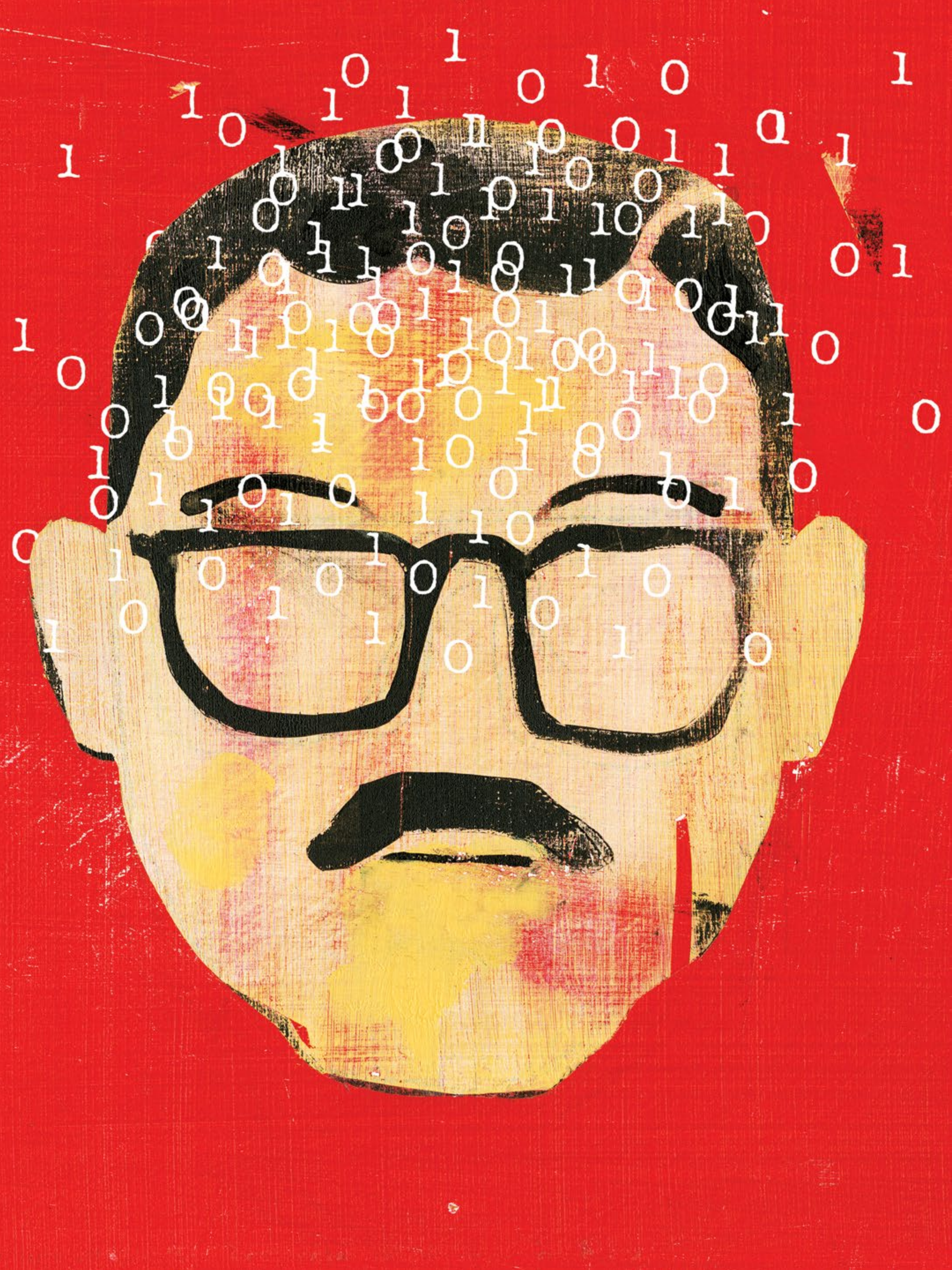
“ARE YOU RESILIENT?”
BY CHRISTINA DACANAY



Meet the Father of Digital Life

This maverick forerunner of artificial life and animation remains largely unknown

BY ROBERT HACKETT

ILLUSTRATION BY DANIEL ZENDER

IN 1953, AT THE DAWN of modern computing, Nils Aall Barricelli played God. Clutching a deck of playing cards in one hand and a stack of punched cards in the other, Barricelli hovered over one of the world's earliest and most influential computers, the IAS machine, at the Institute for Advanced Study in Princeton, New Jersey. During the day the computer was used to make weather forecasting calculations; at night it was commandeered by the Los Alamos group to calculate ballistics for nuclear weaponry. Barricelli, a maverick mathematician, part Italian and part Norwegian, had finagled time on the computer to model the origins and evolution of life.

Inside a simple red brick building at the northern corner of the Institute's wooded wilds, Barricelli ran models of evolution on a digital computer. His artificial universes, which he fed with numbers drawn from shuffled playing cards, teemed with creatures of code—morphing, mutating, melting, maintaining. He created laws that determined, independent of any foreknowledge on his part, which assemblages of binary digits lived, which died, and which adapted. As he put it in a 1961 paper, in which he speculated on the prospects and conditions for life on other planets, "The author has developed numerical organisms, with properties startlingly similar to living organisms, in the memory of a high speed computer." For these coded critters, Barricelli became a maker of worlds.

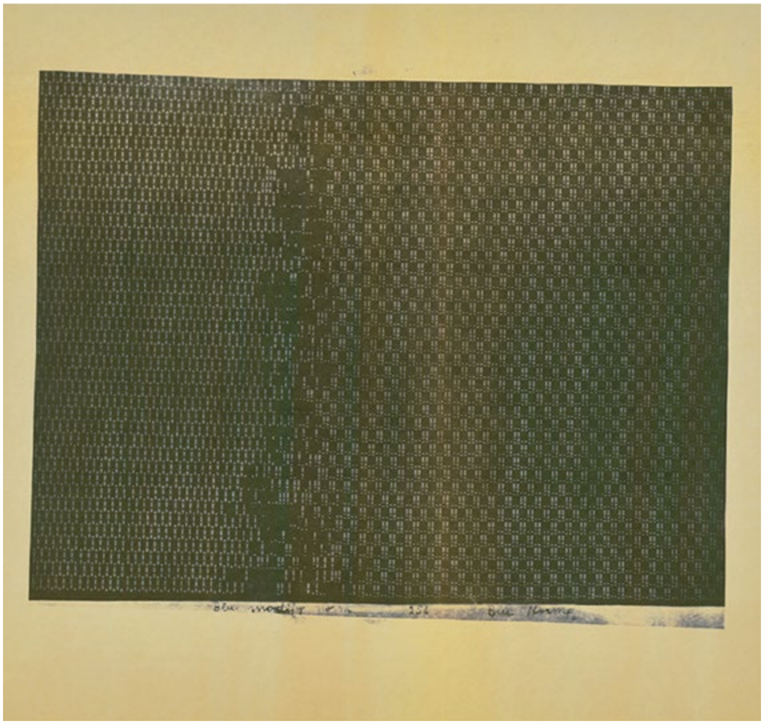
Until his death in 1993, Barricelli floated between biological and mathematical sciences, questioning doctrine, not quite fitting in. "He was a brilliant, eccentric genius," says George Dyson, the historian of technology and author of *Darwin Among The Machines* and *Turing's Cathedral*, which feature Barricelli's work. "And the thing about geniuses is that they just see things clearly that other people don't see."

Pixar cofounder Alvy Ray Smith says Barricelli influenced his earliest thinking about the possibilities for computer animation.

Barricelli programmed some of the earliest computer algorithms that resemble real-life processes: a subdivision of what we now call "artificial life," which seeks to simulate living systems—evolution, adaptation, ecology—in computers. Barricelli presented a bold challenge to the standard Darwinian model of evolution by competition by demonstrating that organisms evolved by symbiosis and cooperation.

In fact, Barricelli's projects anticipated many current avenues of research, including cellular automata, computer programs involving grids of numbers paired with local rules that can produce complicated, unpredictable behavior. His models bear striking resemblance to the one-dimensional cellular automata—life-like lattices of numerical

FROM THE SHELBY WHITE AND LEON LEVY ARCHIVES CENTER, INSTITUTE FOR ADVANCED STUDY, PRINCETON



EVOLUTION BY THE NUMBERS Barricelli converted his computer tallies of 1s and 0s into images. In this 1953 Barricelli print, explains NYU associate professor Alexander Galloway, the chaotic center represents mutation and disorganization. The more symmetrical fields toward the margins depict Barricelli's evolved numerical organisms.

patterns—championed by Stephen Wolfram, whose search tool Wolfram Alpha helps power the brain of Siri on the iPhone. Nonconformist biologist Craig Venter, in defending his creation of a cell with a synthetic genome—"the first self-replicating species we've had on the planet whose parent is a computer"—echoes Barricelli.

Barricelli's experiments had an aesthetic side, too. Uncommonly for the time, he converted the digital 1s and 0s of the computer's stored memory into pictorial images (see Evolution by the Numbers). Those images, and the ideas behind them, would influence computer animators in generations to come. Pixar cofounder Alvy Ray Smith, for instance, says Barricelli stirred his earliest thinking about the possibilities for computer animation, and beyond that, his philosophical muse. "What we're really talking about here is the notion that living things are computations," he says. "Look at how the planet works and it sure does look like a computation."

Despite Barricelli's pioneering experiments, barely anyone remembers him. "I have not heard of him to tell you the truth," says Mark Bedau, professor of humanities and philosophy at Reed College and editor of the journal *Artificial Life*. "I probably know more about the history than most in the field, and I'm not aware of him."

Barricelli was an anomaly, a mutation in the intellectual zeitgeist, an unsung hero who has mostly languished in obscurity for the past half century. "People weren't ready for him," Dyson says. That a progenitor has not received much acknowledgment is a failing not unique to science. Visionaries often arrive before their time. Barricelli charted a course for the digital revolution, and history has been catching up ever since.

BARRICELLI WAS BORN IN Rome on Jan. 24, 1912. According to Richard Goodman, a retired microbiologist who met and befriended the mathematician in the 1960s, Barricelli claimed to have invented calculus before his tenth birthday. When the young boy showed the math to his father, he learned that Newton and Leibniz had preempted him by centuries. While a student at the University of Rome, Barricelli studied mathematics and physics under Enrico Fermi, a pioneer of quantum theory and nuclear physics. A couple of years after graduating in 1936, he immigrated to Norway with his recently divorced mother and younger sister.

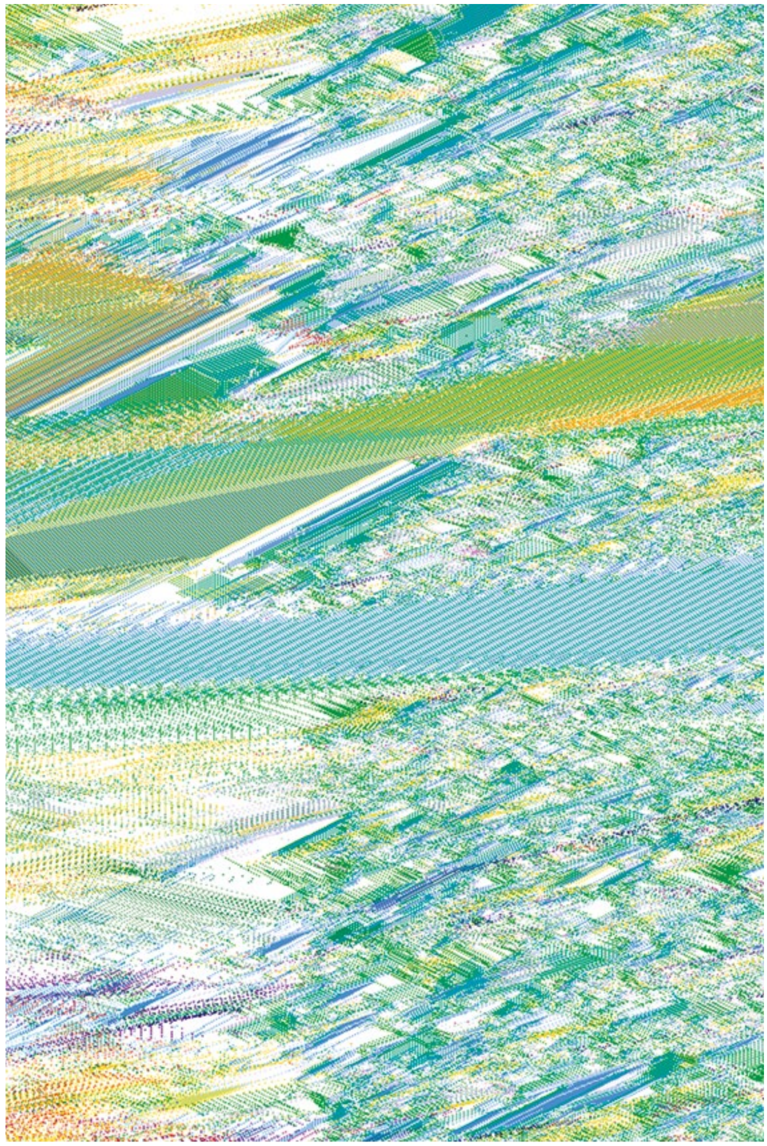
As World War II raged, Barricelli studied. An uncompromising oddball who teetered between madcap and mastermind, Barricelli had a habit of exclaiming "Absolut!" when he agreed with someone, or "Scandaloos!" when he found something disagreeable. His accent was infused with Scandinavian and Romantic pronunciations, making it occasionally challenging for colleagues to understand him. Goodman recalls that one of his colleagues happened to be reading Barricelli's papers at the University of California, Los Angeles, where Barricelli was working, "when the mathematician himself barged in and, without ceremony, began rattling off a stream of technical information about his work on phage genetics," a science that studies gene mutation, and viruses. Goodman's colleague understood only fragments of the speech, but realized it pertained to what he had been reading.

"Are you familiar with the work of Nils Barricelli?" he asked.

"Barricelli! That's me!" the mathematician cried.

Notwithstanding having submitted a 500-page dissertation on the statistical analysis of climate variation in 1946, Barricelli never completed his Ph.D. Recalling the scene in the movie *Amadeus* in which the Emperor of Austria commends Mozart's performance, save for there being "too many notes," Barricelli's thesis committee directed him to slash the paper to a tenth of the size, or else it would not accept the work. Rather than capitulate, Barricelli forfeited the degree.

Barricelli began modeling biological phenomena on paper, but his calculations were slow and limited. He applied to study in the



PSYCHEDELIC BARRICELLI In this recreation of a Barricelli experiment, NYU associate professor Alexander Galloway has added color to show gene groups more clearly. Each swatch of color signals a different organism. Borders between the color fields represent turbulence as genes bounce off and meld with others, symbolizing Barricelli's symbiogenesis.

United States as a Fulbright fellow, where he could work with the IAS machine. As he wrote on his original travel grant submission in 1951, he sought "to perform numerical experiments by means of great calculating machines," in order to clarify, through mathematics, "the first stages of evolution of a species." He also wished to mingle with great minds—"to communicate with American statisticians and evolution-theorists." By then he had published papers on statistics and genetics, and had taught Einstein's theory of relativity. In his application photo, he sports a pyramidal moustache, hair brushed to the back of his elliptic head, and hooded, downturned eyes. At the time of his application, he was a 39-year-old assistant professor at the University of Oslo.

Although the program initially rejected him due to a visa issue, in early 1953 Barricelli arrived at the Institute for Advanced Study as a visiting member. "I hope that you will be finding Mr. Baricelli [sic] an interesting person to talk with," wrote Ragnar Frisch, a colleague of Barricelli's who would later win the first Nobel Prize in Economics, in a letter to John von Neumann, a mathematician at IAS, who helped devise the institute's groundbreaking computer. "He is not very systematic always in his exposition, but he does have interesting ideas."

CENTERED ABOVE Barricelli's first computer logbook entry at the Institute for Advanced Study, in handwritten pencil script dated March 3, 1953, is the title

COURTESY ALEXANDER GALLOWAY

Barricelli saw his computer organisms as a blueprint of life—on this planet and any others.

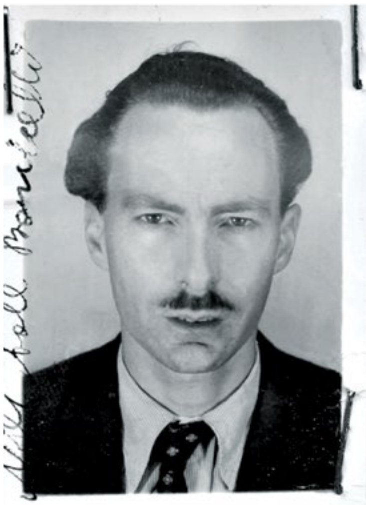
"Symbiogenesis problem." This was his theory of proto-genes, virus-like organisms that teamed up to become complex organisms: first chromosomes, then cellular organs, onward to cellular organisms and, ultimately, other species. Like parasites seeking a host, these proto-genes joined together, and through their mutual aid and dependency, originated life as we know it.

Standard neo-Darwinian doctrine maintained that natural selection was the main means by which species formed. Slight variations and mutations in genes combined with competition led to gradual evolutionary change. But Barricelli disagreed. He pictured nimbler genes acting as a collective, cooperative society working together toward becoming species. Darwin's theory, he concluded, was inadequate. "This theory does not answer our question," he wrote in 1954, "it does not say why living organisms exist."

Barricelli coded his numerical organisms on the IAS machine in order to prove his case. "It is very easy to fabricate or simply define entities with the ability to reproduce themselves, e.g., within the realm of arithmetic," he wrote.

The early computer looked sort of like a mix between a loom and an internal combustion engine. Lining the middle region were 40 Williams cathode ray tubes, which served as the machine's memory. Within each tube, a beam of electrons (the cathode ray) bombarded one end, creating a 32-by-32 grid of points, each consisting of a slight variation in electrical charge. There were five kilobytes of memory stored in the machine. Not much by today's standards, but back then it was an arsenal.

Inside the device, Barricelli programmed steadily mutable worlds, each with rows of 512 "genes," represented by integers ranging from negative to positive 18. As the computer cycled through hundreds and thousands of generations, persistent groupings of genes would emerge, which Barricelli deemed organisms. The trick was to tweak his manmade laws of nature—"norms," as he called them—which governed the universe and its entities just so. He had to maintain these ecosystems on the brink of pandemonium and stasis. Too much chaos and his beasts would unravel into



"SCANDALOOS!" Barricelli was an uncompromising oddball who teetered between madcap and mastermind. People who disagreed with him were regaled with his favorite exclamation.

a disorganized shamble; too little and they would homogenize. The sweet spot in the middle, however, sustained life-like processes.

Barricelli's balancing act was not always easygoing. His first trials were riddled with pests: primitive, often single numeric genes invaded the space and gobbled their neighbors. Typically, he was only able to witness a couple of hereditary changes, or a handful at best, before the world unwound. To create lasting evolutionary processes, he needed to handicap these pests' ability to rapidly reproduce. By the time he returned to the Institute in 1954 to begin a second round of experiments, Barricelli had made some critical changes. First, he capped the proliferation of the pests to once per generation. That constraint allowed his numerical organisms enough leeway to outpace the pests. Second, he began employing different norms to different sections of his universes. That forced his numerical organisms always to adapt.

Even in the earlier universes, Barricelli realized that mutation and natural selection alone were insufficient to account for the genesis of species. In fact, most single mutations were harmful. "The majority of the new varieties which have shown the ability to expand are a result of crossing-phenomena and not of mutations, although mutations (especially injurious mutations) have been much more frequent than hereditary changes by crossing in the experiments performed," he wrote.

When an organism became maximally fit for an environment, the slightest variation would only weaken it. In such cases, it took at least two modifications, effected by a cross-fertilization, to give the numerical organism any chance of improvement. This indicated to Barricelli that symbioses, gene crossing, and "a primitive form of sexual reproduction," were essential to the emergence of life.

"Barricelli immediately figured out that random mutation wasn't the important thing; in his first experiment he figured out that the important thing was recombination and sex," Dyson says. "He figured out right away what took other people much longer to discover" Indeed, Barricelli's theory of symbiogenesis can be seen as anticipating the work of independent-thinking biologist Lynn Margulis, who in the 1960s showed that it was not necessarily genetic mutations over generations, but symbiosis, notably of bacteria, that produced new cell lineages.

Barricelli saw his computer organisms as a blueprint of life—on this planet and any others. "The question whether one type of symbio-organism is developed in the memory of a digital computer while another type is developed in a chemical laboratory or by a natural process on some planet or satellite does not add anything fundamental to this difference," he wrote. A month after Barricelli began his experiments on the IAS machine, Crick and Watson announced the shape of DNA as a double helix. But learning about the shape of biological life didn't put a dent in Barricelli's conviction that he had captured the mechanics of life on a computer. Let Watson and Crick call DNA a double helix. Barricelli called it "molecule-shaped numbers."

WHAT BURIED BARRICELLI IN obscurity is something of a mystery. "Being uncompromising in his opinions and not a team player," says Dyson, no doubt led to Barricelli's "isolation from the academic mainstream." Dyson also suspects Barricelli and the indomitable Hungarian mathematician von Neumann, an influential leader at the Institute of Advanced Study, didn't hit it off. Von Neumann appears to have ignored Barricelli. "That was sort of fatal because everybody looked to von Neumann as the grandfather of self-replicating machines."

Ever so slowly, though, Barricelli is gaining recognition. That stems in part from another of Barricelli's remarkable developments—certainly one of his most beautiful. He didn't rest with creating a universe of numerical organisms; he converted his organisms into images. His computer tallies of 1s and 0s would then self-organize into visual grids of exquisite variety and texture. According to Alexander Galloway, associate professor in the department of media, culture, and communication at New York University, a finished Barricelli "image yielded a snapshot of evolutionary time."

When Barricelli printed sections of his digitized universes, they were dazzling. To modern eyes they might look like satellite imagery of an alien geography: chaotic oceans, stratigraphic outcrops, and the contours of a single stream running down the center fold, fanning into a delta at the patchwork's bottom. "Somebody needs to do a museum show and show this stuff because they're outrageous," Galloway says.

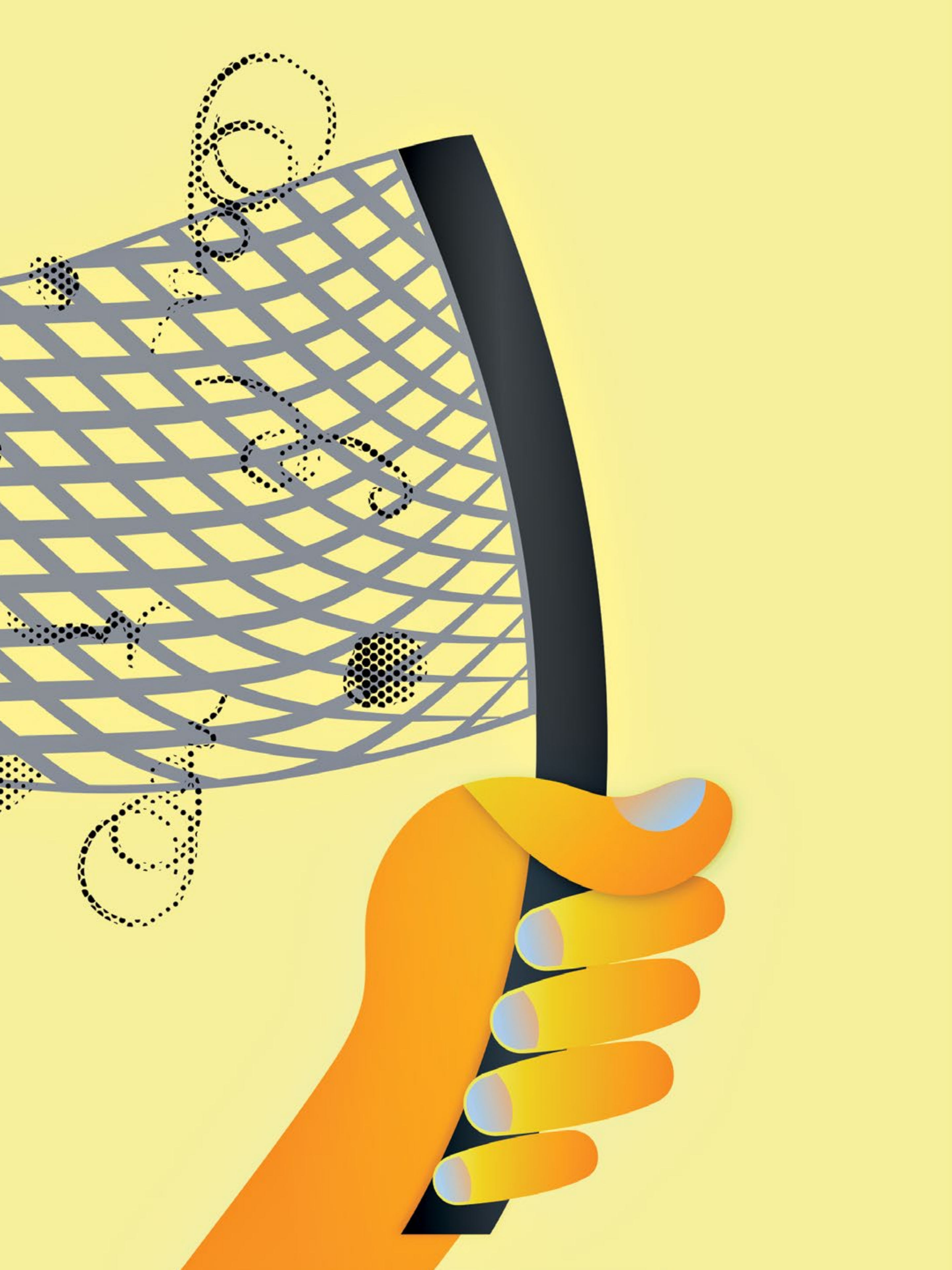
Today, Galloway, a member of Barricelli's small but growing cadre of boosters, has recreated the images. Following methods described by Barricelli in one of his papers, Galloway has coded an applet using the computer language Processing to revive Barricelli's numerical organisms—with slight variation. While Barricelli encoded his numbers as eight-unit-long proto-pixels, Galloway condensed each to a single color-coded cell. By collapsing each number into a single pixel, Galloway has been able to fit eight times as many generations in the frame. These revitalized mosaics look like psychedelic cross-sections of the fossil record. Each swatch of color represents an organism, and when one color field bumps up against another one, that's where cross-fertilization takes place (see Psychedelic Barricelli on page 126).

"You can see these kinds of points of turbulence where the one color meets another color," Galloway says, showing off the images on a computer in his office. "That's a point where a number would be—or a gene would be—sort of jumping from one organism to another." Here, in other words, is artificial life—Barricelli's symbiogenesis—frozen in amber. And cyan and lavender and teal and lime and fuchsia.

Galloway is not the only one to be struck by the beauty of Barricelli's computer-generated digital images. As a doctoral student, Pixar cofounder Smith became familiar with Barricelli's work while researching the history of cellular automata for his dissertation. When he came across Barricelli's prints he was astonished. "It was remarkable to me that with such crude computing facilities in the early 50s, he was able to be making pictures," Smith says. "I guess in a sense you can say that Barricelli got me thinking about computer animation before I thought about computer animation. I never thought about it that way, but that's essentially what it was."

Cyberspace now swells with Barricelli's progeny. Self-replicating strings of arithmetic live out their days in the digital wilds, increasingly independent of our tampering. The fittest bits survive and propagate. Researchers continue to model reduced, pared-down versions of life artificially, while the real world bursts with Boolean beings. Scientists like Venter conjure synthetic organisms, assisted by computer design. Swarms of autonomous codes thrive, expire, evolve, and mutate underneath our fingertips daily. "All kinds of self-reproducing codes are out there doing things," Dyson says. In our digital lives, we are immersed in Barricelli's world.

ROBERT HACKETT is a science, technology, and business reporter for *Fortune* magazine.



This Shape-Shifter Could Tell Us Why Matter Exists

Neutrinos can flit between states effortlessly, hinting at deep new physics

BY MAGGIE MCKEE

NEUTRINO PHYSICS IS FULL of unusual characters. There was Ettore Majorana, who disappeared in 1938 without a trace, taking his savings with him. No record of him has ever been found, though there have been numerous disputed sightings of him throughout the years.

Then there was Bruno Pontecorvo. Suspected of slipping nuclear secrets out of England, he vanished while on vacation in Italy in 1950 and reappeared five years later singing the praises of his new homeland: the Soviet Union.

Strangest of all, though, is the neutrino itself. It is electrically neutral, making it invisible to particle detectors, and bizarrely lightweight, at most 0.0004 percent the weight of the next-lightest particle, the electron. Although it is the most numerous massive particle in the universe, it is so slippery that it can pass through a light-year of lead as if it wasn't there. And then there is the matter of the shape-shifting.

Neutrinos come in three flavors: electron, muon, and tau, each named for the charged particle with which it is associated. But the flavors are not pure essences—each is made up of a different combination (or superposition) of three ingredients, or mass states.

These mass states behave not as simple dumbbells of differing weights, but as waves of differing lengths. Because the waves do not line up with each other perfectly, at different points the height of one mass state will vary with respect to that of the other two. That means that sometimes the combination of mass states will most resemble the recipe for an electron neutrino, while at other times it will look like that of a muon neutrino. As a result, neutrinos appear to oscillate among the three flavors as they travel.

No other fundamental particles do this. "Only the neutrinos can change from one type to another," says André de Gouvêa of Northwestern University in Evanston, Illinois. More than a quirk of nature, this ability to mutate on the fly points to some deep questions in physics, and potentially, some important answers.

ILLUSTRATION BY FRANCESCO IZZO

NEUTRINO MUTATION WOULD NOT be possible if it weren't for the particle's minuscule mass. Because each of the three known mass states is so small and its associated quantum wavelength is so long, the waves corresponding to each state can remain largely in sync, with only small offsets, over cosmic distances. This allows neutrinos to flicker between different flavors in an ephemeral state of multiplicity.

If their masses were larger and their wavelengths shorter, the waves would quickly become so out of phase that this knife-edge balance between different flavors would collapse, forcing the neutrinos into one type or the other. "The different flavors would separate from each other," says de Gouvêa. "They would have a very binary behavior." The fact that neutrinos don't, thanks to their puny mass states, makes sense according to the rules of quantum mechanics, but it is still mind-bending, says neutrino researcher Jason Koskinen of the University of Copenhagen. "I still haven't wrapped my head around this," he admits.

There is just one snag: Neutrinos weren't supposed to have any mass at all. "We built our standard model around the idea that neutrinos are massless," says Janet Conrad of the Massachusetts Institue of Technology (MIT).

The fact that they have mass, however small, is a big problem. The standard model is physicists' best idea of how particles and forces interact—a spectacularly strong edifice whose construction was completed in 2012 with the discovery of its last missing particle, the Higgs boson. "Neutrino oscillation is the only confirmed physics right now that can be done outside the standard model," says Koskinen.

The reason that neutrino mass is so tricky has to do with how any particle gets its mass. Other elementary particles with mass come in two mirror versions—one left- and one right-handed—that correspond to the direction of their spin. Each version can interact with a different force of nature, and both "hands" seem to be required to give particles mass, thanks to their interaction with an invisible quantum "ether" that suffuses all of space: the Higgs field, whose signature particle is the Higgs boson.

The Higgs field acts a bit like a mirror, turning a particle with one spin into its mirror opposite. "The idea is that every once in a while, a left-handed particle will hit the Higgs field and convert to a right-handed particle," says de Gouvêa. "The net effect is that it looks like a particle with mass."

Neutrinos, by contrast, interact only with the one-handed weak nuclear force (and technically gravity, but the strength of this force compared to the others is negligible). And indeed, only left-handed neutrinos have been observed. If neutrinos have no mirror reflection, they should have no mass, according to the standard model, so how they get mass is a physicist's version of the Zen kōan pondering the sound of one hand clapping. "Many particle physicists who work on the subject get confused about it," says de Gouvêa.

One possibility is that neutrinos do have a reflection, but one that only they can see. That is, there are right-handed neutrinos, but their presence has not been detected because they are even more aloof than their southpaw counterparts and have no mass. "That particle doesn't participate in any force," says de Gouvêa of the purported right-handed neutrino. "It literally does not interact with anything, except with the left-handed neutrino to give it a mass."

HOW NEUTRINOS GAIN THEIR mass is a mystery whose solution promises to spill over the boundaries of neutrino physics itself, and into one of the biggest questions of cosmology: Why is there more matter in the universe than antimatter? According to the standard model, equal amounts of matter and antimatter should have been made after the big bang. When matter and antimatter meet, they instantly and completely annihilate each other. So the big bang should have led in quick succession to a great conflagration. The fact that we are here today shows that some process tipped the scales to leave behind more matter. "How did equality evolve into inequality?" asks Boris Kayser, a neutrino theorist at Fermilab in Batavia, Illinois. "Matter and antimatter have to behave differently." Many physicists suspect neutrinos played a role in this imbalance—but if they do, it's unlikely that they get their mass the way other particles do (interacting with the standard Higgs field through a right-handed version of themselves).

Fortunately, there's a loophole, raised nearly 80 years ago by the enigmatic Majorana. Instead of invoking a separate right-handed matter neutrino, the

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neutrino anti-particle (the antineutrino) could act as a mass partner for its lefty counterpart. After all, the antineutrino is right-handed. For this to work, though, neutrinos would need to be their own antiparticles. That means that if two neutrinos ever met each other, they would instantly annihilate.

One way to test whether this is happening is to look for radioactive particle decays that should leave behind signs of two antineutrinos but don't—presumably because the antineutrinos, being their own antiparticles, had annihilated immediately after forming. With the exception of one controversial result reported about a decade ago, this signature, known as neutrinoless double beta decay, has yet to be seen. That doesn't mean the process (two neutrons decaying to produce two protons and two electrons) doesn't exist: It is so rare that it is typically expected to occur on timescales much longer than the age of the universe.

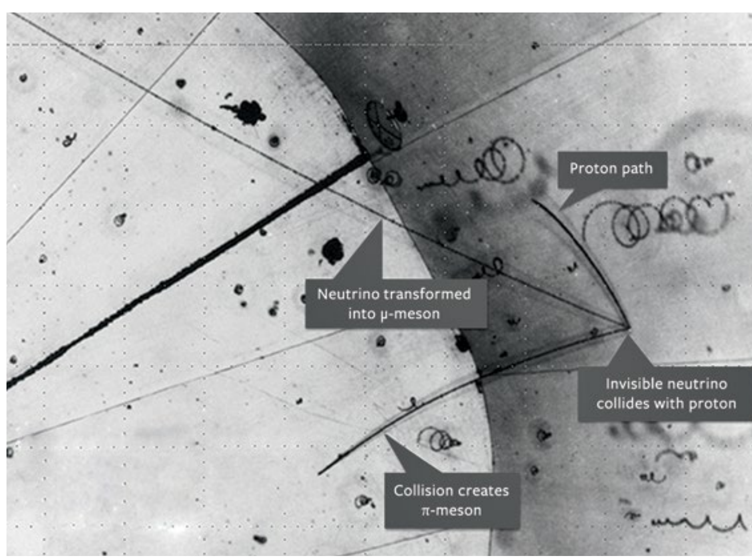
But not always. Statistically, the decay could occur on timescales detectable in the lab. "If somehow we were told we can only look for neutrino masses in one way and only one way, then neutrinoless double beta decay would probably be the highest priority," de Gouvêa says. Several new hunts, including the Italian CUORE and the Canadian SNO+ experiments, aim to scrutinize the radioactive decays of elements such as tellurium for the telltale absence of antineutrinos.

It is so rare that it is typically expected to occur on timescales much longer than the age of the universe.

If neutrinos are not their own antiparticles, neutrinoless beta decay would never happen. Instead, the two neutrons would leave behind two protons, two electrons and two antineutrinos. In that case, the difference between the number of matter and antimatter leptons—that is, neutrinos, electrons, muons, and tau particles—would be zero both before and after the decay. If neutrinos are their own antiparticles, however, two leptons (the electrons) would be left standing after the decay—and no antileptons. The net result would be an increase in the quantity of matter leptons, at the expense of their antimatter counterparts. Similar processes operating in the early universe might provide just the ticket to explain the universe's disparity between matter and antimatter.

That is a promising direction for cosmologists interested in the nature of the universe. But, it also means some new physics is needed to explain how neutrinos

SEEING THE INVISIBLE
An invisible neutrino entering a hydrogen bubble chamber from the right collides with a proton, leaving three visible particle pathways.



The Search for the Sterile Neutrino

Heavy sterile neutrinos could explain why ordinary neutrinos have small masses, but they may be inaccessible even at the largest particle accelerator in the world, the Large Hadron Collider. Even so, all hope for finding new types of neutrinos is not lost. Heavy sterile neutrinos may have lower-mass sterile partners—each weighing perhaps 10 to 100 times as much as an ordinary neutrino—that could show up in oscillation experiments.

If lightweight sterile neutrinos exist, their mass states could be part of the "superposition" that produces the three known flavors of neutrino. That means that oscillation experiments could spot fewer ordinary neutrinos than expected because they would have morphed into a sterile type. Or the experiments could look for oscillations that take place much faster than expected. That's because the heavier mass states of sterile neutrinos would have shorter wavelengths than those of ordinary neutrinos, so when their waves were added to the three ordinary waves, the end result would be more wiggles between neutrino types.

Janet Conrad of MIT is part of a team that hopes to search for the shape of these wiggles in a proposed experiment called IsoDAR. It would create a radioactive isotope of lithium whose decay would produce nearly a trillion trillion antineutrinos over the course of five years. Some of these antineutrinos would go on to interact with a nearby detector, and the variation in the number detected at different energies could reveal the extra wiggle from one or more sterile neutrinos. "You need more than just saying the neutrinos that I did not expect appeared, or the neutrinos that should have been

get their mass; the usual interaction among left-handed, right-handed, and Higgs particles would not work.

One idea is that neutrinos have their own Higgs field, a mirror that reflects only neutrinos and no other particles. "It's like the neutrinos require their own Higgs boson," says de Gouvêa.

Chian-Shu Chen of the National Center for Theoretical Sciences in Hsinchu, Taiwan, and Ya-Juan Zheng of National Taiwan University in Taipei calculate that it is possible that signs of this new Higgs boson could appear at the Large Hadron Collider in Switzerland. "We expect [the] neutrino mass mechanism could have the chance to be revealed within the reach of the LHC," says Chen.

But he acknowledges that it would be "very lucky" if that happened, since physicists would ordinarily expect the new particles to be produced at much higher energies than the LHC can reach. Alexei Smirnov of the Max-Planck Institute for Nuclear Physics in Heidelberg, Germany, agrees. "I would call this activity 'searching under the lamp,' " he says. "There is no other serious motivation for this construction but making something observable at the LHC."

Another possibility is to add one or more extra types of neutrino that would be even less sociable than an ordinary one. This is similar to the idea of simply adding a right-handed neutrino, except in this case, the extra neutrino interacts with itself to provide its own mass. It is referred to as a massive "sterile" neutrino, since it can only affect other particles gravitationally. "The left-handed guys have their own mass, and the right-handed guys have their own mass," says Rabindra Mohapatra of the University of Maryland, College Park.

If a "sterile" neutrino exists, it should have a mass that is inversely proportional to that of the ordinary neutrino, as if the two neutrino types were on opposite sides of a seesaw. And that could help explain a puzzling gap in the distribution of the masses of fundamental particles, says Mohapatra. The quarks that make up protons and neutrons are about 10 times as massive as the electron, but the electron is at least 250,000 times as massive as the next lightest particle, the neutrino. "We were always worried about the fact that the neutrino mass seems to be much smaller than the electron mass," says Mohapatra. In the seesaw mechanism, which Mohapatra helped originate 35 years ago, the extremely low mass of ordinary neutrinos can be explained if there are very heavy steriles as well.

The seesaw mechanism could possibly produce exotic charged particles that would appear in the detritus of proton collisions at the LHC. Finding evidence of massive sterile neutrinos would be exciting "because it would tell us that neutrino masses are evidence for some other independent source of mass" for fundamental particles besides the ordinary Higgs field, says de Gouvêa. Such a discovery would get at the heart of the origin of mass, one of the most basic questions in physics.

As for Pontecorvo, the man who first suggested that neutrinos might shape-shift, his own life was nothing if not a seesaw. He soon came to regret having defected to the Soviet Union. "After a few years, I understood what an idiot I was," Pontecorvo told a reporter in 1992, a year before his death. But it was too late. His defection prevented him from traveling abroad for many years, contributed to his wife's nervous breakdown, and, ironically, shut him out from the nuclear reactor research he had probably left the United Kingdom to pursue, says Pontecorvo biographer Simone Turchetti, a science historian at the University of Manchester. "This really is a story of a man living two completely different lives in two completely different worlds," Turchetti says—rather like the particle he studied.

MAGGIE MCKEE is a freelance science writer focusing mainly on astronomy and physics. Previously an editor at *New Scientist* and *Astronomy* magazines, she lives near Boston with her husband.

there disappeared," she says. "You want to watch the morphing happen. If you were sending out a race with a bunch of cats, and you found some dogs at the end, you would want to understand what happened in between."

If sterile neutrinos exist, they could help solve a number of problems in cosmology, making up at least some of the mysterious "dark matter" that outweighs normal matter by a factor of more than 5 to 1 (ordinary neutrinos, whose production numbers since the big bang can be calculated, are not heavy enough to account for the dark matter).

And indeed, a handful of previous experiments have spotted hints of a lightweight sterile neutrino weighing about one electron volt, or about 0.0002 percent as much as an electron. The problem is that value is different from the proposed mass of the sterile neutrinos that would account for the universe's dark matter and some other estimates of the sterile neutrino's mass. "The only consistent aspect of sterile neutrinos is the inconsistency," says Jason Koskinen of the University of Copenhagen.

15

IN ONE SENSE, TURBULENCE is a typical subject of scientific research, and lies on the harder side of the scientific spectrum. But in another sense, its irreducible complexity requires of the scientist a keen intuitive sense.

This is clear in the history of the subject. Leonardo da Vinci, using just hand-drawn sketches, divined that turbulent flow had "principal" and "random" components, a distinction that would spark a revolution in fluid dynamics when it was more formally described four centuries later by Osborne Reynolds.

Even when they had armed themselves with the tools of modern mathematics, scientists would return to naked observation to guide their work. As Philip Ball describes in his article, "The Scientific Problem That Must Be Experienced," the French mathematician and scholar of turbulence, Jean Leray, is said to have found inspiration by spending hours watching the Seine eddy past the Pont-Neuf.

Today, turbulence continues its slow emergence. While scientists are discovering it in our brains and bodies, our sky and sun, its precise definition remains the subject of debate, making for a rich correspondence between art and science—and a fitting topic for *Nautilus* to explore.

Welcome to "Turbulence."

—MS

"Oxidants may be a primordial messenger of stress in our cells, and a little bit of stress, it turns out, may be good for us."

MOISES VELASQUEZ-MANOFF

"Fruits and Vegetables Are Trying to Kill You" p.138

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Fruits and Vegetables Are Trying to Kill You

Antioxidant vitamins don't stress us like plants do—and don't have their beneficial effect

BY MOISES VELASQUEZ-MANOFF

YOU PROBABLY TRY TO exercise regularly and eat right. Perhaps you steer toward "superfoods," fruits, nuts, and vegetables advertised as "antioxidant," which combat the nasty effects of oxidation in our bodies. Maybe you take vitamins to protect against "free radicals," destructive molecules that arise normally as our cells burn fuel for energy, but which may damage DNA and contribute to cancer, dementia, and the gradual meltdown we call aging.

Warding off the diseases of aging is certainly a worthwhile pursuit. But evidence has mounted to suggest that antioxidant vitamin supplements, long assumed to improve health, are ineffectual. Fruits and vegetables are indeed healthful but not necessarily because they shield you from oxidative stress. In fact, they may improve health for quite the opposite reason: They stress you.

That stress comes courtesy of trace amounts of naturally occurring pesticides and anti-grazing compounds. You already know these substances as the hot flavors in spices, the mouth-puckering tannins in wines, or the stink of Brussels sprouts. They are the antibacterials, antifungals, and grazing deterrents of the plant world. In the right amount, these slightly noxious substances, which help plants survive, may leave you stronger.

Parallel studies, meanwhile, have undercut decades-old assumptions about the dangers of free radicals. Rather than killing us, these volatile molecules, in the right amount, may improve our health. Our quest to neutralize them with antioxidant supplements may be doing more harm than good.

The idea that pro-oxidant molecules are always destructive is "oversimplified to the point of probably being wrong," says Toren Finkel, chief of the center for molecular medicine at the National Heart, Lung, and Blood Institute in Bethesda, Maryland. "Oxidants may be a primordial messenger of stress in our cells, and a little bit of stress, it turns out, may be good for us."

Although far from settled, a wave of compelling

ILLUSTRATIONS BY JOHN HENDRIX

science offers a remarkably holistic picture of health as a byproduct of interactions among people, plants, and the environment. Plants' own struggle for survival—against pathogens and grazers, heat and drought—is conveyed to us, benefitting our health. This new understanding begins, in part, on a treadmill.

IN THE MID-20TH CENTURY, as modern medicine seemed poised to vanquish the infectious diseases of yore, some scientists turned to the degenerative diseases associated with aging. Attention fell on a class of molecules called "reactive oxygen species," or ROS. These volatile substances could damage DNA. Degenerative diseases, such as cancer and cardiovascular disease, often showed evidence of "oxidative stress," suggesting that ROS spurred disease.

Oddly, our mitochondria, the energy factories of our cells, emitted ROS naturally. So degenerative disease seemed to stem in part from our own metabolic function: Your mitochondria "burned" fuel, emitted this toxic exhaust, and inadvertently set the limits on your existence. That was the working hypothesis, at any rate.

Experiments on rats and worms showed that reactive oxygen species, such as hydrogen peroxide, tear atoms from other molecules, destroying them in the process. That can be problematic when those molecules are DNA, our cellular instruction manual. We produce native antioxidants, such as the molecule glutathione, to counteract this pro-oxidant threat. They react with ROS, neutralizing the pro-oxidants before they can damage important cellular machinery.

When scientists blocked rodents' ability to manufacture these protective molecules, lifespan declined. Observational studies, meanwhile, suggested that people who regularly ate vitamin-laden fruits and vegetables were healthier. So were people with higher levels of vitamins E and C in their blood.

Vitamins were strongly antioxidant in test tubes. So the ROS theory of aging and disease rose to prominence. You could slow aging, it followed, by neutralizing free radicals with antioxidant pills. A supplement industry now worth $23 billion yearly in the United States took root.

But if those ROS were so harmful—and the basic design of our (eukaryote) cells was over 1 billion years old—why hadn't evolution solved the ROS problem?

At the same time, scientists began finding that exercise and calorie restriction increased lifespan in animals. Both elevated ROS. According to the ROS model of aging, animals that exercised and fasted should have died younger. But they lived longer.

For Michael Ristow, a researcher of energy and metabolism at the Swiss Federal Institute of Technology in Zurich, the inconsistencies became impossible to overlook. In worms, he found that neutralizing those allegedly toxic ROS reduced lifespan, so he designed a similar experiment in humans.

He had 39 male volunteers exercise regularly over several weeks; half took vitamin supplements before working out. The results, published in 2009, continue to reverberate throughout the field of exercise physiology, and beyond. Volunteers who took large doses of vitamins C and E before training failed to benefit from the workout. Their muscles didn't become stronger; insulin sensitivity, a measure of metabolic health, didn't improve; and increases in native antioxidants, such as glutathione, didn't occur.

Exercise accelerates the burning of fuel by your cells. If you peer into muscles after a jog, you'll see a relative excess of those supposedly dangerous ROS—exhaust spewed from our cellular furnaces, the mitochondria. If you examine the same muscle some time after a run, however, you'll find those ROS gone. In their place you'll see an abundance of native antioxidants. That's because, post-exercise, the muscle cells respond to the oxidative stress by boosting production of native antioxidants. Those antioxidants, amped up to protect against the oxidant threat of yesterday's exercise, now also protect against other ambient oxidant dangers.

Ristow realized the signal of stress conveyed by the ROS during exercise was essential to this call-and-response between mitochondria and the cells that housed them. To improve health, he figured, perhaps we shouldn't neutralize ROS so much as increase them in a way that mimicked what happened in exercise. That would boost native antioxidants, improve insulin sensitivity, and increase overall resilience.

Ristow called this idea "mitohormesis." The term "hormesis" came from toxicology ("mito" was for mitochondrion). It describes the observation that some exposures generally considered toxic can, in minute amounts, paradoxically improve health. For instance, minuscule quantities of X-ray radiation, a known carcinogen, increase the lifespan of various insects.

Hormesis may be most easily grasped when considering exercise. Lift too much weight or run too long, and you'll likely tear muscle and damage tendons. But lift the right amount and run a few times a week, and your bones and muscles strengthen. The intermittent torque and strain increases bone mineralization and density. Stronger bones may better tolerate future shocks that might otherwise cause fractures.

In his experiment, Ristow saw that vitamin supplements interrupted this sequence of stress followed by fortification, probably because they neutralized the ROS signal before it could be "heard" elsewhere in the cell. By interfering in the adaptive response, vitamins prevented the strengthening that would have otherwise followed the stress of physical exertion. Antioxidant supplementation paradoxically left you weaker.

Vitamins are necessary for health. And supplements can help those who are deficient in vitamins. Insufficient vitamin C causes scurvy, which results from defective collagen, a protein in connective tissue. Among other functions, vitamin C aids collagen synthesis. But the primary role of vitamins in our body, according to Ristow and others, may not be antioxidant. And the antioxidant content of fruits and veggies does not, he thinks, explain their benefits to our health. So what does?

MARK MATTSON, CHIEF OF the Laboratory of Neurosciences at the National Institute on Aging, has studied how plant chemicals, or phytochemicals, affect our cells (in test tubes) for years. The assumption has long been that, like vitamins, phytochemicals are directly antioxidant. But Mattson thinks they work indirectly. Much like exercise, he's found, phytochemicals stress our bodies in a way that leaves us stronger.

Plants, Mattson explains, live a stationary life. They cannot respond to pathogens, parasites, and grazers as we might—by moving. To manage the many threats posed by mobile life, as well as heat, drought, and other environmental stresses, they've evolved a remarkable number of defensive chemicals.

We're familiar with many components of their arsenal. The nicotine that we so prize in tobacco slows grazing insects. Beans contain lectins, which defend against insects. Garlic's umami-like flavor comes from allicin, a powerful antifungal. These "antifeedants" have evolved in part to dissuade would-be grazers, like us.

> These recommendations end up sounding rather grandmotherly—if your grandmother was a spartan, no-nonsense peasant who lived off the land.

Mattson and his colleagues say these plant "biopesticides" work on us like hormetic stressors. Our bodies recognize them as slightly toxic, and we respond with an ancient detoxification process aimed at breaking them down and flushing them out.

Consider fresh broccoli sprouts. Like other cruciferous vegetables, they contain an antifeedant called sulforaphane. Because sulforaphane is a mild oxidant, we should, according to old ideas about the dangers of oxidants, avoid its consumption. Yet studies have shown that eating vegetables with sulforaphane reduces oxidative stress.

When sulforaphane enters your blood stream, it triggers release in your cells of a protein called Nrf2. This protein, called by some the "master regulator" of aging, then activates over 200 genes. They include genes that produce antioxidants, enzymes to metabolize toxins, proteins to flush out heavy metals, and factors that enhance tumor suppression, among other important health-promoting functions.

In theory, after encountering this humble antifeedant in your dinner, your body ends up better prepared for encounters with toxins, pro-oxidants from both outside and within your body, immune insults, and other challenges that might otherwise cause harm. By "massaging" your genome just so, sulforaphane may increase your resistance to disease.

In a study on Type 2 diabetics, broccoli-sprout powder lowered triglyceride levels. High triglycerides, a lipid, are associated with an increased risk of heart disease and stroke. Lowering abnormally elevated triglycerides may lessen the risk of these disorders. In another intervention, consuming broccoli sprout powder reduced oxidative stress in volunteers' upper airways, likely by increasing production of native antioxidants. In theory, that might ameliorate asthmatics' symptoms.

Elevated free radicals and oxidative stress are routinely observed in diseases like cancer and dementia. And in these instances, they probably contribute to degeneration. But they may not be the root cause of disease. According to Mattson, the primary dysfunction may have occurred earlier with, say, a creeping inability to produce native antioxidants when needed, and a lack of cellular conditioning generally.

Mattson calls this the "couch potato" problem. Absent regular hormetic stresses, including exercise and stimulation by plant antifeedants, "cells become complacent," he says. "Their intrinsic defenses are down-regulated." Metabolism works less efficiently. Insulin resistance sets in. We become less able to manage pro-oxidant threats. Nothing works as well as it could. And this mounting dysfunction increases the risk for a degenerative disease.

Implicit in the research is a new indictment of the Western diet. Not only do highly refined foods present tremendous caloric excess, they lack these salutary signals from the plant world—"signals that challenge," Mattson says. Those signals might otherwise condition our cells in a way that prevents disease.

Another variant of the hormetic idea holds that our ability to receive signals from plants isn't reactive and defensive but, in fact, proactive. We're not protecting ourselves from biopesticides so much as sensing plants' stress levels in our food.

Harvard scientist David Sinclair and his colleague Konrad Howitz call this xenohormesis: benefitting from the stress of others. Many phytonutrients trigger the same few cellular responses linked to longevity in eukaryotic organisms, from yeasts to humans. Years of research on Nrf2 in rodents suggest that activating this protein increases expression of hundreds of health-promoting genes, including those involved in detoxification, antioxidant production, control of inflammation, and tumor suppression.

Sinclair studies another class of native proteins, called sirtuins, associated with health. They're triggered by exercise and also, Sinclair contends, a molecule called resveratrol, found in grape skins and other plants. "It's too coincidental that time and time again these molecules come out of nature that have the surprising multifactorial benefit of tweaking the body just the right way," Sinclair says.

They're not all antifeedants, he argues. Plants churn these substances out when stressed, prompting further adaptations to the particular threat, be it drought, infestation by grazing insects, or excessive ultraviolet radiation from the sun.

For grazers, these stress compounds in plants may convey important information about environmental conditions. So grazers' ability to "perceive" these signals, Sinclair argues, likely proved advantageous over evolutionary time. It allowed them to prepare for adversity. A grape vine stressed by fungi churns out resveratrol to fight off the infection. You drink wine made from those grapes, "sense" the harsh environmental conditions in the elevated tannins and other stress compounds, gird your own defenses, and, in theory, become more resistant to degenerative disease.

One implication is that modern agriculture, which often prevents plant stress with pesticides and ample watering, produces fruits and vegetables with weak xenohormetic signals. "I buy stressed plants," Sinclair says. "Organic is a good start. I choose plants with lots of color because they are producing these molecules." Some argue that xenohormesis may explain why the Mediterranean diet is apparently so healthful. It contains plants such as olives and nuts that come from hot, dry, stressful environments. Eating food from plants that have struggled to survive toughens us up as well.

Philip Hooper, an endocrinologist at the University of Colorado Anschutz Medical Campus, points out that plant-animal relationships are often symbiotic, and communication goes both ways. One example of direct plant-to-animal, biochemical manipulation comes from the coffee bush. Flowering plants compete with one another for the attention of pollinators, such as bees. Coffee bushes seem to gain advantage in this "marketplace" by using caffeine. The drug excites pollinators' neurons, etching the memory of the plant's location more deeply in their brains. Some think that biochemical tweaking increases the probability that the pollinator, which faces a panoply of flower choices, will return to that particular coffee bush.

In the dance between animals and plants, says Hooper, "I think there's true mutualism. We're in this together, the plants and us."

WHILE XENOHORMESIS IS A COMPELLING idea, it remains unproven. Barry Halliwell, a biochemist at the National University of Singapore, and an expert on antioxidants, has seen the dietary fads, from vitamins to fiber, come and go. He says the hormetic and xenohormetic ideas are plausible, but not certain. Various studies suggest that people who consume a lot of fruits and vegetables have healthier lifestyles generally. Those people probably go easy on the junk food, which alone may improve health.

Even within the hormetic idea, Halliwell sees the attempts to bore down on the individual chemicals as problematic. "That's worked very well in pharmacology, but it hasn't worked at all well in nutrition," he says. He doesn't think any single phytonutrient will explain the apparent health-promoting benefits of fruits and veggies. "Variety seems to be good," he says. That critique speaks to a larger problem: It's often unclear how lab research on simple organisms or cell cultures will translate, if at all, into recommendations or therapies for genetically complex, free-living humans.

What works in genetically uniform organisms, or cells, living in highly controlled environments, does not necessarily work in people. Human studies on resveratrol in particular have yielded contradictory results. Proper dosage may be one problem, and interaction between the isolates used and particular gene variants in test subjects another. Interventions usually test one molecule, but fresh fruits and vegetables present numerous compounds at once. We may benefit most from these simultaneous exposures.

The science on the intestinal microbiota promises to further complicate the picture; our native microbes ferment phytonutrients, perhaps supplying some of the benefit of their consumption. All of which highlights the truism that Nature is hard to get in a pill.

These caveats aside, research into xenohormesis reminds us that we are not at the complete mercy of our genetic inheritance. Genes matter, but health depends in large part on having the right genes expressed at the right time—and in the right amount. If our genome is a piano, and our genes are the keys, health is the song we play on the piano. The science on hormesis, the stresses that may keep us strong, provides hints about what kind of song we should play. Keep the body conditioned with regular exercise. Keep your cells' stress-response pathways intermittently engaged with minimally processed, plant-based food.

These recommendations end up sounding rather grandmotherly—if your grandmother was a spartan, no-nonsense peasant who lived off the land. But the underlying thrust contradicts assumptions about the need to protect oneself from hardship. Certain kinds of difficulty, it turns out, may be required for health. That's because health doesn't result solely from the instructions your genome contains, but from your relationship with the wider world. Resilience isn't completely inherent to your body; it's cultivated by outside stimuli. And some of those stimuli just happen to be mildly noxious, slightly stressful chemicals in plants.

MOISES VELASQUEZ-MANOFF is a science writer and author of *An Epidemic of Absence: A New Way of Understanding Allergies and Autoimmune Diseases*. He lives in California.

Your Brain Is On the Brink of Chaos

Neurological evidence for chaos in the nervous system is growing

BY KELLY CLANCY

IN ONE IMPORTANT WAY, the recipient of a heart transplant ignores its new organ: Its nervous system usually doesn't rewire to communicate with it. The 40,000 neurons controlling a heart operate so perfectly, and are so self-contained, that a heart can be cut out of one body, placed into another, and continue to function perfectly, even in the absence of external control, for a decade or more. This seems necessary: The parts of our nervous system managing our most essential functions behave like a Swiss watch, precisely timed and impervious to perturbations. Chaotic behavior has been throttled out.

Or has it? Two simple pendulums that swing with perfect regularity can, when yoked together, move in a chaotic trajectory. Given that the billions of neurons in our brain are each like a pendulum, oscillating back and forth between resting and firing, and connected to 10,000 other neurons, isn't chaos in our nervous system unavoidable?

The prospect is terrifying to imagine. Chaos is extremely sensitive to initial conditions—just think of the butterfly effect. What if the wrong perturbation plunged us into irrevocable madness? Among many scientists, too, there is a great deal of resistance to the idea that chaos is at work in biological systems. Many intentionally preclude it from their models. It subverts computationalism, which is the idea that the brain is nothing more than a complicated, but fundamentally rule-based, computer. Chaos seems unqualified as a mechanism of biological information processing, as it allows noise to propagate without bounds, corrupting information transmission and storage.

At the same time, chaos has its advantages. On a behavioral level, the arms race between predator and prey has wired erratic strategies into our nervous system.[1] A moth sensing an echolocating bat, for example, immediately directs itself away from the ultrasound source. The neurons controlling its flight fire in an increasingly erratic manner as the bat draws closer, until the moth, darting in fits, appears to be nothing

ILLUSTRATION BY JOSH COCHRAN

but a tumble of wings and legs. More generally, chaos could grant our brains a great deal of computational power, by exploring many possibilities at great speed.

Motivated by these and other potential advantages, and with an accumulation of evidence in hand, neuroscientists are gradually accepting the potential importance of chaos in the brain.

CHAOS IS NOT THE SAME as disorder. While disordered systems cannot be predicted, chaos is actually deterministic: The present state of the system determines its future. Yet even so, its behavior is only predictable on short time scales. Tiny differences in inputs result in vastly different outcomes. Chaotic systems can also exhibit stable patterns called "attractors" that emerge to the patient observer. Over time, chaotic trajectories will gravitate toward them. Because chaos can be controlled, it strikes a fine balance between reliability and exploration. Yet because it's unpredictable, it's a strong candidate for the dynamical substrate of free will.

The similarity to random disorder (or stochasticity) has been a thorn in the side of formal studies of chaos. It can be mathematically tricky to distinguish between the two—especially in biological systems. There are no definite tests for chaos when dealing with multi-dimensional, fluctuating biological data. Walter Freeman and his colleagues spearheaded some of the earliest studies attempting to prove the existence of chaos in the brain, but came to extreme conclusions on limited data. He's argued, for example, that neuropil, the extracellular mix of axons and dendrites, is the organ of consciousness—a strong assertion in any light. Philosophers soon latched onto these ideas, taking even the earliest studies at face value. Articles by philosophers and scientists alike can be as apt to quote Jiddu Krishnamurti as Henri Poincaré, and chaos is often handled with a semi-mystical reverence.[2,3]

As a result, researchers must tread carefully to be taken seriously. But the search for chaos is not purely poetic. The strongest current evidence comes from single cells. The squid giant axon, for example, operates in a resting mode or a repetitive firing mode, depending on the external sodium concentration. Between these extremes, it exhibits unpredictable bursting that resembles the wandering behavior of a chaotic trajectory before it settles into an attractor. When a periodic input is applied, the squid giant axon responds with a mixture of both oscillating and chaotic activity.[4] There is chaos in networks of cells, too. The neurons in a patch of rat skin can distinguish between chaotic and disordered patterns of skin stretching.[5]

More evidence for chaos in the nervous system can be found at the level of global brain activity. Bizarrely, an apt metaphor for this behavior is an iron slab.[6] The electrons it contains can each point in different directions (more precisely, their spins can point). Like tiny magnets, neighboring spins influence each other. When the slab is cold, there is not enough energy to overcome the influence of neighboring spins, and all spins align in the same direction, forming one solid magnet. When the slab is hot, each spin has so much energy that it can shrug off the influence of its neighbor, and the slab's spins are disordered. When the slab is halfway between hot and cold, it is in the so-called "critical regime." This is characterized by fluctuating domains of same-spin regions which exhibit the highest possible dynamic correlations—that is, the best balance between a spin's ability to influence its neighbors, and its ability to be changed.

The critical state can be quite useful for the brain, allowing it to exploit both order and disorder in its computations—employing a redundant network with rich, rapid chaotic dynamics, and an orderly readout function to stably map the network state to outputs. The critical state would be maintained not by temperature, but the balance of neural excitation and inhibition. If the balance is tipped in favor of more inhibition, the brain is "frozen" and nothing happens. If there is too much excitation, it will descend into chaos. The critical point is analogous to an attractor.

But how can we tell whether the brain operates at the critical point? One clue is the structure of the signals generated by the activity of its billions of neurons. We can measure the power of the brain's electrical activity at different oscillation frequencies. It turns out that the power of activity falls off as the inverse of the frequency of that activity. Once referred to as $1/f$ "noise," this relationship is actually a hallmark of systems balanced at their critical point.[7] The spatial extent of regions of coordinated neuronal activity also depend inversely on frequency, another hallmark of criticality.

The brain's main function is to protect us, like an umbrella, from chaos.

When the brain is pushed away from its usual operating regime using pharmacological agents, it usually loses both these hallmarks,[8, 9] and the efficiency of its information encoding and transmission is reduced.[10]

THE PHILOSOPHER GILLES DELEUZE and psychiatrist Felix Guattari contended that the brain's main function is to protect us, like an umbrella, from chaos. It seems to have done so by exploiting chaos itself. At the same time, neural networks are also capable of near-perfect reliability, as with the beating heart. Order and disorder enjoy a symbiotic relationship, and a neuron's firing may wander chaotically until a memory or perception propels it into an attractor. Sensory input would then serve to "stabilize" chaos. Indeed, the presentation of a stimulus reduces variability in neuronal firing across a surprising number of different species and systems,[11] as if a high-dimensional chaotic trajectory fell into an attractor. By "taming" chaos, attractors may represent a strategy for maintaining reliability in a sensitive system.[12] Recent theoretical and experimental studies of large networks of independent oscillators have also shown that order and chaos can co-exist in surprising harmony, in so-called chimera states.[13]

The current research paradigm in neuroscience, which considers neurons in a snapshot of time as stationary computational units, and not as members of a shifting dynamical entity, might be missing the mark entirely. If chaos plays an important role in the brain, then neural computations do not operate as a static read-out, a lockstep march from the transduction of photons to the experience of light, but a high-dimensional dynamic trajectory as spikes dance across the brain in self-choreographed cadence.

While hundreds of millions of dollars are being funneled into building the connectome—a neuron-by-neuron map of the brain—scientists like Eve Marder have argued that, due to the complexity of these circuits, a structural map alone will not get us very far. Functional connections can flicker in and out of existence in milliseconds. Individual neurons appear to change their tuning properties over time[14, 15] and thus may not be "byte-addressable"—that is, stably represent some piece of information—but instead operate within a dynamic dictionary that constantly shifts to make room for new meaning. Chaos encourages us to think of certain disorders as dynamical diseases, epileptic seizures being the most dramatic example of the potential failure of chaos.[16] Chaos might also serve as a signature of brain health: For example, researchers reported less chaotic dynamics in the dopamine-producing cells of rodents with brain lesions, as opposed to healthy rodents, which could have implications in diagnosing and treating Parkinson's and other dopamine-related disorders.[17]

Economist Murray Rothbard described chaos theory as "destroying math from within." It usurps the human impulse to simplify, replacing the clear linear relationships we seek in nature with the messy and unpredictable. Similarly, chaos in the brain undermines glib caricatures of human behavior. Economists often model humans as "rational agents": hedonistic calculators who act for their future good. But we can't really act out of self-interest—though that would be a reasonable thing to do—because we are terrible at predicting what that is. After all, how could we? It's precisely this failure that makes us what we are.

KELLY CLANCY studied physics at MIT, then worked as an itinerant astronomer for several years before serving with the Peace Corps in Turkmenistan. As a National Science Foundation fellow, she recently finished her Ph.D. in biophysics at the University of California, Berkeley. She will begin her postdoctoral research at Biozentrum in Switzerland this fall.

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“TO PREDICT TURBULENCE, JUST COUNT THE PUFFS”
BY PING ZHU

The Scientific Problem That Must Be Experienced

To understand turbulence we need the intuitive perspective of art

BY PHILIP BALL

WHEN THE GERMAN PHYSICIST Arnold Sommerfeld assigned his most brilliant student a subject for his doctoral thesis in 1923, he admitted that "I would not have proposed a topic of this difficulty to any of my other pupils." Those others included such geniuses as Wolfgang Pauli and Hans Bethe, yet for Sommerfeld the only one who was up to the challenge of this subject was Werner Heisenberg.

Heisenberg went on to be a key founder of quantum theory and was awarded the 1932 Nobel Prize in physics. He developed one of the first mathematical descriptions of this new and revolutionary discipline, discovered the uncertainty principle, and together with Niels Bohr engineered the "Copenhagen interpretation" of quantum theory, to which many physicists still adhere today.

The subject of Heisenberg's doctoral dissertation, however, wasn't quantum physics. It was harder than that. The 59-page calculation that he submitted to the faculty of the University of Munich in 1923 was titled "On the stability and turbulence of fluid flow."

Sommerfeld had been contacted by the Isar Company of Munich, which was contracted to prevent the Isar River from flooding by building up its banks. The company wanted to know at what point the river flow changed from being smooth (the technical term is "laminar") to being turbulent, beset with eddies. That question requires some understanding of what turbulence is. Heisenberg's work on the problem was impressive—he solved the mathematical equations of flow at the point of the laminar-to-turbulent change—and it stimulated ideas for decades afterward. But he didn't really crack it—he couldn't construct a comprehensive theory of turbulence.

Heisenberg was not given to modesty, but it seems he had no illusions about his achievements here. One popular story goes that he once said, "When I meet God, I am going to ask him two questions. Why relativity? And why turbulence? I really believe he will have an answer for the first."

ART BY GOH SHIGETOMI

It is probably an apocryphal tale. The same remark has been attributed to at least one other person: The British mathematician and expert on fluid flow, Horace Lamb, is said to have hoped that God might enlighten him on quantum electrodynamics and turbulence, saying that "about the former I am rather optimistic."

You get the point: turbulence, a ubiquitous and eminently practical problem in the real world, is frighteningly hard to understand. Nearly a century after Heisenberg, scientists are still trying to figure it out. And it's still a cutting-edge problem: Russian mathematician Yakov Sinai won the 2014 Abel Prize for mathematics—often seen as the Nobel of math—partly for his work on turbulence and chaotic flow.

Yet I propose that to fully articulate and understand turbulence we need to add the intuitive, contemplative perspective of art to the detailed analysis of science. There is a long-standing dialogue between art and science on this elusive problem. It is no coincidence the science of turbulence has often been forced to fall back on qualitative, descriptive accounts, while art that celebrates turbulence sometimes resembles a quasi-scientific gathering of data and idealization of form: a search for underlying patterns and regularities.

The interplay of the two perspectives can enhance both. Intuition of turbulent flow can serve the mathematician and the engineer, while careful observation and even experiment can benefit the artist. Scientists tend to view turbulence as a form of "complexity," a semi-technical term which just tells us there is a lot going on and that everything depends on everything else—and that a reductionist approach therefore has limits. But rather than regarding turbulence as a phenomenon awaiting a complete mathematical description, we should see it as one of those concepts, like life, love, language, and beauty, that overlaps with science yet is not wholly contained within it. Turbulence has to be experienced to be grasped.

We should see turbulence as one of those concepts, like life, love, language, and beauty, that overlaps with science yet is not wholly contained in it.

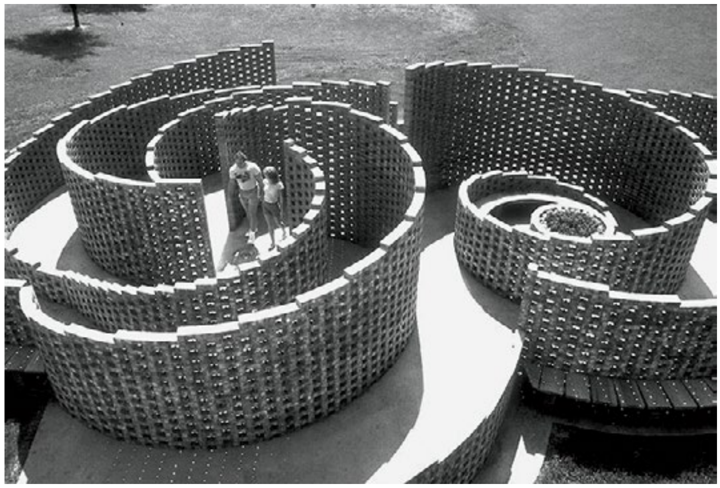
Into the Storm

Pretty much all scientific histories of the problem of turbulence start in the same place: with the sketches of wild water flows made by Leonardo da Vinci in the 15th century. What Leonardo was up to was rather profound. In the words of art historian Martin Kemp, Leonardo regarded nature "as weaving an infinite variety of elusive patterns on the basic warp and woof of mathematical perfection."

Leonardo was trying to grasp those patterns. So when he drew an analogy between the braided vortices in water flowing around a flat plate in a stream, and the braids of a woman's hair, he wasn't just saying that one looks like the other—he was positing a deep connection between the two, a correspondence of form in the manner that Neoplatonic philosophers of his age deemed to exist throughout the natural world. He saw fluid flow as a static, almost crystalline entity: His sketches have a solidity to them, seeming almost to weave water into ropes and coils.

Yet what mattered was not the superficial and transient manifestations of these forms but their underlying essence. Leonardo didn't imagine that the artist should be painting "what he sees," but rather what he discerns within what he sees. It behooves the artist to invent: painting is "a subtle inventione with which philosophy and subtle speculation considers the natures of all forms." That's not a bad definition of science either, when you think about it.

Still, it would take centuries for science to develop Leonardo's ideas about turbulent flow. It's not hard to see why—and I mean that literally. When you look at a turbulent flow—cream being stirred into coffee, say, or a jet of exhaled air traced out in the smoke of a cigarette—you can see that it is full of structure, a profound sort of organization made up of eddies and whirls of all sizes that coalesce for an instant before dissolving again. That's rather different to what we imply in the colloquial use of the word to describe, say, a life, a history, or a society. There we tend to mean the



GOING WITH THE FLOW With public works like *Marianthe*, made of brickwork and cedar, American artist Athena Tacha invites people inside turbulent forms to experience them as if they were a particle borne along in the flow.

thing in question is chaotic and random, a jumble within which it is difficult to identify any cause and effect. But pure randomness is not so hard to describe mathematically: It means that every event or movement in one place or at one time is independent of those at others. On average, randomness blurs into dull uniformity.

A turbulent flow is different: It does have order and coherence, but an order in constant flux. Flows of fluids—liquids and gases—generally become turbulent once they start flowing fast enough. When they flow slowly, all of the fluid moves in parallel, rather like ranks of marching soldiers. But as the speed increases, the ranks break up. You could say that the "soldiers"—little parcels of fluid—begin to bump into one another or move sideways, and so swirls and eddies begin to form.

This transition to turbulence doesn't happen at the same flow speed for all fluids—more viscous ones can be "kept in line" at higher speeds than runny ones. For flow down a channel or pipe, a quantity called the Reynolds number determines when turbulence appears. Roughly speaking, this encodes the ratio of the flow speed to the viscosity of the fluid. Turbulence develops at high values of the Reynolds number. The quantity is named after Osborne Reynolds, an Anglo-Irish engineer whose pioneering work on fluid flow in the 19th century provided the foundation for Heisenberg's work.

Many of the flows we encounter in nature—in rivers and atmospheric air currents like the jet streams—have high Reynolds numbers. The eddies and knots of air turbulence can make for a bumpy ride when an aircraft passes through them.

Turbulence provides a perfect example of why a problem is not solved simply by writing down a mathematical equation to describe it. Such equations exist for all fluid flows, whether laminar or turbulent: They are called the Navier-Stokes equations, and they amount largely to an expression of Isaac Newton's second law of motion (force equals mass times acceleration) applied to fluids. These equations are the bedrock of the modern investigation of flow in the science of fluid dynamics.

The problem is that, except in a few particularly simple cases, the equations can't be solved. Yet it's those solutions, not the equations themselves, that describe the world. What makes the solutions so complicated is that, crudely speaking, each part of the flow depends on what all the other parts are doing. When the flow is turbulent, this interdependence is extreme and the flow becomes chaotic, in the technical sense that the smallest disturbances at one time can lead to completely different patterns of behavior at a later moment.

A New Confluence

The constant appearance and disappearance of pockets of organization in a disorderly whole has a beautiful, mesmerizing quality. For this reason, turbulence is as irresistible to artists as it is intransigent to scientists.

Leonardo's representations of fluid flow found few takers in the West. But a comparable tradition of seeking fundamental forms in the changing flux was already well developed in Eastern Asia. In the late 17th century, the Chinese painter Shitao drew an analogy between water waves and mountain ranges—a comparison that is explicitly rendered by Shitao's friend Wang Gai in *The Mustard-Seed Garden Manual of Painting*. Here the serried ranks of waves could almost be the limestone peaks of Guilin, while the frothy tendrils of breaking wave-crests recall the pitted and punctured pieces of rock with which Chinese intellectuals loved to adorn their gardens.

For Chinese artists, the forms of turbulent flow were defined by the ebb and flow of a natural energy called *qi*, which supplies the creative spontaneity of Taoist philosophy. The artist captured this energy not with slow, meticulous attention to detail, but with a free movement of the wrist that imparted qi to the watery ink on the brush and to the trace it left on silk. The wrist, Shitao wrote, should be "flowing deep down like water." It is this insistence on dynamic change that makes Chinese art a profound meditation on turbulence.

One can't help noticing how its traditional schema for depicting flow resemble the attempts of modern fluid dynamicists to capture the essentials of complex flow in so-called streamlines, which, to a rough approximation, trace the trajectories of particles borne along in the fluid. Are these resemblances more than superficial and coincidental? I think so: They express a recognition that turbulent flows contain orderly patterns and forms, and that these have to be visualized in order to be appreciated.

However, for scientists in the 20th century, this "deep structure" of turbulence became increasingly an abstract, mathematical notion. One of the key advances in the science of turbulence came from the Soviet mathematical physicist Andrei Kolmogorov, under whose guidance Sinai began his work in the 1950s. By this time, turbulence was regarded as a hierarchy of eddies of all different sizes, down which energy cascades from the largest to the smallest until ultimately being frittered away as heat in the friction of molecules rubbing viscously against one another. This picture of turbulence was famously captured by the English mathematician Lewis Fry Richardson, another pioneer of turbulence theory, in a 1922 poem indebted to Jonathan Swift:

Big whirls have little whirls
That feed on their velocity,
And little whirls have lesser whirls
And so on to viscosity.

In the 1940s Kolmogorov calculated how much energy is bound up in the eddies of different sizes, showing that there is a rather simple mathematical relationship called a power law that relates the energy to the scale: Each time you halve the size of eddies, the amount of energy contained in all the eddies of that size decreases by some constant factor. This idea of turbulence as a so-called spectrum of different energies at different size scales is one that was already being developed by Heisenberg's work on the subject. It's a very fruitful and elegant way of looking at the problem, but one in which the actual physical appearance of turbulent flow is subsumed into something much more recondite. Kolmogorov's analysis can supply a statistical description of the buffeting, swirling masses of gases in the atmospheres of planets—but what we see, and sometimes what concerns us most, is the individual vortices of a tropical cyclone on Earth or the Great Red Spot on Jupiter.

But there were, at the same time, stranger currents at play. While Heisenberg was juggling with equations, an Austrian forest warden named Viktor Schauberger was grappling toward a more intuitive understanding of turbulent flow. Schauberger's interest in the subject arose in the 1920s from his wish to improve log flumes so that they didn't get jammed as they carried timber through the forest. This led him to develop an idiosyncratic theory of turbulent vortices which mutated into something akin to a theory of everything: a view of how energy pervades the universe, which alleged to yield Einstein's $E=mc^2$ as a special case. It is said that Schauberger was forced by the Nazis to work on secret weapons related to his "implosion theory" of vortices, and even that he was taken for an audience with Hitler. After the war Schauberger was brought to the United States, where he was convinced that all his ideas were being stolen for military use.

Inevitably this is the stuff of conspiracy theory—Schauberger is said to have designed top-secret flying saucers powered by turbulent vortices. The spirit of his approach can be discerned also in the ideas of the German anthroposophist Theodor Schwenk in the 1950s and '60s. Schwenk claimed that his work was "based on scientific observations of water and air but above all on the spiritual science of Rudolf Steiner," and he believed that the flow forms of water, and in particular the organization of vortices, reflects the wisdom of a teleological, creative nature. These "flow forms," he said, are elements of a "cosmic alphabet, the word of the universe, which uses the element of movement in order to bring forth nature and man."

Schauberger and Schwenk were not doing science; it is not unduly harsh to say that, in the way they clothed their ideas in arcane theory disconnected from the scientific mainstream, they were practicing pseudo-science. Their appropriation by New Age thinkers today reflects this. But we shouldn't be too dismissive of them on that account. One way to look at their work is as an attempt to restore the holistic, contemplative attitude exemplified by Leonardo to a field that seemed to be retreating into abstruse mathematics.

The gorgeous photographs of complex flow forms, of turbulent plumes and interfering waves and rippled erosion features in sand, in Schwenk's 1963 book *Sensitive Chaos*, offered a reminder that *this* was how flow manifests itself to human experience, not as an energy spectrum or hierarchical cascade. Such images seem to insist on a spontaneous natural creativity that is a far cry from the deterministic mechanics of a Newtonian universe. Schwenk himself suggested that representations of vortices and waves in primitive art, such as the stone carvings on the Bronze Age burial chamber at Newgrange, Ireland, were intuitions of the fecund cosmic language of flow forms.

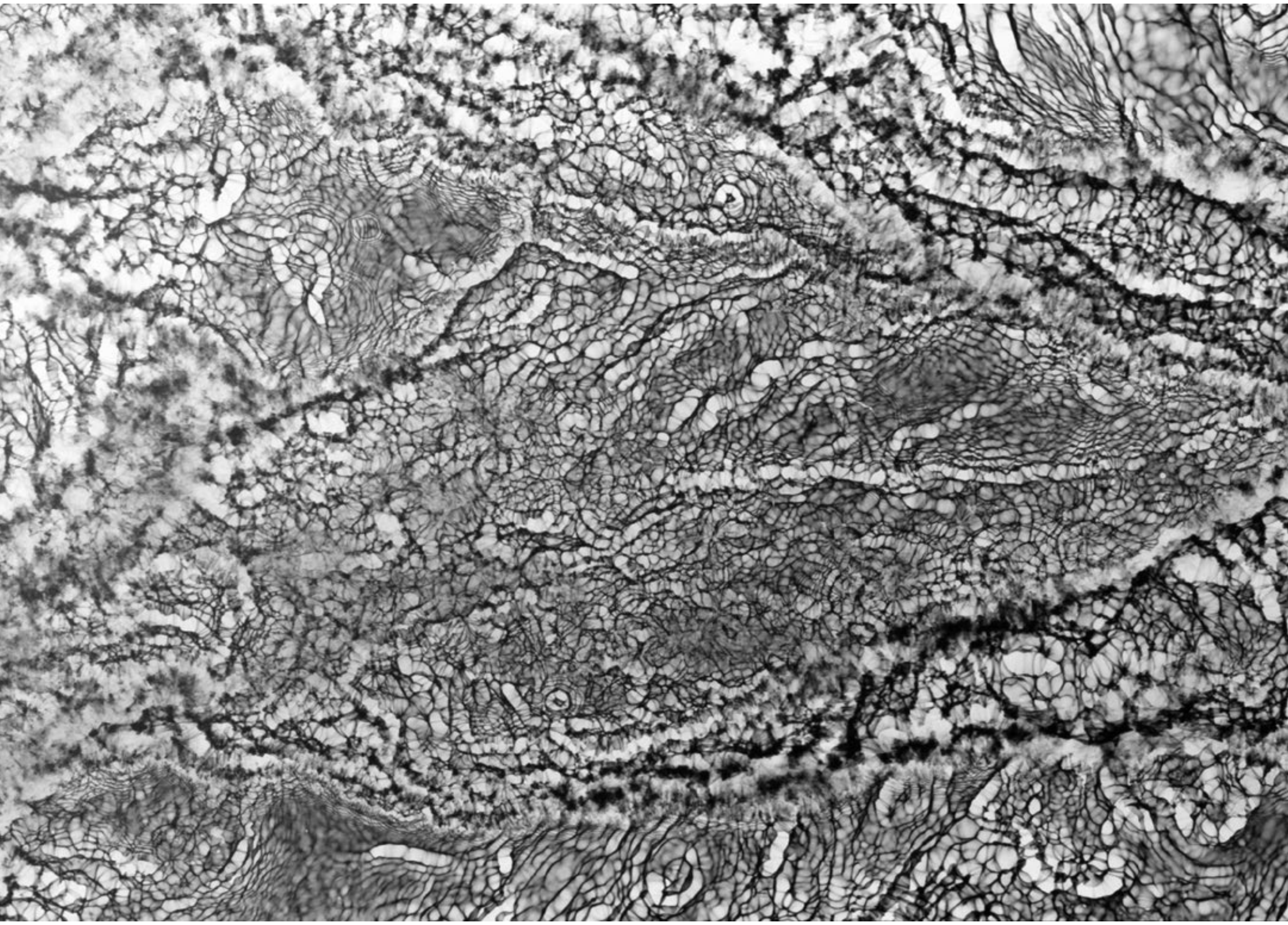
Flow on Film

However sniffy scientists might be about Schauberger and Schwenk, their ideas have captivated artists and designers, and continue to do so. The contemporary British artist Susan Derges, who has made several works concerned with waves and flow in water, says that she was inspired by their ideas. Growing up beside the Basingstoke Canal in southern England, Derges spent a lot of time exploring the towpath walks. "I was intrigued by the mixture of orderly patterning and interference set up by barges and bird life moving through the water," she says. She began to explore how waves and interference patterns give rise to orderly, stable patterns: "It was a way of revealing a sense of mysterious but ordered processes behind the visible world."

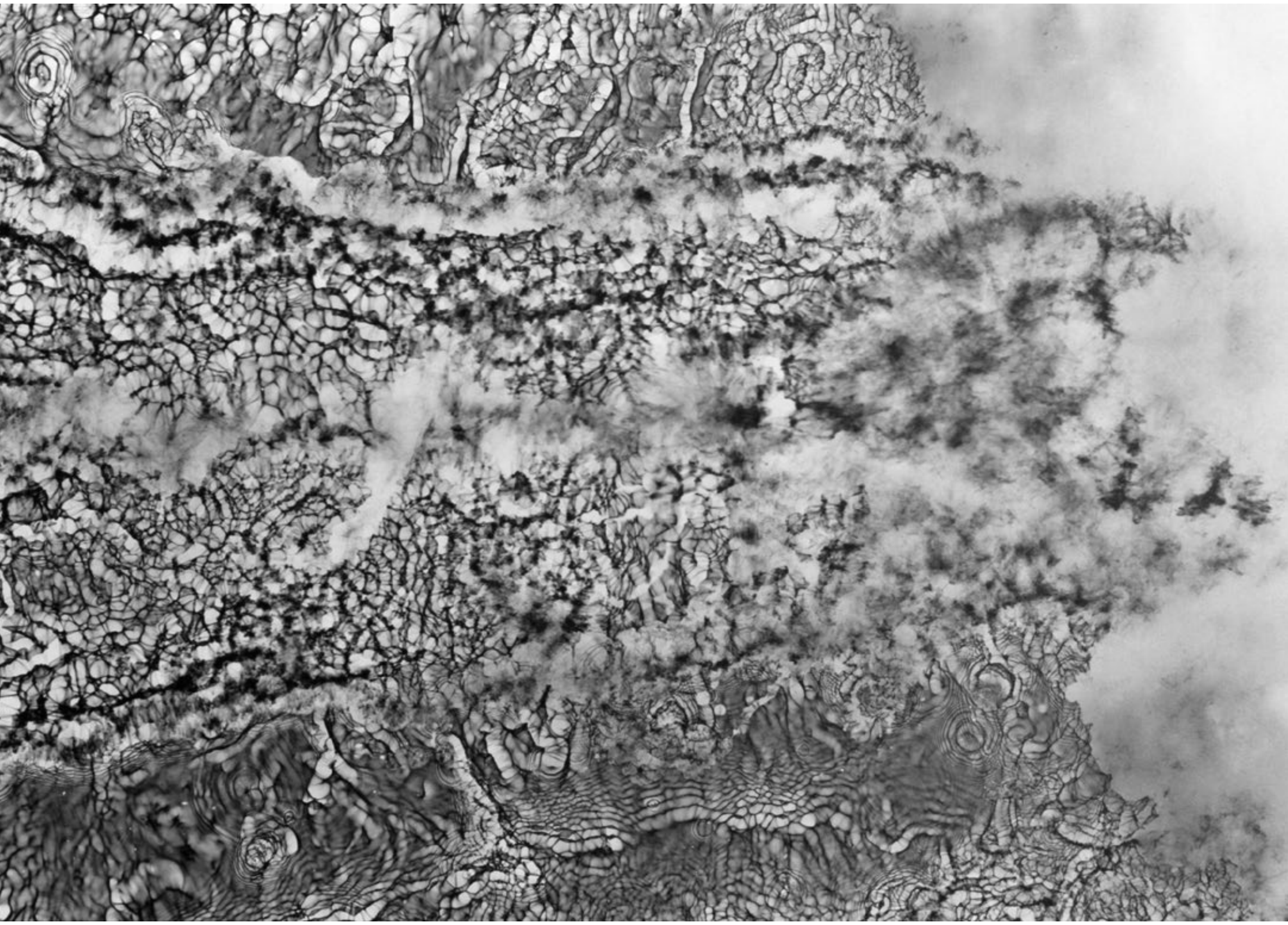
When she moved to Dartmoor in southwest England in the 1990s, Derges encountered the torrent rivers coming down from the high moor. "I found it fascinating that a huge amount of energy, momentum, and complex, chaotic movement could give rise to stable vortices and flow forms that remained in areas of the river's course," she says. "It seemed to suggest a metaphor for how one might consider all apparently constant and solid appearances as being sustained by a more fluid energetic underlying process."

In a series of works in the 1990s, Derges captured these turbulent structures in the *River Taw on Dartmoor* by placing large sheets of photographic paper, protected with a waterproof covering, just beneath the water surface at night and exposing them with a single bright flash of light. In her inspiration, motives, and techniques, there is little distance between what Derges did and what an experimental scientist might do: Such "shadowgraphs" are commonly used by fluid dynamicists to capture and study flow structures. But for Derges this "data gathering" becomes an artistic moment.

Like Derges, American artist Athena Tacha was inspired by Leonardo's sketches of vortices, a debt that she made particularly explicit in her 1977 sculpture maquette *Eddies/Interchanges* (*Homage to Leonardo*). Much of Tacha's work over the past several decades is an enquiry into the deep structures of turbulent flow,



THE ART OF DATA To create *River Taw 22 January 1998*, British artist Susan Derges placed a large sheet of photographic paper just beneath the River Taw at night and exposed it with a flash of light. Such "shadowgraphs" are also used to study fluid dynamics.



which she often reduces to their abstract essence and transforms into something more permanent and rigid. Because her work includes large-scale public commissions, these architectural sculptures allow people to literally get inside the forms and experience them as if they were a particle borne along in the flow. They include, in the brickwork-trellis maze of *Mariathne* (1985-6) and the stepped crescent forms of the terraced courtyard space *Green Acres* (1985-7). If you want a visceral sense of the real tantalizing confusion of a turbulent maelstrom, no scientific description will improve on Tacha's photographic series such as *Chaos* (1998).

"I think I respond to turbulence because I am generally interested in fluid forms that evoke the state of 'chaos' in nature—which I consider a different kind of *order*, with constant irregularities and changes, but ultimately extremely organized," Tacha says. Kolmogorov and his scientific successors would find little to object to in that claim.

Nothing, perhaps, better captures the sense of a flow frozen into an instant than Tacha's sculpture *Wave*, which allows the viewer to experience the terrifying beauty of Japanese artist Hokusai's *Great Wave* (c. 1831-33) without fear of being pulled under. If this work hints at the connection to an East Asian appreciation of flow, that context is unmistakable in the work of contemporary Japanese artist Goh Shigetomi. Shigetomi has found a way to disperse black sumi ink into natural streams so that it can imprint an image of the flow on paper. He modestly equivocates about his status as an artist at all, since, as he puts it, the water itself "spontaneously draws lines." Only the right ink and the right paper (Japanese rice paper) will work, and it took years of experimentation to refine the technique.

The results are unearthly, and Shigetomi expresses them in almost magical terms, reminiscent of Schwenk: "'New-born' water is full of infinite live force." He believes that "the water remembers every single thing which has happened on and around the earth," and that one can see "the fragments of the memories in flows and movements of water as certain patterns."

Can these claims be in any sense true from a scientific viewpoint? Not obviously; they seem closer to a form of thaumaturgy, of divination from natural symbols. (Shigetomi literally believes that a "spirit of water" is sending him messages.) But the complexity of the inky traceries, when seen firsthand, are richer and more subtle than anything I have seen in a strictly scientific photograph. They seem to conjure up much more than a cold physical trace of the technical process of their production. I find it hard not to see these "water figures" as an extension of Shitao's instruction that the painter must find a spontaneous, unforced way of applying ink to paper, a way that captures the dynamic force of *qi*. Shigetomi explains that it takes a finely developed sensibility to make these "experiments" work—one cultivated by 38 years of standing in rivers, waiting for the right moment. Derges says the same: "I had to be very aware of the tide and the wave patterns... One would watch and wait for the seventh wave and one needed split second timing." These artists have developed the same patient, observant sensitivity to flow that characterizes both the meditations of the Chinese Tang Dynasty water poets Li Bai and Du Fu and the sketches of Leonardo.

But can this attitude of contemplative observation, rather than careful testing and measurement, serve the scientist too? Certainly it can. In 1934 the French mathematician Jean Leray proved that the Navier-Stokes equations have so-called "weak" solutions, meaning that there are solutions that satisfy the equations on average but not in detail at every point in space: flow patterns that "fit," you could say, so long as you don't examine them with a microscope. And Leray is said to have found much of his inspiration for this mathematical tour de force not by poring over his desk into the small hours but by leaning over the Pont-Neuf in Paris and watching, hour after hour, the eddies of the Seine surging around the piles.

Order and Chaos

There is, however, a more dramatic example of how these intuitions of the form of turbulence can cross boundaries between art and science. One of the most striking and certainly famous artistic depictions of turbulence is Vincent van Gogh's *Starry Night* (1889). It is a fantastical vision, of course—the night sky is not really alive with these swirling stellar masses, at least not in a way that the eye can see. But spiral galaxies and stellar nebulae were known in van Gogh's day, having been revealed in particular by the telescopic studies of William Herschel 100 years earlier. It is tempting to

A sensitive and receptive artist can penetrate to the core of a complex phenomenon, even if the result falls short of a scientific account.

conclude that van Gogh's notion of a turbulent heavens was simply a metaphor for his tumultuous inner world—but whether or not this is so, the artist seems to have had a startlingly accurate sense of what turbulence is about.

Kolmogorov's work showed how to relate the velocity of the flow at one point to that at some other point a certain distance away: something that varies from place to place but which has a constant mathematical relationship on average. In 2006, researchers in Mexico, led by physicist Jose Luis Aragon of the National Autonomous University in Mexico City, showed that this same relationship deduced by Kolmogorov also describes the probabilities of differences in brightness, as a function of distance, between points in *Starry Night*. The same is true of some of van Gogh's other "swirly" works, such as *Road with Cypress and Star* (1890) and *Wheat Field with Crows* (1890). These paintings offer a way to visualize an otherwise recondite and hidden regularity of turbulence: They show us what Kolmogorov turbulence "looks like."

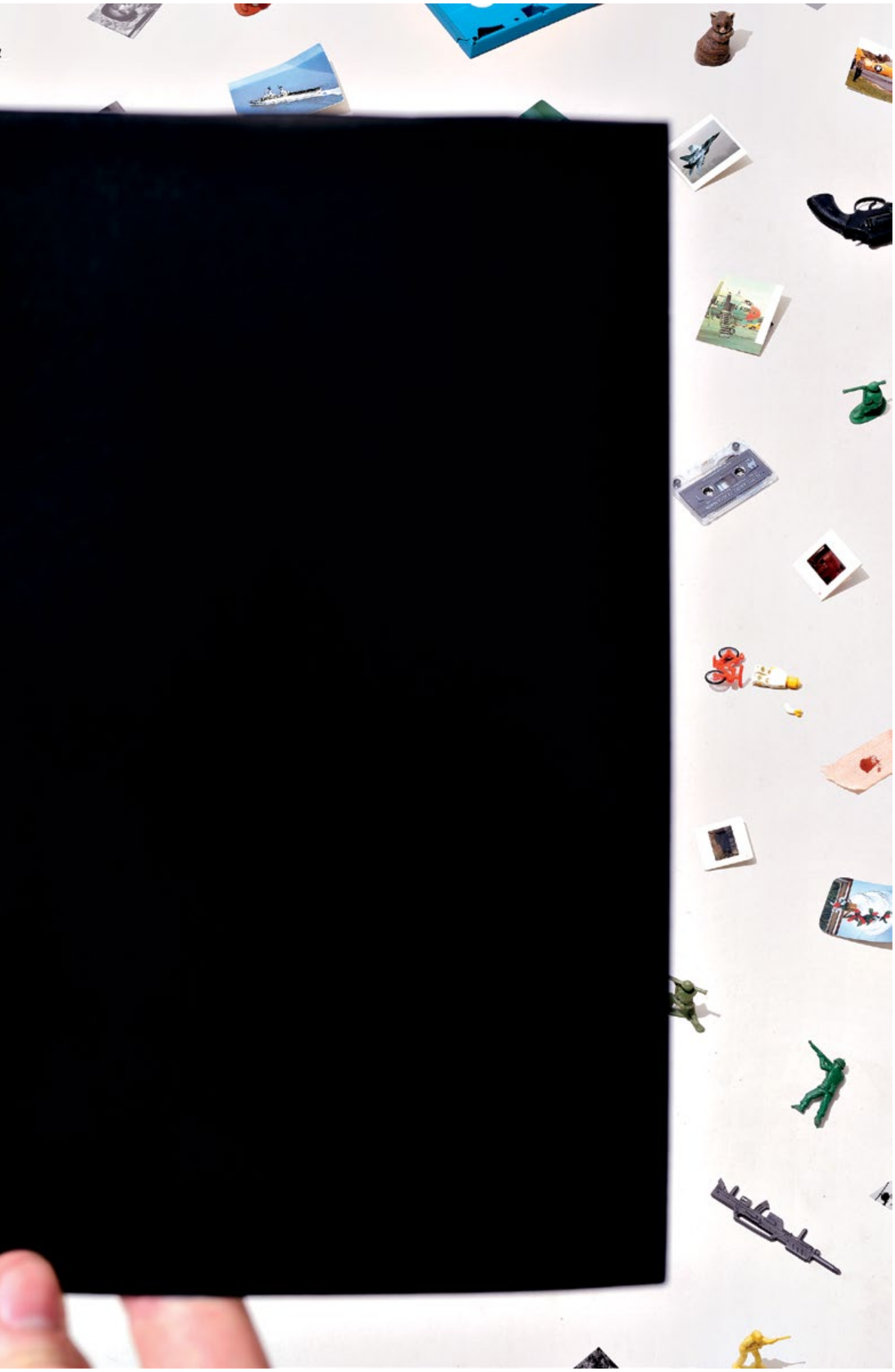
These works were created when van Gogh was mentally unstable: The artist is known to have experienced psychotic episodes in which he had hallucinations, minor fits, and lapses of consciousness, perhaps indicating epilepsy. "We think that van Gogh had a unique ability to depict turbulence in periods of prolonged psychotic agitation," says Aragon. Any psychological explanation is sure to be tendentious, but the connection does seem to be more than just chance—other, superficially similar paintings such as Edvard Munch's *The Scream* don't have this mathematical property connecting the brush strokes, for example.

Of course, it would be absurd to suggest that van Gogh had somehow intuited Kolmogorov's result before the Russian mathematician deduced it. But the incident does imply that a sensitive and receptive artist can penetrate to the core of a complex phenomenon, even if the result falls short of a scientific account. That, I think, is what Derges is implying when she suggests that the most revealing images of turbulent flow patterns "need to be situated in between something that has been closely observed and something that has been emotionally experienced."

Some scientists agree. Last fall, physical oceanographer Larry Pratt of the Woods Hole Oceanographic Institution in Massachusetts and performing artist Liz Roncka led a workshop near the Massachusetts Institute of Technology (MIT) in Cambridge in which the participants, mostly mathematicians and scientists, were encouraged to dance their interpretation of turbulence. As Genevieve Wanucha, science writer for the "Oceans at MIT" program, reported, Pratt "was able to improvise complex movements that responded fluidly to the motion of his partner's body, inspired by obvious intuition about turbulence." Wanucha explains that Pratt uses dance "as a teaching tool to elegantly and immediately represent to the human mind how eddies transport heat, nutrients, phytoplankton, or spilled oil down beneath the ocean surface." He believes the approach will help young scientists working on ocean flows to "gain a more intuitive understanding" of their work.

An intuitive understanding has been an essential part of any great scientist's mental toolkit. It is what has motivated researchers to make physical models and draw pictures, immerse themselves in virtual sensory environments that display their data, and create "haptic interfaces" that let them feel their way to understanding. I daresay that dance and other somatic experiences could also be valuable guides to scientists. This interplay of art and science should be especially fruitful when applied to a question like turbulence that is so hard to grasp, so elusive and ephemeral yet also governed and permeated by an underlying regularity. How, one wonders, might Heisenberg have fared if he had set aside his calculations and picked up a sketchbook?

PHILIP BALL is the author of *Serving the Reich* and many books on science and art.



“IF TRAUMA VICTIMS FORGET, WHAT IS LOST TO SOCIETY?”
BY ANDREW B. MYERS

Cloudy With a Chance of War

His weather forecasts changed the world. Could his predictions of war?

BY DAVID BERREBY

THE BURIAL DETAIL, which had come for the corpses in the pigpen, was surprised. The "dead" were getting up and speaking English. *Qu'est-ce que c'est?* Ah, they were an ambulance crew. British volunteers, in the trenches with the French Army on the Western Front. In the ruins and wreckage near the front lines, they'd found nowhere else to sleep.

The medical corpsmen were all pacifists, serving humanity even as they refused to serve in any military. Still, they lived like the troops. They bunked in rat-infested dugouts, on the floors of shelled buildings, in hay-filled barns. They dove for cover when incoming shells moaned and screamed, and struggled with their masks when the enemy fired gas canisters. At any moment, they could be called to go to the front lines, gather wounded men, and drive—lights off on roads cratered by shells, packed with trucks and troops, with every jostle making the blood-soaked soldiers in the back cry out in pain—to a hospital.

It was the last place in the world to look for a scientist at work. Yet one soft-spoken corpsman, known as "Prof," filled his downtime with experiments and calculations. "We thought nothing of seeing him wandering about in the small hours checking his instruments," one of his fellow corpsmen recalled. Once, for example, he'd set a bowl of water on a record-player he had somehow got hold of, cranked up the machine, and measured the radius of the curve on the water's surface. A rotating fluid, he thought, might serve as a useful model of the atmosphere. (Though his record player wasn't up to the task, later work would prove him right.)

"Prof" was the English physicist and mathematician Lewis Fry Richardson, for whom doing science came as naturally as breathing. "It was just the way he looked at the world," recalls his great-nephew, Lord Julian Hunt. "He was always questioning. Everything was an experiment." Even at the age of 4, recounts his biographer Oliver Ashford in *Prophet or Professor? Life*

ILLUSTRATION BY JOSH COCHRAN

and Work of Lewis Fry Richardson, the young Lewis had been prone to empiricism: Told that putting money in the bank would "make it grow," he'd buried some coins in a bank of dirt. (Results: Negative.) In 1912, the now-grown Richardson had reacted to news of the Titanic's sinking by setting out in a rowboat with a horn and an umbrella to test how ships might use directed blasts of noise to detect icebergs in fog. (Onlookers might have shaken their heads, but Richardson later won a patent for the fruit of that day's work.) Nothing—not fellow scientists' incomprehension, the distractions of teaching, or even an artillery bombardment—could dissuade him when, as he once put it, "a beautiful theory held me in its thrall."

In 1916, *two* beautiful ideas gripped Richardson's attention. At the heart of both was the complex interplay of predictability and randomness that is turbulence.

His first idea was rooted in his principles as a Quaker pacifist who believed "science should be subordinate to morals." Everyone spoke of this Great War as if it had been a catastrophic surprise. Who could predict a lone assassin in Sarajevo? Or that the belligerents would not find a way to defuse the crisis, as they had before? Or that plans for a quick victory would sour into this stalemate in the trenches? War, Richardson thought, far from being an unforeseeable accident, might instead be the consequence of as-yet-unknown laws operating on measurable facts. Beneath its seemingly random and chaotic course were the regular patterns of these laws. With the right data and the right equations war might be predictable—and thus preventable. He believed that humanity could some day avoid war as ships could some day avoid hidden icebergs.

Whenever he could, in quiet moments or when his ambulance corps was rotated to the rear for a rest, Richardson worked on a long paper on "the mathematical psychology of war." ("I remember him telling me, 'let *x* be the will to hate,' " recalled one of his less equation-oriented friends in the unit. "It beat me!")

But it was Richardson's other great idea that would come to fruition first, and make him famous. In fact, after many decades of obscurity it would come to be appreciated as one of the most significant technologies of the 20th century. At the front lines, and in the rest billets where the corps was rotated out for a break every few weeks, Richardson was looking for a way to forecast the weather.

AT THE TURN OF the last century, the notion that the laws of physics could be used to predict weather was a tantalizing new idea. The general idea—model the current state of the weather, then apply the laws of physics to calculate its future state—had been described by the pioneering Norwegian meteorologist Vilhelm Bjerknes. In principle, Bjerknes held, good data could be plugged into equations that described changes in air pressure, temperature, density, humidity, and wind velocity. In practice, however, the turbulence of the atmosphere made the relationships among these variables so shifty and complicated that the relevant equations could not be solved. The mathematics required to produce even an initial description of the atmosphere over a region (what Bjerknes called the "diagnostic" step) were massively difficult.

To get a forecast without stumbling on the impossible calculus of the differential equations, Bjerknes represented atmospheric changes using charts. For example, as the historian Frederik Nebeker explains in *Calculating the Weather: Meteorology in the 20th Century*, the chart might show more air flowing horizontally

A NUMBERS MAN Richardson believed numbers cut through the cant of war. "Counting is an antiseptic against prejudice," he said. He toted up "deadly quarrels" of every type from 1820 onward. Once, explaining the algebra of violence to a war buddy, he said, "Let *x* be the will to hate."

Many scientists would not publish such a resounding dud of an experiment. But the Quaker and scientist in Richardson valued plain honesty over self-promotion.

into a region than out, allowing the forecaster to predict that the remainder of the incoming air is flowing upward in the form of vertical winds.

As it happened, since Richardson's graduation from Cambridge in 1903, he had confronted similarly difficult equations as he moved restlessly among posts in academia and industry. Analyzing stresses in dams and the flow of water through peat, he had developed a different work-around.

Only differential equations, with their infinitely small quantities changing over infinitely small units of time, described the continuous change he wanted to model. But since those equations couldn't be solved, Richardson reworked the math to replace the infinitesimals of calculus with discrete measurements occurring at discrete time intervals. Like a series of snapshots of a ball flying through the air, Richardson's "finite difference" equations only approximated the reality of the constant change they described. But they could be solved, with simple algebra or even arithmetic. And their solutions would be far more precise than any obtained with a chart.

Richardson's finite-difference work had been too novel and unfamiliar to win him a research post at a major university. But in 1913, it helped get him a plum job: directing a research laboratory for Britain's Meteorological Office, which hoped Richardson would bring both rigorous thinking and practical lab skills to the search for accurate weather forecasts. Here, with a good salary, a house to himself, and a lab far from any distractions, he would have ample time for research.

NOAA/WIKIPEDIA

The following year, however, the Great War arrived. At age 32, with his important research ongoing, Richardson could have kept to his agreeable job. Yet even as his principles would not permit him to serve in the military, he still felt he should take part in the war. "In August 1914," he later wrote, "I was torn between an intense curiosity to see war at close quarters, an intense objection to killing people, both mixed with ideas of public duty, and doubt as to whether I could endure danger." Rebuffed when he requested a leave of absence to serve in the ambulance corps, in 1916 he simply quit. A few weeks later, he and his slide rule, notes, and instruments were at the front.

And so for the next few years Richardson's theories of war and weather advanced in and around the combat zone. Over six weeks in 1916, with a bale of hay for his desk, Richardson patiently solved equation after equation for hundreds of variables. His aim was to demonstrate his method of "weather prediction by numerical processes" by creating a real forecast.

Richardson decided to do a "hindcast," so his results could be compared with real weather on a target date in the past. He chose the weather over Central Europe on May 20, 1910—a date for which Bjerknes had already published a trove of data about temperature, humidity, barometric pressure, and wind speed.

Richardson created a map of the atmosphere over the region, split into 25 equal-sized cells with sides of about 125 miles. Every block was further divided into five layers with about the same mass of air in each layer. (Because atmospheric density decreases with altitude, these layers were divided at heights of 2, 4, 7, and 12 kilometers above the ground.)

Richardson divided the 25 big blocks into two types: P cells, for which he recorded the atmospheric pressure, moisture, and temperature; and M cells, for which he calculated wind speed and direction. He alternated P and M cells on his grid, creating a sort of checkerboard. He could calculate the "missing" data for each cell by looking at the data of cells adjoining it. (For example, wind speed in an M cell could be deduced by pressure changes in the P cells that surrounded it.) Plugging all the available data from 7 a.m. into the equations, then patiently solving them for a time six hours later, he arrived at a "forecast" for conditions at 1 p.m.

Results: Negative. The recorded weather for the day

The Richardson number is used today to predict where turbulence will occur in both the atmosphere and the ocean.

showed Richardson's "forecast" was wrong. He had predicted a dramatic shift in wind speed and direction that didn't happen. He had also predicted a freakish rise in atmospheric pressure over Munich. In fact, the barometer had held steady that day.

Many scientists, then and now, would not publish such a resounding dud of an experiment. But the Quaker and scientist in Richardson valued plain honesty over self-promotion. And he believed the merit of the method would be obvious even if the first practical application needed work. When he published *Weather Prediction by Numerical Processes* in 1922 (see Forecast Factory), he described his disappointing results, in great detail.

Perhaps, Richardson wrote, the weather-balloon measurements he'd obtained were simply wrong. Or perhaps the gaps between measuring stations were too great (the finite-difference method needed sufficiently fine-grained data to approximate the continuous changes in weather, just as an adequate number of snapshots would be needed to portray the continuous motion of a ball). Another suspect was the need to interpolate data in cells where it was lacking. In fact, a few years ago, Peter Lynch of the Irish Meteorological Service showed that the trouble was simply that 1910 data-collection methods failed to correct for minor noise in the data. Richardson couldn't prove it, but his model worked.

BUT THERE WAS ANOTHER source of potential error, which Richardson realized required further research: the turbulence that knocked air out of predictable paths, sending eddies of air up or down or sideways, where they banged into other eddies, passing energy from whirl to whirl. Air that gets knocked around like this further disturbs the flow of things by creating smaller local currents that move in the opposite direction from the main stream. Finally, at the smallest scale, too little energy is left to overcome viscosity—the resistance to motion created by friction between individual molecules of air. More poetically, in the chapter devoted to turbulence in *Weather Prediction by Numerical Processes*, Richardson explained it this way: "Big whirls have little whirls that feed on their velocity; and little whirls have lesser whirls, and so on, to viscosity—in the molecular sense."

As Hunt explains in his introduction to Richardson's collected papers, in the first decades of the 20th century meteorologists didn't have a good grasp of turbulence, especially as it affected movements of air in the first 2 kilometers of the atmosphere. Turbulent eddies in this layer are crucial to weather prediction, because they carry heat and moisture up into the higher atmosphere and down toward the surface of the earth, shaping the weather.

For instance, Richardson had observed how fluctuations in wind speed seemed to depend on the difference in wind speeds at different heights and the difference in temperature at those heights. When ground temperature fell, resulting in a greater difference between ground temperature and temperatures higher up, wind fluctuations became less frequent. He concluded this was due to buoyancy forces caused by eddies moving through different temperature zones interacting with eddies moving through regions of different wind speeds. He devised an equation to predict the occurrence of turbulence based on a ratio of these two effects. As Giles Foden has written in *Turbulence*,

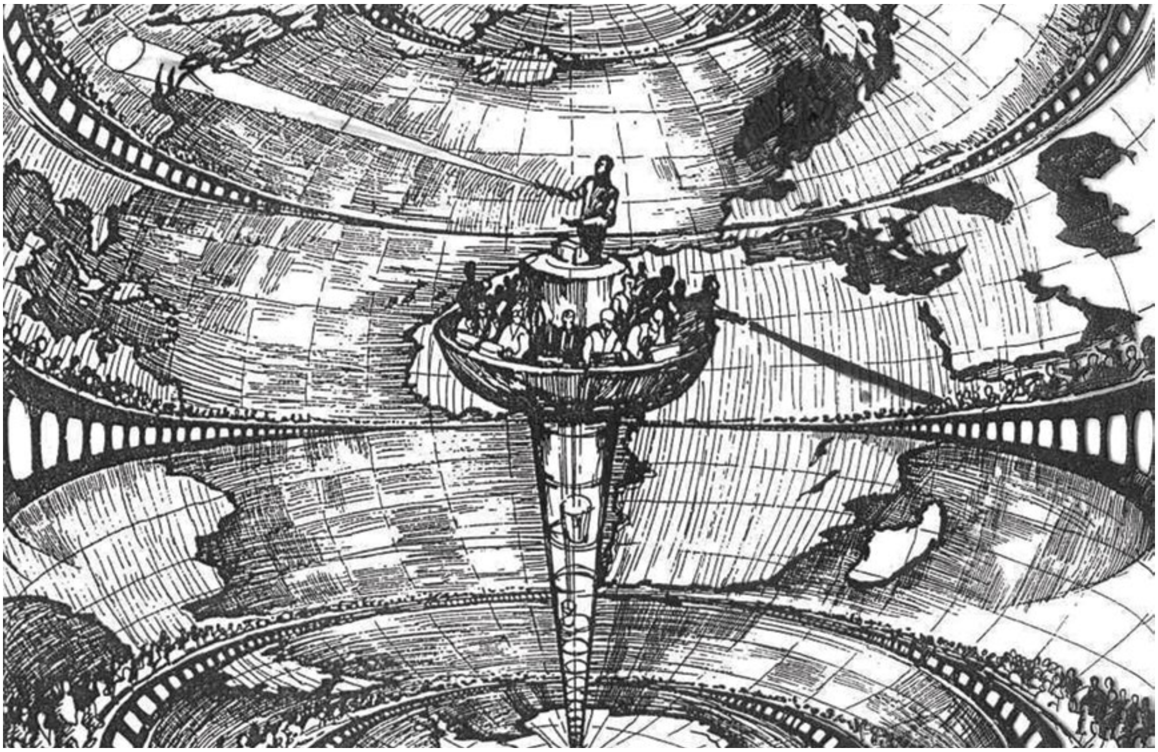


IMAGE COURTESY OF L. BENGTSSON/NOAA.GOV

FORECAST FACTORY In his seminal 1922 book, *Weather Prediction by Numerical Process*, Richardson imagined a large theater with 64,000 human "computers." Each would work on weather in one region, while their leader, "like a conductor of an orchestra" blended their work into a global forecast. Decades before "parallel processing" in computing, Richardson had hit on the concept.

his novel inspired by Richardson's work, the equation "dramatizes the relationship between wind and heat."

That ratio of heat energy to wind energy, now called the Richardson number, is used today to predict where turbulence will occur in both the atmosphere and the ocean. When the ratio is high, warmer air is adding energy, making more and larger eddies. Because the whirls of turbulence can be hundreds of miles wide or small enough only to bother a gnat, the Richardson number is "dimensionless"—it is not associated with any particular quantity. In other words, for turbulence, scale does not matter, as the same patterns are seen in the smallest and largest instances.

Of course, we experience turbulence differently when it is blowing a dust mote around than when it is creating a massive storm. Turbulence is, in fact, in the eye of the beholder. A pilot flying through eddies too small to bump his plane around will not notice them—the effect of all the tiny eddies is averaged out into a general sense that the ride is smooth. On the other hand, neither will he notice an enormous eddy that enfolds the entire plane, any more than a fish would notice the water in which it swims. As Richardson writes in *Weather Prediction*, a pilot who calls the air "turbulent" is noticing eddies that occur on a scale about the size of one airplane wing. In this sense, as Foden observes, "every so-called 'accident,' every piece of turbulence, is part of a sequence, bigger or smaller, whose scale you cannot see."

Richardson's turbulence research was quickly recognized in the 1920s, but his greatest meteorological insight—his forecasting method—was considered a failure. It was too difficult to do in real time, many thought, and it had not produced an accurate prediction. His proposal languished for decades before technology caught up with it. Only after the advent of computers capable of doing quick calculations did his numerical-process approach become the standard method for forecasting. Today, his technique remains the basis for weather forecasts and climate modeling.

Richardson often suffered from this sort of scientific "prematurity," as the mathematician and father of fractal geometry Benoit Mandelbrot put it. Mandelbrot knew this firsthand. In his quest to understand the role national boundaries play in causing wars, Richardson had written a paper on the difficulties of measuring national coastlines. He did not realize he was wrestling with the fact that coasts are fractals—twisty irregular shapes that are the same at any scale, from an inch to a mile. Mandelbrot, however, saw that Richardson had supplied him with a practical case for the importance of such fractals, and wrote his first major paper on the subject as a result.

"People in the classic turbulence world and the diffusion world and the differential equation world didn't begin to appreciate what he had done until the 1940s," said Hunt, who is also a climate modeler and meteorologist. But by the time Richardson's achievement in meteorology was recognized, most of his attention had shifted to war.

THOUGH RICHARDSON HAD RETURNED to work for the Meteorological Office in 1919, he only stayed for one year. In 1920, a government reorganization placed the agency under the Air Ministry, which was in charge of the Royal Air Force. As his conscience would not allow him to work for any military organization, Richardson felt duty bound to resign. His breakthrough work on turbulence in the 1920s was conducted in his spare time, as he supported his wife Dorothy and their three adopted children with a professorship at a teacher's college. The war had marked him—one of his children recalls Richardson screaming in terror at sudden loud noises, and explaining that he had "shell shock"—and his concern for understanding collective violence was growing. By the end of the 1920s, he had enrolled in university to study psychology. In the next few years, war replaced the weather as his main focus.

For two decades before his death in 1953, Richardson painstakingly collected data about arms races, economic upheavals, insurgencies, revolutions, riots, and combat. "He was all the time compiling statistics about conflicts around the world," Hunt recalls from boyhood holidays with his great-uncle. "Letters would keep pouring in from friends and colleagues and relatives. He had these deep ideas, but he was all the time looking at data."

Where others looked at war and saw only unpredictable turbulence that math could not master, Richardson was once again looking for measurable quantities and inexorable laws that could be modeled with equations. His goal was to build a model of the current state of political and economic tensions among nations—with measurements for "war weariness," "internationality" (roughly a nation's engagement with other countries, partly derived from figures about its international trade), and "preparedness for war" (a function of economic data and spending on arms and defense).

As with his weather work, he was producing papers, but also working toward another magnum opus. Posthumously published in 1960, *The Statistics of Deadly Quarrels*, would, he hoped, help people set aside the illusions and self-serving jingoism that passed for analysis, and see, as he put it, "what has happened often is likely to happen again, whether we wish it or not." Any attempt at a science of war would have its flaws and blind spots, but at least it would offer some much-needed clarity.

After all, then as now, most of what passes for analysis of wars and conflict consists of talk about one individual eddy or another in the vast political atmosphere. Changing relationships among world leaders, individual skirmishes and attacks, armistices, and so on are the kind of events that "may be likened to the eddying view of a wind," Richardson wrote. His theory, by contrast, would offer a way to step out of our local turbulence, and see the larger patterns.

As he had in meteorology, Richardson sought hard data—measurements that would not vary with the politics or passion of the observer. Any interpretation would be clouded by bias. He wrote: "counting is an antiseptic against prejudice." He would ignore disputes about who was a terrorist or a freedom fighter, and whether a military action was a fight for freedom or a bandit raid. Instead, he would simply count the dead.

A "deadly quarrel," Richardson decided, was to be defined as any conflict in which a person's death was deliberately caused by another. He toted up "deadly quarrels" of every type from 1820 onward. (He had planned to review a century's worth of data, and he picked starting and ending dates that marked relatively peaceful times following great wars. Later, he extended the dataset to include the violent 1930s, '40s, and the start of the '50s.)

He then sorted his "deadly quarrels" the way geologists classify earthquakes, ranking each "quarrel" according to the base-10 logarithm of the number of deaths it produced. The base-10 logarithm of a number describes how many times 10 must be multiplied to produce that number. A riot that leaves 100 dead in this system has a magnitude of 2 (the base—10—must be multiplied by itself to yield 100). And a conflict that kills 10 million people has a magnitude of 7 (multiplying seven tens will yield 10 million). Defining "deadly quarrels" on a logarithmic scale also served Richardson's project to get people thinking about violence without illusion. Like the Richter scale for earthquakes, his logarithmic graphs let the reader see *all* quarrels, from murders to global war, as a single phenomenon on a single scale.

Something interesting emerges from those figures. As the atmosphere is full of small eddies, so humanity experiences many small deadly quarrels, which result in a few fatalities. But now and again come huge storms, which kill millions. These are just the sort of outbreaks, like the world war Richardson had seen for himself, that people think of as surprising. Yet when Richardson plotted the frequency of wars against the number of deaths caused by each one, he found a constant and predictable relationship. On his graphs, the violence obeyed a "power law"—a constant relationship between the size and frequency of measurements. In his turbulence work, Richardson had found that such a power law governed the relationship between the rate of diffusion of objects in a turbulent stream and their distance from one another. Now he had found evidence of an underlying law in the supposedly unpredictable realm of politics.

Anyone might observe that extremely big wars were much more rare than "deadly quarrels" that killed only a few people. But the power law relationship suggested that the giant wars were just as predictable as the smaller ones. Like giant earthquakes (which also obey a power law), giant wars were not appalling surprises, arising out of unique circumstances. They appeared to be roughly predictable.

This finding was long considered a curiosity in peace research. However, over the past 10 years, a number of researchers have found power law relationships in modern statistics about violence. Neil Johnson, a physicist at the University of Miami, Michael Spagat, an economist at University College London, and their co-authors have found a similar power law in data about conventional war, terrorist attacks, and cyber-attacks. These findings offer some suggestions as to when future attacks are most likely to occur, and when it would be most effective to try to prevent them. And they offer a starting point for the quest for an underlying law governing outbreaks of violence, once considered too complex and idiosyncratic to predict.

War, Richardson taught us, can be as out of our control as a summer thunderstorm. The least we might do is check the forecast.

DAVID BERREBY is the author of *Us and Them: The Science of Identity*, and writes the Mind Matters blog at Bigthink.com.

Dude, Where's My Frontal Cortex?

There's a method to the madness of the teenage brain

BY ROBERT SAPOLSKY

IN THE FOOTHILLS OF the Sierra Mountains, a few hours east of San Francisco, are the Moaning Caverns, a cave system that begins, after a narrow, twisting descent of 30-some feet, with an abrupt 180-foot drop. The Park Service has found ancient human skeletons at the bottom of the drop. Native Americans living there at the time didn't make human sacrifices. Instead, these explorers took one step too far in the gloom. The skeletons belonged to adolescents.

No surprises there. After all, adolescence is the time of life when someone is most likely to join a cult, kill, be killed, invent an art form, help overthrow a dictator, ethnically cleanse a village, care for the needy, transform physics, adopt a hideous fashion style, commit to God, and be convinced that all the forces of history have converged to make this moment the most consequential ever, fraught with peril and promise.

For all this we can thank the teenage brain. Some have argued adolescence is a cultural construct. In traditional cultures, there is typically a single qualitative transition to puberty. After that, the individual is a young adult. Yet the progression from birth to adulthood is not smoothly linear. The teenage brain is unique. It's not merely an adult brain that is half-cooked or a child's brain left unrefrigerated for too long. Its distinctiveness arises from a key region, the frontal cortex, not being fully developed. This largely explains the turbulence of adolescence. It also reflects an important evolutionary pressure.

The frontal cortex is the most recently evolved part of the human brain. It's where the sensible mature stuff happens: long-term planning, executive function, impulse control, and emotional regulation. It's what makes you do the right thing when it's the harder thing to do. But its neurons are not fully wired up until your mid-20s. Why?

It's a central tenet of genetics that the genome that we start off life with, back when we were just a fertilized egg, is passed on to every subsequent cell in the

ILLUSTRATION BY JOHN HENDRIX

body. But if the frontal cortex is the last part of the brain to fully mature, it's the brain region least shaped by that genome and most sculpted by experience.

Our success as primates, and as individuals, revolves around social intelligence and adapting to the subtleties and idiosyncrasies of the environment. This is the portfolio of the frontal cortex. So if it's going to develop the ability to do this right, it's going to have to be profoundly shaped and informed by every smidgen of experience along the way.

Like evolution itself, though, maturation seldom follows a straight and narrow path. Adolescence reminds us that life has many rivers to cross, some fraught with turbulence.

The delayed maturation of the frontal cortex helps explain the defining feature of adolescence, namely the weird predilection for bungee jumping.

AROUND THE ONSET OF adolescence, the frontal cortex is the only brain region that has not reached adult levels of gray matter, made up of neuronal cell bodies. It would seem logical that gray matter levels would increase thereafter. But no, over the course of adolescence, frontal cortical gray matter volume *decreases*.

This occurs because of one of the cleverest things that brains ever evolved. During fetal development, mammalian brains generate far more neurons than are found in the adult brain. Why? Because the fetal brain holds a dramatic competition. Winning neurons get to migrate to the correct location and form the optimal number of connections with other neurons. Neurons that miss the cut undergo "programmed cell death." Neuronal overproduction followed by competitive pruning (a process that has been termed "Neural Darwinism") allows more complex and optimized neural circuitry, a wonderful example of less being more.

The same plays out in the adolescent frontal cortex. At the beginning of adolescence, gray matter volume is greater than it is in adults, and subsequently declines, as less optimally connected neurons are pruned away. Within the frontal cortex, it is the evolutionarily oldest sub-regions that mature first; the spanking new dorsolateral prefrontal cortex, for example, does not even begin to lose gray matter volume until the end of adolescence. This delayed frontal cortical maturation means that adolescents aren't at adult levels of expertise at various cognitive tasks, like recognizing irony or Theory of Mind—the ability to operate with the knowledge that someone else has different information than you do.

In an adult, the frontal cortex steadies the activity of parts of the limbic system, a brain region involved in emotion; in contrast, in the teenage brain, the limbic system is already going at full speed, while the frontal cortex is still trying to make sense of the assembly instructions. One result of this imbalance is that emotions are more intense. Stick people in a brain scanner and show them pictures of faces expressing strong emotions. In the adult, there is activation of a prime limbic structure, the amygdala; shortly after, there is activation of frontal cortical regions, which damp the amygdaloid response: "OK, calm down, it's just a picture of an angry/sad/happy/scared face, not the real thing."

But in the teenager, the frontal cortical response is muted, and the amygdala's response is augmented. That means emotional highs are higher, and the lows are lower. This is shown in studies of limbic pathways that release dopamine, a neurotransmitter central to anticipation of reward and pleasure (cocaine, for example, works on this limbic dopamine system). Average dopamine levels in adolescents and adults do not differ; what differs are patterns of dopamine release. Put an adult in a brain scanner, give them a small reward, and there's a small degree of activation of this dopamine circuitry. Medium reward, medium activation; big reward, big activation. Now do the same with a teenager. Medium reward, medium activation, same as in the adult. With a big reward, though, dopamine signaling increases far more than in an adult. Small reward and dopamine signaling *decreases*. A small reward feels like a punishment. This is a neurochemical gyroscope that's way off kilter.

One more day with the same baboons, and he was going to scream.

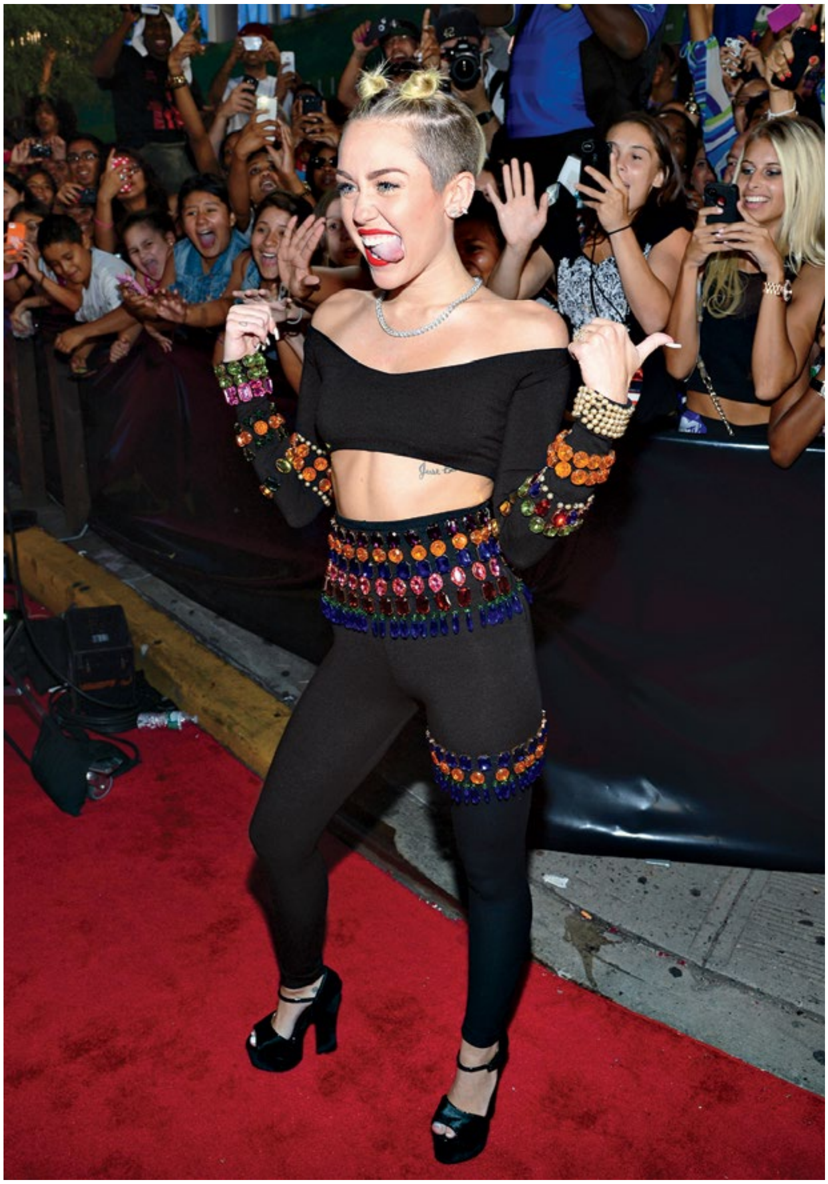
The delayed maturation of the frontal cortex also helps explain the defining feature of adolescence, namely the weird predilection for bungee jumping. During risky decision-making, adolescents show less activation of some key sub-regions of the frontal cortex than do adults, and among adolescents, the less activity in these regions, the poorer the risk assessment.

And adolescents are bad at risk assessment in a particular way, shown by Sarah-Jayne Blakemore of University College London. Ask test subjects to estimate the likelihood of some event happening to them and then tell them the actual likelihood of it happening. The feedback can constitute good news, as subjects learn that a good event is more likely to occur than they thought. Conversely, the feedback can constitute bad news, as subjects learn an event can happen more often than they expected. Both adults and teens are likely to adjust their assessments when asked again about the likelihood of good news. But teens alone don't get the picture about bad news. Researcher: What do you think the odds are of your having a car accident if you're driving drunk? Adolescent: One chance in a gazillion. Researcher: Actually, the risk for people in general is 50 percent; now what do you think your chances are? Adolescent: Hey, we're talking about me; one chance in a gazillion. This helps explain why adolescents have 2 to 4 times the rate of pathological gambling than adults.

So adolescents are lousy at risk assessment and take more risks. But there's more to the story of those skeletons in Moaning Caverns. It's not the case that adolescents and adults have an equal desire to do the same dumb-ass thing, and the sole difference is that the fully mature frontal cortex in the latter prevents them from doing so. Adolescents *feel* the allure of jumping off things. Middle-aged adults just recklessly cheat on their diets. Adolescents not only take more risks, they seek more novelty.

Adolescence is the time of life when we develop our tastes in music, food, and fashion, with openness to novelty declining thereafter. We're not alone. When are lab rats most willing to try a novel food? During rodential adolescence. Among many social mammals, the adolescents of one of the sexes leave their natal group, avoiding inbreeding. Consider impalas, who live in a "harem structure," a group of related females and offspring with one breeding male (and where the rest of the males knock around disconsolately in "bachelor herds"). When a young male hits puberty, he is driven out by the resident breeding male.

It's different among primates. Take baboons. Two troops encounter each other on opposite sides of a stream. The males hoot and holler at each other in a manly fashion until they get bored and go back to foraging, ignoring the interlopers. An adolescent stands on the edge of the stream, riveted. "New baboons, a



PARTY IN THE BRAIN In adolescence, the frontal cortex is diluted with superfluous connections, dopamine is careening all over the place, and the brain is being marinated in the ebb and flow of hormones. That should explain Miley Cyrus.

whole bunch of 'em!" Nervous and agitated, he runs five steps toward them, runs back four. He tentatively crosses the stream, sits on the very edge of the other bank, scampers back as soon as anyone so much as glances at him.

The next day he stays on the other side for an hour. Then an afternoon. Then a night, breaking the umbilical cord. He wasn't pushed out of his home troop, as with impalas. He had reached the point where if he had to spend one more day with the same baboons he's known his whole life, he's going to scream. The same thing happens with adolescent female chimps, who can't get off the farm fast enough, heading off into the great unknown in the next valley. We primates don't get driven out of our herds at adolescence. We get a mad craving for novelty.

These traits are exacerbated when adolescents are around peers. In one study, Laurence Steinberg of Temple University discovered that adolescents and adults, when left on their own, don't differ in the risks they take in a driving simulator. Add peers egging them on and rates don't budge in adults but become significantly higher in teens. When the study is carried out in a brain scanner, the presence of peers (egging on by intercom) lessens frontal cortical activity and enhances activity in the limbic dopamine system in adolescents, but not in adults.

This teenage vulnerability to peer pressure is worsened by the fact that such pressure rarely takes the form of hesitant adolescents coerced into joining in the fun of committing random acts of kindness. Instead, pressure disproportionately takes the form of "deviance training," increasing the likelihood of risky sexual behavior, poor health habits, substance abuse, and violence. As has been said, the greatest crime-fighting tool available to society is a 30th birthday.

One brain-imaging study reveals the neural depths of adolescent pain in not belonging. Put someone in a scanner to play a video game with two other individuals, and manipulate things so that the subject believes they are being ostracized. In adults, this social exclusion activates the amygdala along with other limbic regions associated with pain, disgust, anger, and sadness. But then the frontal cortex kicks in—"Come on, it's a stupid game"—and the limbic structures quiet down. Do the same with an adolescent and the frontal cortex remains silent and that agonized limbic network of teenage angst wails.

The slowpoke frontal cortex is not the only explanation for teen behavior. Another factor comes into play that keeps that teen brain off balance, namely gonadal hormones like estrogen and progesterone in females, and testosterone in males. This helps explain why adolescence is more turbulent than childhood—the frontal cortex is immature at both ages, but the tsunamis of hormones haven't started in pre-adolescents. Hormones have numerous effects on the function of both the limbic system and frontal cortex. Testosterone decreases the ability of the frontal cortex to communicate with and rein in the amygdala. Not surprisingly, landmarks of adolescent maturation in brain and behavior are less related to chronological age than to time since puberty.

The onset of puberty is not merely about the sudden onslaught of gonadal hormones. The defining feature of ovarian endocrine function is, of course, the oscillations of hormone release. In adolescent females, puberty does not arrive in full flower, so to speak, with one's first period. Instead, for the first few years, only about half of cycles actually involve ovulation and the accompanying hormonal surges. So not only are there major fluctuations in gonadal hormone levels due to ovulation, but also higher-order fluctuations as to whether ovulation occurs. And fluctuations in hormones affect emotion and cognition. (While an adolescent male does not have the hormonal fluctuations of his female counterparts, it can't be a great thing that his frontal cortex probably keeps getting hypoxic from all that priapic blood flow to his crotch.)

As adolescence dawns, the frontal cortex's efficiency is diluted with superfluous connections failing to make the grade. The limbic system is fully online and dopamine is careening all over the place. Meanwhile, the brain is being marinated in the ebb and flow of gonadal hormones. No wonder the human species produces beings like Justin Bieber and Miley Cyrus, making a handy living catering to their constituency.

BUT ADOLESCENCE ISN'T ALWAYS as dark as it's made out to be. There's a feature of adolescence that makes up for the stupid risk-taking and hideous fashion decisions. And that's an adolescent's frenzied, agitated,

GETTY IMAGES FOR MTV

incandescent ability to feel someone else's pain, to feel the pains of the entire world, to want to right all its wrongs. Adolescents are nature's most wondrous example of empathy, where the forcefulness of feeling as the other can border on nearly *being* the other.

This intensity is at the intersection of so many facets of adolescence. With the highs higher and lows lower, the empathic pain scalds and the glow of having done the right thing makes it seem plausible that we are here for a purpose. Another factor is the openness to novelty. An open mind is a prerequisite for an open heart, and the adolescent hunger for the new readily presents opportunities to walk a mile in someone else's shoes. And there is the egoism of adolescence. There was a period during my late adolescence where I hung out with Quakers. They'd often say, "All God has is thee." This is God of limited means, not just a God who needs the help of humans to right a wrong, but who needs *your* help most of all. Egoism is tailor-made for adolescents. Throw in inexhaustible energy and the sense of omnipotence and it seems possible to make the world whole.

A few years ago, I saw a magnificent example of the empathy that a sluggish frontal cortex can produce in teenagers. My daughter is seriously into theater and at the time she was in a production of a superb, searing play about the Bosnian genocide, Stefanie Zadravec's *Honey Brown Eyes*. She played a 12-year-old Bosnian girl for whom things don't go so great, and whose life-or-death fate is ambiguous as the play ends.

Some high school kids had come to a performance as a group outing for an English class. About halfway through the play, my daughter's character appears for the first time, cautiously emerging from a ventilation duct in her kitchen where she'd been hiding, unaware that the soldier who had just left the apartment after killing her mother was going to return. Up until that point, she had only been hinted at as a character. The soldier had his ethnic-cleansing to-do list of names of Bosnians in the building to kill, and kept demanding of the mother, "Where's your daughter? It says you have a daughter." "I don't have a daughter," the mother repeated up until her death. So as the girl begins to emerge from the ventilation duct, the realization sweeps through the audience: There *is* a daughter. As my daughter began to crawl out, the teenagers in the audience did something you're not supposed to do in a theater, something no adult with a developed frontal cortex would do. After a moment of hushed silence, two or three voices called out, "No!" Another called, "Go back in, it's not safe!," another, "He's coming back!" After the play, the teenagers clustered around my little girl when she came out of the stage door, hugging her, reassuring themselves that both she and her character were OK.

> A feature of adolescence makes up for the stupid risk-taking and hideous fashion decisions: a frenzied, agitated, incandescent ability to feel someone else's pain.

This is the picture of adolescents with their hearts on their sleeves, limbic systems going full blast, and their frontal cortices straining to catch up with some emotional self-regulation. When I see the best of my university students in that agitated, optimistic state, I always have the same thought: It used to be so much easier to be like this. Having this adult frontal cortex of mine probably enables me to do good in a more efficacious, detached way. The trouble, though, is the same detachment makes it so much easier to decide that it's really not my problem.

SO WHAT IS THE adaptive advantage of human brain development evolving this way? Potentially, there is no advantage. Perhaps the human frontal cortical maturation is delayed because it is the most challenging construction project the brain undertakes. In this view, wiring up something like the visual cortex can pretty much be wrapped up in the first year of life, but doing the same in the frontal cortex takes another quarter century. This seems unlikely. The frontal cortex has the same basic structure as the rest of the cortex, uses the same neurotransmitters and types of neurons. On a nuts and bolts level, its maturation is slower than necessary, suggesting that there has indeed been active selection for the delay, that there is something advantageous about it.

One possibility, of course, is the adolescent turbulence. If the frontal cortex wired up at the same speed as the rest of the brain, there'd be no *Sturm und Drang*, no emotional fireworks, no psychic acne. Just a simple transition from kids to fertile adults around age 12. One can imagine that something would then be lost—that developmental phase of antsy, itchy exploration and creativity that has been evolutionarily enriching. We might not have had that long line of pimply adolescent geniuses who worked away to invent fire, cave-painting, and the wheel.

Maybe. But this just-so story has to accommodate the fact that behavior doesn't evolve for the good of the species, but for passing on copies of genes of individuals. And throughout history, for every teenager who scored big-time in the reproduction department thanks to some adolescent inventiveness, there've been far more who broke their necks from some adolescent imprudence.

No, I think that the genetic program of brain development has evolved to help free the frontal cortex from the straightjacket of genes. If the frontal cortex is the last part of the brain to fully mature, it is by definition the brain region least shaped by that genome and most sculpted by experience. With each passing day, the frontal cortex is more the creation of what life has thrown at you, and thus who you become.

A key theme in current neuroscience—the plasticity of the adult brain—underscores how this happens. As shown with a vast body of research, repeated stimulation of a synapse (the connection between two neurons) causes it to become more excitable, to pass on messages more readily; the synapse "remembers," as a likely building block of how memory works. Similarly, the dense arbor of neuronal processes that determine which neurons connect to each other can expand or contract, depending on experience. Spend a summer learning how to juggle and entire circuits in the motor cortex will remap. Despite a zillion years of neuroscience dogma, it is now clear that the adult brain makes new neurons in response to things like an enriched environment. All of these occur in adults of any age, but most readily in the young adult brain. And if the frontal cortex is unique in still developing then, that makes it the brain's hotspot for plasticity.

Why is this important? One answer comes from recent studies of intelligence in education. Some educators stress that a student's "emotional intelligence" or "social intelligence" (as measured various ways) is a better predictor of adult success and happiness than their IQ or SAT scores. It's all about social memory rather than memory of vocabulary words, about emotional perspective-taking, impulse control, empathy, ability to work with others, self-regulation.

There's a parallel in other primates, with their big, slow-maturing frontal cortexes. What makes a "successful" male baboon in a world of dominance interactions? Attaining a high rank is all about muscle, sharp canines, well-timed aggression. But once alpha status has been achieved, maintaining it is all about social smarts—which potential coalitions to form, which to stay away from, how to cow a rival through psychological intimidation, having sufficient impulse control to walk away from provocations, and avoiding displacing aggression onto everyone else when you're having a bad hair day. This is the realm where doing the right thing is often the harder thing, and adult life is filled with consequential forks in the road where intelligence lights the way forward.

This is all worth keeping in mind the next time you find yourself being an adolescent, or dealing with one who has the volume up to 11 in every domain. Sure, adolescence has its downsides, but it has its abundant pluses—the inventiveness, the optimism, the empathy. Its biggest plus is that it allows the frontal cortex time to develop. There's no other way we could navigate the ever-increasing complexity of our social world.

ROBERT SAPOLSKY is a professor of biology, neurology, and neurosurgery at Stanford University.

To see a video interview with the author, visit go.nautil.us/Sapolsky_Speaks

When Good Waves Go Rogue

Even in calm seas, waves can become monsters

BY TOM VANDERBILT

ILLUSTRATION BY JOHN HENDRIX

E**ARLY IN THE MORNING** on Sept. 11, 1995, the cruise liner the Queen Elizabeth 2, on its way from Southampton to New York, was being lashed by the tail end of Hurricane Luis, somewhere off the coast of Newfoundland. As if sensing its imminent demise, Luis had galvanized one last time, twitching to life and whipping the North Atlantic into a torrent of 130 mph winds and 40-foot waves. None of this caused undue concern for the ship's captain, Ronald Warwick, a 30-year sailing veteran well acquainted with rough seas. Luis was hardly unexpected; since leaving England, the ship had steadily tracked the storm's path. "This was fair game for us," the retired Commodore recalls from his home in Somerset, England. "We are a transatlantic liner."

At dinner, Warwick had advised the ship's passengers that things might get a bit rough during the night, and to secure any loose possessions in their cabin. He then did what any captain would do in heavy seas. With the ship steered into the waves, Warwick slowed it to a few knots. "Heaving to" it is called, the idea being to ride out the waves as gently as possible, while maintaining just enough speed to maintain steering control. Far below the ship's bridge, where winds roared and whipped against the armored windows, a handful of passengers held casual vigil in a bar.

Just after 2 a.m., Warwick and his officers suddenly saw a surging monster of water and convulsive white froth in the near distance. "If you're standing on the bridge of the QE2," he says, "your height of eye above sea level is 90 feet." From what they could discern through the rain-soaked darkness, the crest of the looming wave was as high as the bridge itself. Warwick, who says he had never encountered anything so large in the ocean before, said it was as if they were heading into the "white cliffs of Dover."

A minute or so later, the wave crashed across the forward deck of the QE2. "We didn't go over the top of it," says Warwick. "We virtually went through it." A series of judders shot through the ship. The wall of water crashed down on the ship's deck, buckling its steel plates some 18 inches. Still, this was all within the operating bounds of the ship. "We weren't knocked off our feet or anything," he says. "Most passengers were in bed."

But the anomalousness of this one wave still haunts Warwick. For an old North Sea hand, 40-foot waves, the kind that would terrify most of us, were nothing out of the ordinary. But the emergence from nowhere of a single wave that was more than twice as high as the others was exceptional. Warwick had encountered a rogue wave.

IN THE COMMON PARLANCE, "rogue wave" has come to mean any wave that is unusually large. But a rogue wave does not have to be big on an absolute scale, nor is it necessarily associated with a heavy storm. Burkard Baschek, director of the Institute of Coastal Research, in Geesthacht, Germany, defines it as any wave that is statistically extreme. "[A rogue wave is] at least twice as high as the so-called significant wave height," he says. The significant wave height is defined as the average of the largest one-third of waves at any given moment, "the waves you would see by eye if you're out there and looking at the sea state."

This means you have probably experienced a rogue wave and not noticed. How? "If you're out in calm conditions," says Baschek, "and the waves are one meter high, and suddenly you experience a two meter wave, so what?" In fact, Baschek says one wave per day, somewhere in the world's oceans, is a rogue wave. While at the University of California, Los Angeles (UCLA), You have probably experienced a rogue wave and not noticed.

he analyzed data from a number of buoys off the west coast of the United States and, extrapolating the figures globally, estimated that ships trawling the North Atlantic (like the QE2) would "encounter 20-30 of these rogue waves during their service lives of 25 years," or about one a year.

That rogue waves are, at base, mathematical objects has meant that sailors, then scientists, have been slow to grasp their nature. Late into the 19th century, the line between sailors' lore and science could be as blurred as a fog-bound horizon, with reputable journals routinely reporting on the sightings of "monsters of the sea." By the mid-20th century, though, most of these monsters had been dispelled or explained—but not rogue waves, which continue to be misidentified and incompletely understood today. Even one of civilization's most famous waves, Hokusai's *The Great Wave off Kanagawa*, is often misinterpreted as a tsunami—the woodcut has even been used as the symbol of a UNESCO tsunami warning sign—when it is actually most likely to be a rogue wave, as several scholars have argued.[1,2]

The science of rogue waves began to take shape in the early 1960s, not in the ocean but in a wave tank—essentially a long, shallow trough with a "paddle" for generating waves of varying frequencies—in Cambridge University's Engineering Department. There, the physicist and fluid dynamics expert T. Brooke Benjamin, aided by a graduate student named Jim Feir, were having trouble trying to prove something that had long been assumed: the stability of the so-called "Stokes wave," the sort of Ur-wave, or prototypical wave, of fluid dynamics, theorized by the renowned 19th-century Cambridge University mathematician George Gabriel Stokes. Stokes, inspired by a British engineer's faintly astonished report of a "solitary heap of water," pushed along by a slowing boat, that had maintained its speed and shape for nearly two miles as it traveled through a canal, looked for an equation that could describe a wave propagating in shallow water without changing shape.[3]

It had been rather taken for granted that the Stokes "wave trains," as they were called, were essentially stable. But engineers working in wave tanks—testing ships' hydrodynamics and the like—were finding instabilities.[4] As they set out in their own search of stability, Feir and Benjamin noticed something odd. Their colleague, J.C.R. Hunt, wrote that the two "observed how waves generated at the wave maker started as a regular train with constant frequency and wavelength, but then about 5 m down the tank began to form into groups of waves with varying frequencies and wavelengths."[5] Thinking it might be a problem with the wave generating hardware, they first worked out a solution to keep the frequency from shifting. They then moved to a larger tank, with a programmable wave maker. But the results were the same. As the wave moved down the tank, it was buffeted by "sidebands" of higher and lower frequency. Critically, these sidebands grew exponentially in amplitude, or height, as they traveled down the tank.

The effect, now known as the "Benjamin-Feir instability," offered a hint as to how rogue waves form. As J.B. Zirker describes in his book, *The Science of Ocean Waves*, the wave group, once it found a kind of sweet spot of modulation, stole energy from itself to produce a single high wave—higher than might be expected from the normal dynamics of the waves—then "returned" it to the primary wave. "The sidebands grew exponentially in height at the expense of the primary wave, which eventually disintegrated," he writes. "Nobody had ever seen or expected the likes of this before."

SURF'S UP *The Great Wave off Kanagawa* by Hokusai is often assumed to depict a tsunami, but is more likely to be a rogue wave.

What ultimately made the concept of rogue waves so striking was not simply that they could grow to unexpected heights, but that they occurred more frequently than they were expected to. As Eric Heller, a physicist at Harvard University, explains it, much of the thinking on large wave creation was influenced by M.S. Longuet-Higgins, the noted mathematician and oceanographer, who was, as he wrote in one study, trying to "study theoretically the statistical properties of a random, moving Gaussian surface." In other words, the ocean.

"His theory was based on the random addition of waves," Heller says. "He was uniformly adding them up over large areas and asking how many unlucky additions you would get resulting in large waves." It was a linear process. According to Heller, there was just one problem: "There were more freak wave events [in reality] than that theory could ever really account for. Light bulbs went off in people's heads—it must be non-linear evolution!"

And so rogue waves crashed into the longstanding "Gaussian seas" model of randomly distributed wave heights. They were not quite as long-tail as had been thought, and new probabilities, like the so-called "Tayfun distribution" (which coincidentally sounds like "typhoon" but is named for a Turkish scholar) have gained currency to predict the likelihood of rogue waves.

ONE OF THE BIGGEST boons to the study of rogue waves came not in the laboratory, but in the ocean itself. On the night in 1995 that the QE2 was struck by the giant wave, there was another witness, one who experienced the wave from a deeply immersive position: "Buoy 44139," an instrumented floating beacon monitored by the Canadian Forces Meteorological Office at Halifax. The statistical graph it generated during the torment is simple, yet chilling. There is a slightly jagged saw-tooth line of wave heights, the 40-foot rollers that Warwick had hove to against. But then, with no anticipatory buildup, there rises a single, dramatic peak, leaping toward the top of the page, almost, literally, "off the charts." Just as suddenly, it plunges again, as if it were never there.

Buoys like 44139, equipped with accelerometers and other measuring devices, brought precision to an arena where sailor's accounts and estimations had dominated. Before their advent, gauging the heights of waves was an inexact process. One early, and complicated, effort involved photographing the ocean from an airplane and mathematically estimating wave height via the reflection of light.[6]

But buoys are far from perfect. They get overtopped by waves, or knocked on their sides. There is also an issue of selection bias. Most instrumented buoys are located close to shore, says Baschek, while the largest rogue waves occur more frequently on the open ocean. Not all buoys can measure the direction of waves. And the big wave measurements that have been captured—the QE2, or, in another well-known instance earlier that same year, a 30-meter wave captured on the oil platform Draupner off the coast of Norway—are single point measurements. "It's a buoy or a radar point," he says. "But you have no idea what the crest length is. If you measure a rogue wave, is it one local spray, or is it going over miles and miles? How long does it persist? Does this rogue wave form right before your buoy and fall apart right after that? This is also something you don't know."

As a striking reminder of how science, even with its ever more sophisticated and powerful measurement capabilities, is still catching up with the enormity of the ocean, it was only in 2011 that the long-suspected, but never observed, phenomena of "merging tsunami"—two waves (formed non-linearly) becoming (linearly) a more powerful one—was finally observed in the wild, thanks to a procession of satellites orbiting over the tsunami. The capture of the merging tsunami was a "one in 10 million chance" random observation, as an investigator put it.[7]

On the night in 1995 that the QE2 was struck by the giant wave, there was another witness.

WIKIPEDIA

For these reasons, even in this age of networked data and supercomputer simulations, some of the best data on rogue waves continues to come from the men and women who work on the sea.

IN JANUARY 2010, the crab boat Early Dawn (featured, as it happens, in the *Deadliest Catch* reality series), operating near the town of St. Paul, Alaska, was struck by a wave that was said to be twice as high as the significant wave height. In the course of a subsequent insurance investigation concerning injuries to a crew member, Baschek was called in to help answer a necessary but difficult question: Should the captain have known about the possibility of such a wave, and was he prepared enough? This involved the usual problem of the probabilities of such waves, with an unusual twist. The wave that struck the boat that winter did not come from the prevailing wave direction.

This violated the traditional linear theories, Baschek says, of the superposition of waves coming out of the same direction and combining into a larger wave. "This was a total puzzle," he says. "Because we don't know the physics behind it, all we could do was dig out the records we had of the West Coast of the U.S., about 100 years of total data." The question they wanted to answer: How likely is it the rogue wave occurs at an angle that differs from the prevailing wave direction? He says they found a likelihood of about 1 percent. "It is now up to a judge to decide if this was likely or not," he says. "That's where science ends."

As you travel down the tail of the probability distribution, rogue waves become ever stranger. Not only can their size and direction be unexpected, but they can appear in some unlikely places. When I reach Nail Akhmediev, a professor in the Research School of Physics and Engineering at the Australian National University in Canberra, and one of the world's leading experts in nonlinear dynamics (he has a special kind of nonlinear wave, an "Akhmediev breather" to his name), he points out that our very conversation, conducted via Skype, may be subject to rogue waves.

"Right now, when we are talking, all this sound, it travels through optical fiber," he says. "It's waves. Whether ocean waves or waves in optical fibers, it's basically the same equations." In optical fiber, he notes, waves can be chaotic and turbulent. The pipes that connect Canberra and New York City are comprised of many channels—thousands of people talking at once. "In a fiber, it's all unidirectional," he says. "But because there are several channels, they cross each other."

Under the right conditions, even rogue waves can appear, a fact first reported by UCLA physicist Daniel Solli and colleagues in a 2007 paper in *Nature*, in which they noted the appearance of "a noise-sensitive, nonlinear process in which extremely broadband radiation is generated from a narrowband input." And while it is unlikely that a particularly voluble Skype conversation is going to trigger a catastrophic pulse across global telecommunications networks, as physicist Neil Broderick points out, the emergence of optical rogue waves remind us that the nonlinear math looks much the same across waves in many different kinds of systems; perhaps "seed pulses," he notes, could be used, along with artificial reefs, to create "perfect waves" for surfers.[8]

This thought came to me as I watched a video of an experiment that Akhmediev and his colleagues conducted in a wave tank in Hamburg. In the video, a small Lego pirate ship sits gently bobbing atop the silky undulations of the tank's mirror-surface water, as, unseen, a wave generator beats out a steady pulse of fluid dynamics. And then there it is, a dark band in the distance, which engulfs and capsizes the hapless boat. It is a "super" rogue wave, not twice the significant wave height, but *five* times. I envisioned, for a moment, an indoor water park where swimmers, placidly bathing, would be delightedly and unexpectedly jostled by exquisitely derived nonlinearity.

But the experiment was a stark reminder of how much mystery still lay in the generation of rogue waves. They are the ocean's black swans. We know that rogue waves occur, in a general statistical sense, but we do not know where or when—or, fully, how—they will, or will not, occur. Perhaps there are even 5x rogue waves yet to be discovered in the world's seas. It is not surprising, says Heller, that so much of wave science is about probability; even if we had all the data to understand the ocean, we would not have computers powerful enough to crunch it. "Statistics is very much a part of physics these days," he says. "There will be cases in quantum mechanics where there's nothing *but* statistics," no way other than guesses as to where or even if a particle's going to appear. Even the calmest sea is a veneer—an alibi—for chaos, actual and statistical.

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

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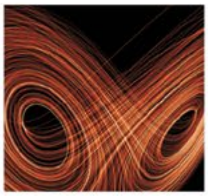
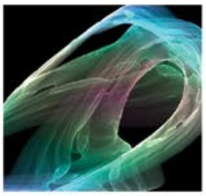
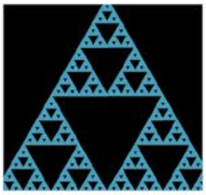

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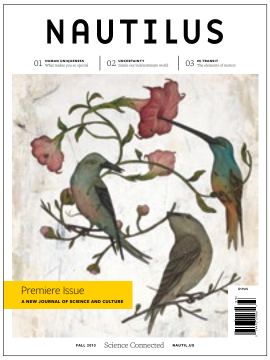

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Diane Ackerman

The naturalist and author of The Human Age *reflects on the themes in* Nautilus

INTERVIEW BY KIRSTEN WEIR

ON TURBULENCE

In only 200 years, humankind has become the dominant source of change on the planet. We've left our signature everywhere: altering the climate and oceans, redrawing the outline of continents, rerouting rivers, lopping off the tops of mountains, rearranging plants and animals, causing mass extinctions, even creating new forms of matter. We're suddenly in the midst of a majestic Information Age, but also a sustainability revolution, a nanotechnology revolution, a revolution in how we examine and imagine the body. There's also the disturbing evidence of mass extinction of animals, among countless other worries, shocks, uncertainties, and new normals. These are turbulent times indeed. But that also makes it a rich and exciting time to be alive. Evolution is an inherently turbulent biological process. So is human nature. What a combo. I think we should always expect the unexpected.

ON MUTATION

We've been genetically modifying plants and animals for millennia. The first wild corn looked nothing like the colossal ears we enjoy now, and heaven knows Chihuahuas and dachshunds look little like their lupine ancestors. We've been tailoring plants and animals to suit our palate, needs, whims, and existential loneliness for a very long time. What's different now is that we can mix the DNA from completely unrelated species, and we don't know yet what biological whirlwinds that may unloose. We want the benefits of genetic engineering—fixing a child's hereditary disease, or breeding mosquitoes free from dengue fever. But do we really need tomatoes with salmon genes swimming inside them, or animals that glow green? We're much better at tampering with nature than we are at understanding it.

ON SYMMETRY

We find special beauty in the chaos of fractals' perfect symmetry, or a diamond's house-of-mirrors dazzle. Although I was taught in biology that we prefer more symmetrical faces because we equate their balance with good health, this isn't always true. A craggily *interesting* face—even if it's lined like a Shar-Pei's—may appeal because it resembles a loved one's. Fortunately, nature favors both perfect and imperfect symmetries. Symmetry applied to human nature is always imperfect, but no less powerful for that. As a species, we've created a lot of planetary chaos we didn't mean to. A vital symmetry is there: Our inventiveness got us into this mess, and we can refocus our inventiveness to get us out.

ILLUSTRATION BY ANDY FRIEDMAN


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