NAUTILUS

Outside Looking In

A PHOTOGRAPHER IN THE FOREST p.18

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A Summer Gaze

WHEN MR. AND MRS. MONARCH stride into a painter's office in the Henry James short story, "The Real Thing," it is to try to earn a pittance. Recently separated from their substantial wealth—"it's an awful bore," says Mrs. Monarch—they would like to pose as models for illustrations of the well-heeled. The painter, seeing in their faces "the blankness, the deep intellectual repose of the twenty years of country-house visiting," decides that they should serve well, and agrees.

But he is soon frustrated. For whatever reason, his drawings of the real but recently impoverished aristocrats appear fake. His work becomes convincing only when he begins, instead, to use the poor Cockney model, Miss Churm—who is assuredly not the real thing. The philosopher Slavoj Žižek interprets the story in terms of "gazes": The illustrator's gaze is inscribed inextricably into the models, which in turn look back at him. Representation and represented are mixed together, and the idea of the "real" is quickly lost.

How might a scientist, with a heavy investment in the real, negotiate such mixing? On page 18, Nigel Pitman tells us in his own words how his understanding of the object of his science (the Amazonian jungle) was challenged and shifted by a set of apparently unremarkable photographs taken by a visiting artist. On page 30, we pair this account with a fictional story of a hypnotist who derives his power from the gaze of a watching crowd.

The two stories challenge us to consider how we negotiate a world that is, in part, our own construction. And they remind us of the mission *Nautilus* embarks on every month, to redefine our view of a single topic in science, and to discover ourselves in its midst.

Welcome to the summer 2014 *Nautilus Quarterly*.

—Michael Segal
Editor-in-Chief


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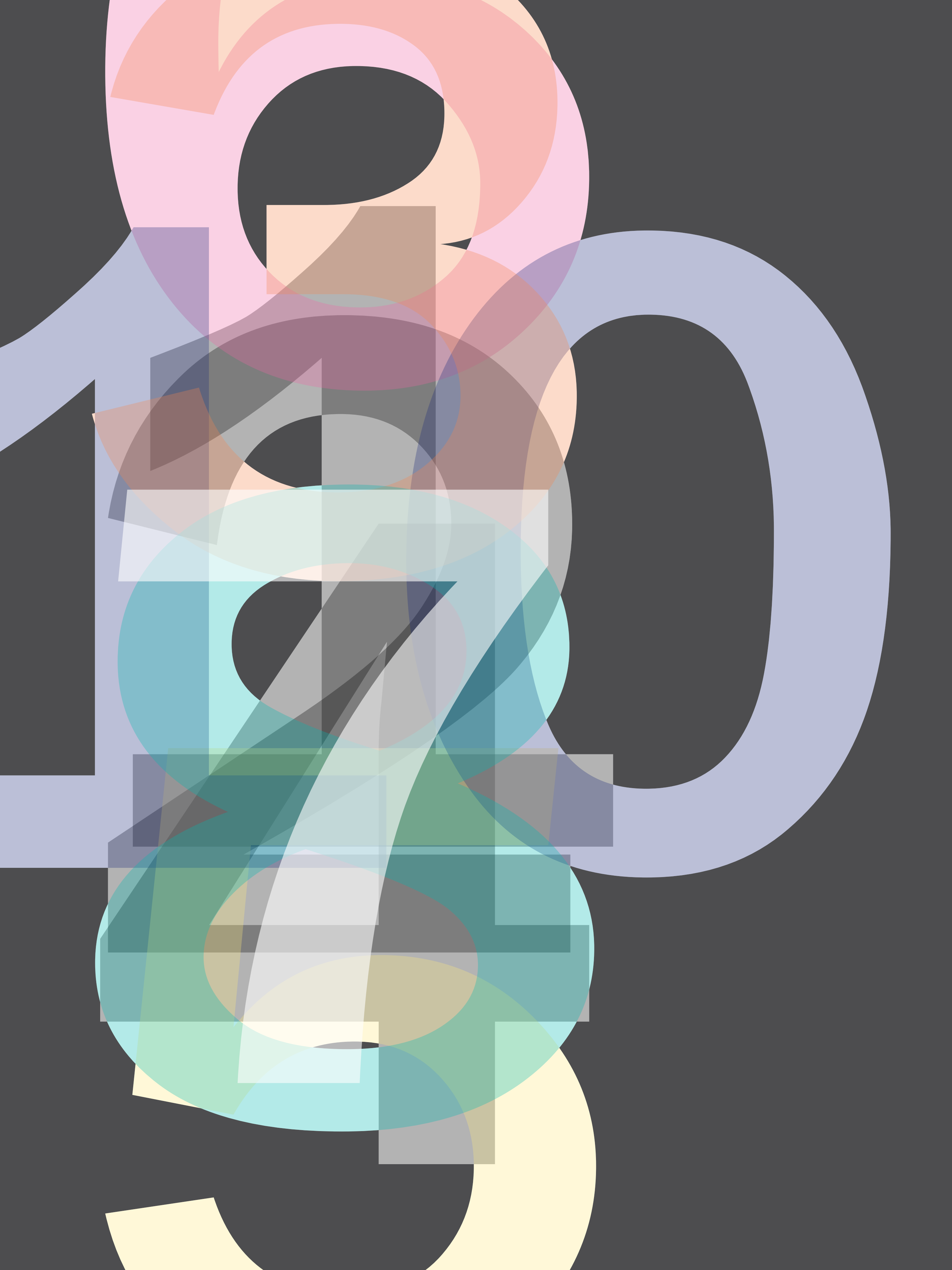


Preludes

SOCIOLOGY

Found: The World's Favorite Number

When emotion trumps reason

GO AHEAD, ADMIT IT. Like a lot of people, you have a favorite number.

Maybe your favorite number is your birthday, or the jersey you wore in high school. Or maybe it is your significant other's birthday. (That would be smart, because then you would never forget it.)

But what is the *world's* favorite number?

Alex Bellos, a mathematics blogger for *The Guardian*, found that one of the most frequent questions he got from readers was, "What's your favorite number?" Quite to his surprise, he found that a lot of people were passionate about numbers... or at least one number in particular.

Bellos set up the website http://favouritenumber.net, and after more than 44,000 votes, he saw some patterns. "Definitely, non-mathematical reasons were more frequent than mathematical ones," he says. "Dates and birthdays are the most common." Odd numbers did better, in general, than even ones. In China, 8 was popular because it sounds like "prosperity." English has sound-alikes, too: One voter said his favorite was 11, because "it sounds like lovin'."

Round numbers, ending in 0 or 5, are quite unpopular. "My theory, which is not scientifically proven, is that we use round numbers to mean approximate things," says Bellos. "When we say 100, we don't usually mean exactly 100, we mean around 100. Why would you have something as your favorite that is so vague?" It seems that we like our numbers to be unique, which may be why prime numbers are popular.

Bellos recently published the results in his book, *Alex Through the Looking-Glass*. Let's count them down:

The bronze medal goes to the number 8. Hey, all those Chinese people can't be wrong!

The silver medal goes to the number 3. That should go over well with fans of the Three Musketeers, the Three Stooges, and the Three Little Pigs.

But the number cited most often as a favorite number is (drum roll, please)... 7.

To be honest, this is hardly a shock. "People's strongest emotional reaction is to the number 7, and this has been true throughout history," says Bellos. But no one really knows why. "The argument most frequently given, which I think is not credible, is that there are seven visible planets or seven days in the week," Bellos says. He thinks we like 7 because it's the only number between 2 and 10 that is neither a multiple nor a factor of any other.

But if you don't feel any attachment to 7, that's okay. Rebels like the number 13, which finished way up in sixth place. If you like the number 0, join the smart aleck club—people seemed to pick 0 because they thought it was a clever thing to do. As for the world's "least favorite" number, that would be 110. It was the smallest whole number that didn't get any votes at all.

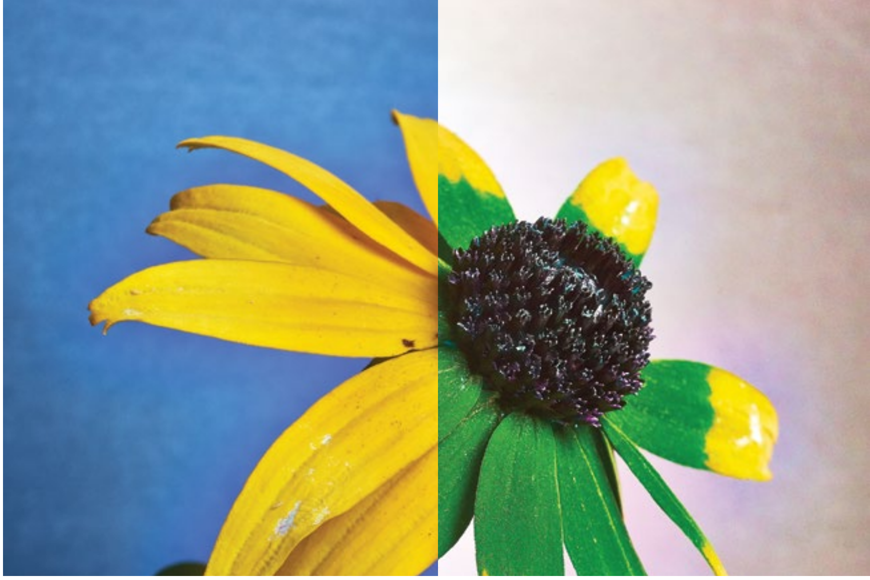
—*Dana MacKenzie*

ILLUSTRATION BY LEN SMALL

ZOOLOGY

How Animals See the World

Look through the eyes of cats and bees



HUMAN VS. BEE Left: A human's view of a flower petal. Right: A bee's view.

LIVING CREATURES' VISUAL perception of the world depends on how their eyes process light. Humans are trichromats. Our eyes have three types of the photoreceptors known as cone cells, sensitive to red, green, and blue. A different photoreceptor called rods detect small amounts of light; this allows us to see in the dark. Animals process light differently—some creatures have only two types of photoreceptors, which renders them partially colorblind. Others have three photoreceptor types like humans, but are able to see ultraviolet light.

"None of us can resist thinking that we can imagine what another animal is thinking," says Thomas Cronin, a professor at the University of Maryland who studies visual physiology. Nevertheless, looking at the world through their eyes is possible.

CAT

Cats are dichromats; they have only two kinds of cones in their retinas. They see similarly to humans with red-green colorblindness. To model a cat's vision, one has to pool everything that's red or green into one color.

HUMAN VS. CAT Left: A human's apple view. Right: A cat's.

The ability to see ultraviolet light lets bees spot patterns on flower petals that guide them to nectar.

Cats' eyesight has a lower resolution than ours so they see objects slightly blurrier than we do. Human vision is among the sharpest of all animals, thanks to densely packed cones at the center of our retina. However, cats have more rods than humans, so by moonlight the advantage is reversed.

BEE

Bees are trichromats like humans. Yet their three types of photoreceptors are sensitive to yellow, blue, and ultraviolet light. The ability to see ultraviolet light lets bees spot patterns on flower petals that guide them to nectar. Unlike human eyes, which have only one lens, bees have compound eyes composed of thousands of lenses that form a soccer-ball-like surface; each lens produces one "pixel" in bees' vision. Yet bees' eyes have extremely low resolution, so their vision is very blurred. This image doesn't show the fuzziness of a bee's eyesight, but does capture the ultraviolet vision we lack.

— *Elizabeth Preston*

BEE PHOTOGRAPHY © DR SCHMITT, WEINHEIM, GERMANY.

COSMOLOGY

The Most Massive Object in the Universe—How Was It Created?

Let's talk black holes

THE GALAXY KNOWN PROSAICALLY as M87 doesn't look like much. Unlike beautiful spiral galaxies (including the Milky Way), M87 appears as an orangish blob of stars. Its only noticeable feature is the long streamer of gas emanating from the galactic center.

But the source of that jet is far from prosaic: It's a black hole 6.6 *billion* times the mass of the sun. No other known object is as massive; this black hole by itself outweighs entire star clusters and small galaxies.

How does a black hole grow so massive? The simple answer: Just as big galaxies grew by colliding and merging, the largest black holes form when pairs of smaller black holes merge. But to understand the process in more detail will require some clever and very challenging investigation.

Theoretical models show that during galactic mergers, black holes fall into mutual orbit, gradually spiraling in toward each other, radiating energy away in the form of gravitational radiation as they draw ever closer. Eventually their event horizons will touch, and the system emits a lot more gravitational waves in a phase known as "ring-down," as the lumpy, uneven merged mass becomes a smooth, perfectly symmetrical black hole.

Unfortunately, that smooth black hole contains no information about its lumpy past: We can't tell by looking at a black hole if it formed out of a merger or if (to quote the famous theoretical physicist Lady Gaga) it was born that way. But all the lumpiness and complex history of what happened during the collision are encoded in the gravitational-wave signal—provided we can catch coalescence in the act. That's the goal of experiments such as the ground-based Laser Interferometer Gravitational-wave Observatory (LIGO) and the space-based Laser Interferometer Space Antenna (LISA).

> We can't tell by looking at a black hole if it formed out of a merger or if (to quote the famous theoretical physicist Lady Gaga) it was born that way.

Theoreticians, meanwhile, are not just waiting to see results roll in, but refining their models of this process. That's important for two reasons. First, they may find that it's possible to see gravitational radiation from a black-hole collision that's hidden from ordinary telescopes. Second, if the signal observed at LIGO or LISA deviates from predictions, theory could tell us if these regions of absurdly high gravity also are home to some new and unexpected physical phenomena.

— Matthew Francis

HISTORY

One Question for Simon DeDeo

Do we steer culture or does it steer itself?

WHAT THE DATA SEEM to show is that the ways in which culture evolves are in many ways blind to the individual. People like Martin Luther King, Rosa Parks, or Gandhi do not see themselves as primarily moral entrepreneurs or agents of the future. They see themselves as articulate voices in the right place at the right time, who see something larger than themselves. The great men and women of history maybe are not so important; at least they are not the drivers of things. That might seem distressing. But there's a different story you can tell where this is actually quite heartening.

—SIMON DEDEO *is a professor at Indiana University and a research fellow at the Santa Fe Institute.*

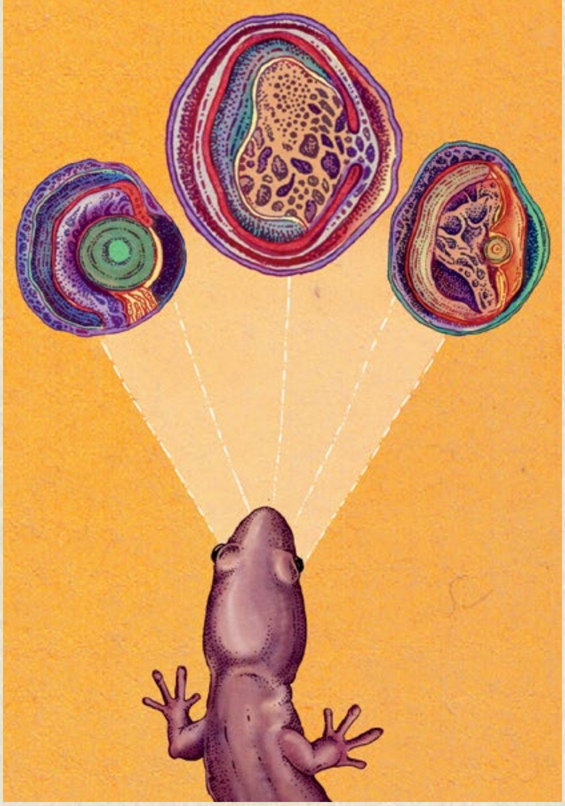
Eye of Newt

A regenerating lens alters science time and time again

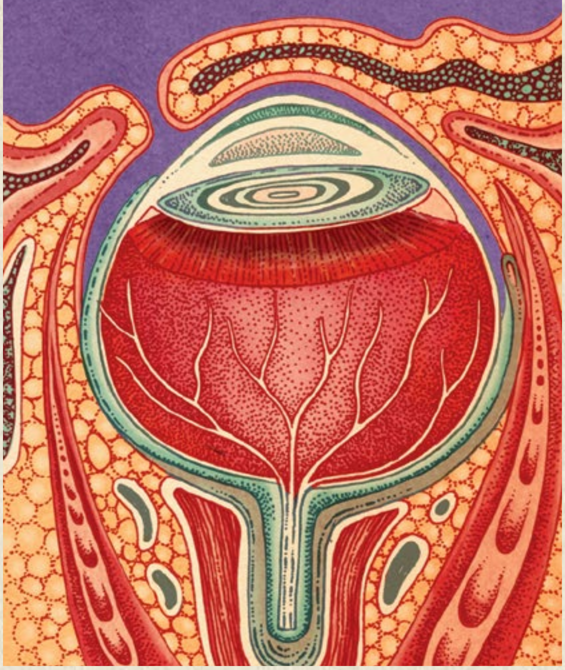
BY AMY MAXMEN ILLUSTRATIONS BY KATIE SCOTT

IN THE LATE 1700s, zoologists decapitated snails and sliced off salamanders' limbs, all to watch the parts regrow. Their meticulously illustrated observations clashed with the prevailing view of the time, called preformation, which held that animals exist in their current form before birth, simply unfolding as they grow. So-called materialists offered a competing theory, named epigenesis, in which body parts transform during development. That upset the establishment by according nature an autonomous power independent of God.

BY THE MID-1800s, preformation theories had faded, but salamanders continued to fascinate. After Darwin published his theory of evolution by natural selection, another biologist, Gustav Wolff, applied Darwin's ideas to newts. When Wolff removed the lenses in their eyes, they regenerated completely. If this capability were truly a product of "survival of the fittest," Wolff wondered why some salamanders and other animals couldn't do the same. He suggested that regeneration was an inherent characteristic, rather than a Darwinian adaptation molded by the environment.*



IN THE 1960s AND 1970s, scientists in Japan removed salamander lenses, and studied how cells at the back of their eyeballs regressed into a "blank" state, reprogrammed, and transformed into glassy cells that aligned in geometrical arrangements to form a lens. If humans could reprogram cells like these creatures could, millions of people with degenerative eye disorders would see clearly.



IN 2006, cell biologist Shinya Yamanaka discovered a recipe for regeneration: Four genes could transform cells from human adults back to a nearly blank state. A few years after his finding, one of the biologists who had sliced salamander eyes in Japan, Panagiotis Tsonis, reported that salamanders use three of the same four genes when they regenerate their lenses. People therefore have the tools to rejuvenate eye parts, but somehow the ability is repressed. Now Tsonis wants to unlock our buried powers to begin again.

*A century after Wolff questioned the Darwinian nature of regenerating lenses, zoologists discovered why some salamanders and newts might be endowed with the adaptation whereas others are not. Parasitic worms frequently infect the eyes of those that regenerate, so the ability presumably allows them to see and survive.

Six Pictures of Paradise

I was puzzled by the artist's photographs of my home in the Amazon. Then I looked again.

BY NIGEL PITMAN
PHOTOGRAPHS BY THOMAS STRUTH

F**OR MANY YEARS I RAN** a field station in Amazonian Peru. The station was a five-hour canoe ride from the nearest road, and every Friday our boat made the long trip upriver carrying crates of groceries, drums of gas for the generator, a mountain of scuffed-up backpacks and duffel bags, and the latest crop of scientists. The station buildings sat on a high bluff that looked a long way down the river, and late Friday afternoon I would begin to hear the buzz of the outboard motor when the boat was still a tiny comet-shaped object rounding the farthest bend. By the time I made it down the long wooden stairway to the riverbank, the sunburnt boat driver was pulling in with his sunburnt passengers.

Of the thousands of people who stepped off that boat during my time at the station—ornithologists, limnologists, philanthropists, schoolchildren, gold miners, filmmakers—one I still puzzle over with some regularity is Thomas Struth, a fine art photographer who worked at the station for a few days in 2005. I had never heard of Struth, but I had seen enough photographers come through the station to know they were usually looking for something specific. Struth seemed different. On his first day I showed him a map of the area and pointed out some of the most photogenic sites around camp. He replied in a quiet way that those places sounded very interesting and that he would very much like to visit them, but that he would probably not take his camera. At first I understood it to be a logistical problem, because he was traveling with a camera the size of a suitcase. But that wasn't the reason at all.

He was after something else. For a long time I didn't understand what it was, and he and his assistant couldn't explain it to me, apart from observing in stilted English that they were "searching for complexity." I gave them a trail map and left them to their own devices. It was no skin off my nose. I had plenty of other things to keep me busy at the station, including a shortage of roof thatch, a pile of unanalyzed data, half a dozen underperforming solar panels, a 2-year-old, and an infant.

"Paradise 28" All images taken in Madre de Dios, Peru, 2005

Then there were the scientists. Some of them were there because they had a newfangled notion about white-lipped peccaries, whereas others wanted to know which flowers a particular butterfly fed on in the dry season, and all of us were burning to write up whatever we learned in some technical journal that, years later, an associate professor might glance at on his coffee break. We even had some honest-to-God eccentrics on hand, including a primatologist who had over the years piled up in her cabin what was surely, at that time, the most comprehensive collection in the southern hemisphere of *Soap Opera Weekly*. Now someone wanted to take pictures of complexity. Shrug—back to the laptop in my cabin—because there were more of these people coming next week, and they needed someone to tell them where to get on the boat.

You looked into a forest understory and your brain started casting about for something to grab onto.

I might never have figured out who Struth was and what he was doing at the station if he hadn't offered to give a talk about his work in our weekly lecture series. Lectures were held in the dining room, after the dinner dishes had been cleared away. We had a fancy projector that looked out of place in the middle of the Amazon, and one of those screens that rolls up like a window shade. When everything went smoothly it felt like you were attending a lecture at the Museum of Comparative Zoology. When things did not go smoothly we lit candles and slapped at mosquitoes until Leo got the generator running again.

Struth started the talk by showing a selection of his best-known photographs, a half-dozen images that are familiar to museumgoers around the world. He was facing a tough crowd, though. Most of the people in the audience that night were museumgoers, but we had been going to a different kind of museum—the kind in Lima or Cusco where the night watchman lets you in after hours so that you can sit up late surrounded by stacks of pressed plants, trying to decipher your handwriting in a muddy field book, where the Plaster-of-Paris dinosaur in the foyer is missing a foot, the doorjambs are covered with schoolboys' initials, and the cleaning lady hasn't had a raise in years. Most of the audience would have felt more comfortable in a lecture on the phytogeography of the nutmeg family. As we sat there in the tropical night looking at Struth's pictures—looking at pictures of parked cars in Düsseldorf; looking at pictures of tourists in the Louvre; looking, for Christ's sake, at a *German family in their living room*—we couldn't help but wonder what on Earth had prompted us that evening to saunter over to the grimy median that separates art from science and see what was happening on the other side. The pictures kept coming. Through the window we could see our colleagues over in the lab building: the happy ones who had chosen to skip the lecture and were contentedly measuring out formalin into tuna fish cans.

Struth, for his part, was also ill at ease. For one thing, in the dark dining room the lit-up projector screen was attracting moths. This was never much of a problem during scientific talks, when anything that landed on the screen provided some decoration to the log-scale axes. But the photographs Struth was showing seemed to focus on stillness, and they were images that he knew down to the finest detail, and he must have found it unsettling to discover a ctenuchid moth fluttering in their corners. Time after time Struth would call up a new photo, step back to appreciate it, and then rush in, arms waving, to scare off a moth. Some of the moths would take flight, and some of the moths would stay where they were. Some turned out not to be moths at all but brown spots left behind by the cockroaches that inhabited the screen between lectures.

Eventually he got to a series he was calling "Paradise." These were photographs he had been taking in forests around the world—and the reason he was visiting the station. They made the biologists in the audience sit up straighter. Here, at last, was something that made sense. But soon enough the audience started to slump again. For every picture that earned an

"Paradise 32" © Thomas Struth, 2014.

appreciative "mmmmm" because it looked beautiful or seemed meaningful, three or four clicked past in awkward silence because they weren't pretty and felt pointless. The scenes of tangled vegetation that Struth had sought out were not necessarily beautiful or symmetrical, not blessed with remarkable lighting or visually striking objects or any kind of grandeur. They were not the kind of thing that your brain could easily tell itself a story about. You looked into a forest understory crisscrossed with vines and shadowed with branches and palm fronds and your brain started casting about for something to grab onto—some way in. Then that picture was gone and you were staring at the next, and it started all over again.

Struth had given up worrying about the moths. Most likely he had noted the audience's unease, and perhaps he was even enjoying it. None of us knew it at the time, but in an interview a few years earlier he had said of the "Paradise" photographs, "One can spend a lot of time in front of these pictures and remain helpless in terms of knowing how to deal with them."

Finally the slideshow was over. The lights came on, Struth said a quiet thanks, and the audience clapped half-heartedly. He hadn't shown any of the photographs he'd taken at the station, and he hadn't said very much about the pictures he had shown. As the scientists filed out of the dining room there was some headshaking, and I realized that my colleagues were angry

"Paradise 29" © Thomas Struth, 2014.

at me for having dragged them to such a flaky event. A mammalogist whispered accusingly, "What the fuck was *that*?"

I wasn't sure. But there was plenty going on at the station that month, and soon enough Struth and his assistant had packed up their things and left, and we moved onto the next thing. A few months later I was eating lunch with a newly arrived researcher. When I happened to mention Struth's visit, she dropped her fork. The last time she visited the Metropolitan Museum of Art, she said, there had been one enormous banner across the facade that said LEONARDO DA VINCI, another enormous banner that said GENGHIS KHAN, and a third enormous banner that said THOMAS STRUTH.

I dropped my fork, too. As my dictionary says: "**struth**, *interj*. A mild oath used to express surprise or dismay."

LIFE WENT ON; many peccaries were captured. At some point our little station had become the busiest research destination in the Amazon. Every Friday the boat was loaded with scientists and students, and I didn't have time to think of anything else. One morning, three years after Struth's visit, a note from Struth turned up in my inbox. Appended to the note were six pictures he had taken at the station. I clicked through them, taking note of what was happening in my brain as they flashed on the screen. In the letter, Struth mentioned that he was exhibiting these pictures at enormous sizes. The largest print was as large as two king-size beds pushed together—so large that you could stand a comfortable distance away and see nothing else. Knowing this made the pictures on my computer screen seem especially tiny. On the other hand, we could do big art. I sent my assistant to scrub the cockroach shit off our projector screen, and after dinner a few weeks later I called everyone together for a slideshow.

By then the National Science Foundation had built us a new, screened-in venue for lectures, and there were so many people in the audience that night that we had to bring over chairs from the lab. For the slideshow, I assembled some of the most interesting photos taken at the station over the last few months, and it only occurred to me too late that it had been a mistake to put Struth's photographs toward the end. Before the audience got their first glance of his work they were treated to a picture of a jaguar pacing a riverbank a few meters from a passing canoe, a camera-trap picture of a gold miner who had wandered onto station property with his shotgun and was peacefully scratching his balls when the shutter clicked, and a picture of a woman giving birth on the floor of our canoe.

By the time Struth's photos came on the screen, the crowd had long since picked its favorites. Following Struth's example, I left his photographs on the screen for an uncomfortably long time, until I heard people starting to shift in their seats. Around the third photo someone in the crowd muttered, "*Ya pues.*" You could translate that as "Enough already," but the more

"Paradise 27" © Thomas Struth, 2014.

“Paradise 30” © Thomas Struth, 2014.

accurate translation in that context would be: "Show more jaguars."

Again people were disappointed. The most common remark I heard over the next few days was, "Are you *kidding* me? I could take those pictures." Which was true, in a broad sense. Struth had taken his photos close to camp, on trails we walked all the time. But that was one of the things that made them interesting: the fact that although any of us *could* have taken those pictures, only one person actually *did*. The thousands of photographs that scientists have given me over the years feature monkeys and macaws and butterflies *ad nauseum*. But the only ones that show what the forest actually looks like on 999 out of 1,000 steps you take on the trails around the station were taken by the guy whose name is on the Metropolitan Museum of Art. Among the thousands of images in my photo library they are immediately recognizable. The only other photo that resembles them at all records the moment in which a botany student from Lima felt the unscientific urge to point her camera straight up at the blue sky and white clouds.

OVER THE NEXT FEW months I spent a lot of time looking at Struth's pictures. To tell the truth, I needed the distraction. Having reached their apogee, things at the station had begun to run rapidly downhill. We had started to run out of money, or had finished running out of money, or had run out of money the year before and not realized it—the accountants in Cusco were trying to figure out which. The fundraising notes I sent out were meeting stiff competition in the form of that year's headlines, which were about global economic collapse. The laboratory roof was leaking, the dining hall roof was leaking, *my* roof was leaking, and the cleaning lady hadn't had a raise in years. Gold miners had invaded station property and were converting a patch of our forest into a gravel pit; they smiled at our protests because gold was selling for $900 an ounce. At the end of the day, after the children had been put to bed and the generator switched off and the only signs of life in the clearing were the far-off flashlight beams of researchers working late in the lab, I used to slump in my chair in the dark and fill the screen of my laptop with Struth's photographs.

Sometimes it helped to pretend I was seeing them through someone else's eyes—one of those people, maybe, who were gazing at them in a white-walled exhibition hall in Basel, where high heels clicked on the polished concrete floors. At one level, as I understood it, those people were looking at a rainforest version of Duchamp's urinal and deriving aesthetic pleasure from an object that was both visually complex and completely free of narrative possibility. Strolling the floors with those pleasantly baffled museumgoers, I liked to reflect, too, on the deeper games Struth was playing. For one thing, those senseless tangles of leaves and vines weren't, it seemed to me, some artifact that we could set on a shelf or hang on a wall. They're our home. They're the place we live. I strolled through the exhibit turning these things over in my mind, turning them over and letting them tumble and scatter, and soon enough I found myself lounging in a café around the corner from the museum in the company of a blonde, to whom I mused, in French, "Perhaps *we* are hanging on *its* wall." Then she suggested an amusing analogy between the Paradise photos and the Garden of Eden, and I countered by asking why 21st-century Man felt so uncomfortable, anyway, in the presence of *l'état sauvage*, and she wondered aloud in a husky voice whether Eve would have liked those pictures better before or after the apple. I nodded shrewdly and leaned back in my chair, savoring the strong coffee and visualizing both of them—Eve and the blonde—stark naked.

Sometimes, waking from those dreams, I'd sit there in my thatched-roof hut wondering in an idle way whether the interest I felt for Struth's photographs wasn't fundamentally pretentious. After all, if a grad student had sent me those pictures I wouldn't have paid them much attention. I might well have thrown them away, grumbling about these beetle taxonomists who take pictures of nothing. But that line of thought never troubled me for long. What intrigued me about the photographs was not that they had been taken by a famous artist, but that they had been taken by a person who had looked at six places in that forest very closely and was now requesting, without much in the way of explanation, that I look at them with the same deliberation.

I'd start looking at the pictures like a scientist determined to miss the point—reducing each of the photographs to a list of plant species.

So I did. The whole here's-an-inscrutable-scene-in-which-you're-going-to-see-nothing line bugged me, though. One reason is that these were pictures of a place I'd lived in for years, a place that hundreds of colleagues had crisscrossed with their backpacks and collecting poles and snake hooks, explicitly trying to make sense of: naming things and tracking them down and trying to figure out just what it was we were seeing. Also, a large part of my own research involves walking into supposedly unfathomable forests and working out what they consist of. I describe forests for a living—and I found it sort of annoying that this German guy with a giant camera seemed to be saying I couldn't.

The forest Struth had photographed was a place in which I couldn't take more than a few steps without thinking, "This is where Darío found the giant armadillo snoring," "That tree is hollow and full of bats," and "There's the hole Diego fell into." One of Struth's pictures had been taken close to the place where one evening, just before sunset, I had felt the need to go bushwhacking off trail, in flip-flops, and had gotten lost. Others were taken a few steps away from a cliff top from which you could watch the sun set over the Andean glaciers. I saw a lot of young rubber trees in the pictures, several of which were taken along a trail where rubber trees were so common that on hot afternoons you could hear the fruits snapping like popcorn and raining down on the understory. In a different season the rubber tree leaves turned blood red before falling, which made them stand out like lit torches in the green canopy, but which also reminded you that the Indians who had lived there 100 years earlier had been massacred by rubber tappers. In one of Struth's pictures, half-hidden among the vines and bamboo stems, I noticed a yellow rope that a grad student who was writing a dissertation on fruit flies had once used to pull his traps up into the canopy.

Then I'd start looking at the pictures like a scientist determined to miss the point—reducing each of Struth's photographs to a list of the plant species it contained and some observations on the successional state of the forest. To my botanist's eye all six photographs give an impression of disturbed forest. The understory is too crowded and the vines too abundant for old-growth, and in every photograph you can see at least one leaf belonging to the Cecropiaceae, which dominates South American clearings. I also noticed very few plant species that tell you just where you are in the Amazon. No matter how scientific I was feeling, knowing these things lent a melancholy tinge to the photographs, because what I was looking at was forest that I'd probably describe to a colleague as "trashed"—the sort of forest I'd hike through on my way to the better stuff, if I were in a part of the Amazon where there still is better stuff.

Sooner or later, meandering in that mood, I'd find myself in a different kind of imaginary café, around the corner from a different kind of museum, drinking beer with a gloomy entomologist who was complaining about a shortage of specimen pins, about the chrysomelids in the collections that were going to waste in the humidity, and about the Amazonian park he had just come back from where the mahogany loggers ruled like kings. Now and then a noisy bus roared past on the street outside. In cafés like that there are no blondes.

WE LEFT THE STATION for good toward the end of 2008. By then, the accountants in Cusco had worked out that I was no longer earning a salary, and under her mosquito netting at night our younger daughter had started having what seemed like epileptic fits. All in all, it felt like a reasonable time to move the family to a place where the elementary schools weren't underwater during the rainy season. By boat, then taxi, then barge, bus, and plane we traveled to the other side of the South American continent, to a city in Brazil where my wife had kept a house for this sort of eventuality. A week later, we were re-learning how to drive a car and pay the monthly electric bill. You'd think it would be impossible, but the memories of the years we spent living on a cliff in the Amazon began to fade.

Eventually you find out the dark nights stretch late on this side of South America too. It was a surprise to discover that the photographs I had brought with me from Peru didn't offer much solace. There were too many faces, too many memories and worries that went along with them. I couldn't look at them without feeling it all starting to weigh on me again: whether the park guards had gotten the raise they deserved or if they were still buttoning up the same crappy canvas uniforms each morning, hoping things might improve next year; whether the roofs were still leaking and whether the staircase had fallen down yet in a landslide; whatever happened to that student who went crazy and spent the whole night sobbing scandalous secrets to me until we could get him out on a canoe at dawn, escorted by park guards to keep him from throwing himself overboard; what kind of school the child born on the floor of our canoe is going to and what sorts of things they teach him there; why I never managed to produce a soils map for the station or survey the largest trees or raise a million-dollar endowment; whether any of those things will get done eventually; and why it is that otherwise sensible people would spend the best years of their lives trying to construct something ambitious in a place where everything rots.

On nights like that, when I get to feeling tired and unsure about where I stand in life, I like to take another long look at Struth's photographs. I've come to love them. Just knowing that these scenes aren't the most beautiful places along the trail system provokes a rush of tenderness for that forest. It's the same thing I feel looking at pictures of my wife caught unaware she's being photographed, when she looks ordinary instead of radiant. It still looks like paradise to me—even if it's paradise on a hot afternoon when the cicadas are buzzing. These are not the kind of pictures you look at and think: Look how beautiful that forest is. Two thousand kilometers away and half a dozen years later, I sit up late with those pictures and think: I loved that forest, and this is what it looked like.

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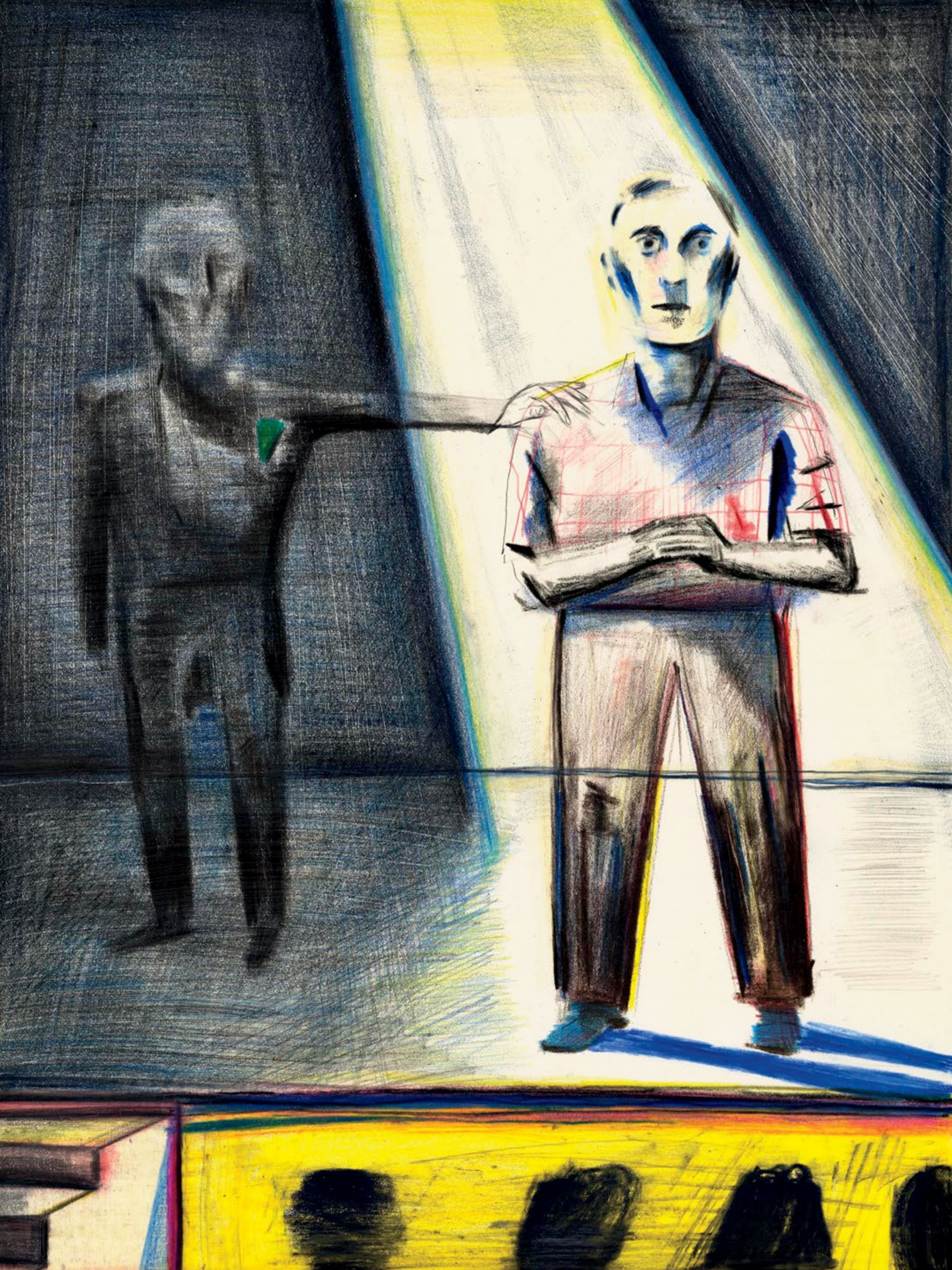

The Great Lindemann

BY DANIEL KEHLMANN

THE LIGHT DIMMED and the murmur of conversation died away. The curtain opened. Lindemann was standing on the stage.

He was plump and had a bald spot made all the more noticeable by the few sparse hairs combed over the nakedness of his skull, and he was wearing black horn-rim spectacles. His suit was gray, and there was a little green handkerchief in the breast pocket. Without preamble, without so much as a bow, he softly began to speak.

Hypnosis, he said, was not the same as sleep, but rather a state of inner wakefulness, not submission, but self-empowerment. The audience would witness astonishing things today, but nobody need have cause for concern, for nobody could knowingly be hypnotized against their will, and nobody could be made to perform some act that in the depths of their soul they were not ready to perform. He then paused for a moment, and smiled as if he'd just delivered some rather abstruse joke.

A narrow set of steps led down from the stage into the audience. Lindemann descended them, touched his glasses, looked around, and walked up the center aisle. Obviously he was now deciding which people to take back up onto the stage. Ivan, Eric, and Martin lowered their heads.

"Don't worry," said Arthur. "He only takes grownups."

"So maybe it'll be you."

ILLUSTRATION BY YANN KEBBI

"It doesn't work on me."

They were about to see something big, said Lindemann. Anyone who didn't want to participate mustn't worry, he wouldn't come too close, the person would be excused. He reached the last row, ran back surprisingly nimbly, and jumped up onto the stage. For starters, he said, something light, just a joke, a little something. Everyone in the first row, please come up here!

A murmur ran through the theater.

Yes, said Lindemann, the first row. All of you. Please be quick!

"What does he do if someone says No," whispered Martin. "If someone just stays in his seat, then what?"

Everyone in the first row stood up. They whispered to one another and looked around unwillingly, but they obeyed and climbed up onto the stage.

"Stand in a line," Lindemann ordered. "And hold hands."

Hesitantly, they did so.

No one was to let go of anyone else, said Lindemann as he walked along the line, no one would want to so no one would do it, and because no one would want to, no one would be able to, and because no one would be able to, it wouldn't be wrong to declare that everyone was literally sticking to one another. As he was talking, he reached out here and there to touch people's hands. Tight, he said, hold hands tight, really tight, nobody step out of the line, nobody let go, really tight, indissoluble. Anyone who wanted to should try and see what happened now.

Nobody let go. Lindemann turned to the audience, and there was some timid applause. Ivan leaned forward to get a better look at the people on stage. They looked uncertain, absentminded, somehow frozen. A little man was clenching his jaws, the hands of a lady with hair pulled into a bun were shaking, as if she wanted to tear free, but was finding that her neighbor's grip, just like her own, was too strong.

He would count to three, said Lindemann, then everyone's hands would let go. "So one. And two. And...," he slowly lifted his hand. "Three!" and snapped his fingers.

Uncertainly, almost unwillingly, they let go, looking at their hands in embarrassment.

"Now go sit down again quick" said Lindemann. "Down. Quick. Quick." He clapped his hands.

The woman with the bun was pale, and swayed as she walked. Lindemann took her gently by the elbow, led her to the steps, and spoke to her quietly. When he let go, she was more sure-footed, went down the steps, and reached her seat.

That had been a little experiment, said Lindemann, an opening trick. Now for something serious. He went to the front of the stage, took off his glasses, and squinted with his eyes scrunched up. "The gentleman in front over there in the pullover and the gentleman right behind him, and you, young lady, please come up."

Smiling awkwardly, the trio climbed onto the stage. The woman waved at someone, Lindemann shook his head in reproof, and she stopped. He positioned himself next to the first of them, a tall, heavyset man with a beard, and held his hand in front of the man's eyes. He spoke into his ear for a while, then suddenly called, "Sleep!" The man fell over, Lindemann caught him and laid him down on the floor. Then he stepped over to the woman next to him and the same thing happened. And then again with the other man. They all lay there motionless.

"And now be happy!"

He must explain, he said. Lindemann turned toward the audience, removed his horn-rims, pulled the green handkerchief out of his breast pocket, and began to polish them. They were all only too familiar, were they not, with the stupid suggestions that mediocre hypnotists—pretentious and untalented incompetents of the sort you encounter by the dozen in any profession—love to instill in their guinea pigs: freezing cold or boiling heat, bodily stiffness, sensations of flying or falling, not to mention the universally beloved forgetting of your own name. He paused and stared thoughtfully into the air. It was hot in here, wasn't it? Terribly hot. So what could be going on? He mopped his brow. Such idiocies were familiar to everyone and he would skip them without further ado. My God, wasn't it hot!

Life being a short day between two endlessly long nights, one should enjoy the bright moments even more and dance for as long as the sun still shone.

Ivan pushed his wet hair back off his forehead. The heat seemed to be rising off the floor in waves, the air was damp. Eric's face was all shiny too. Programs were flapping the air all over the audience.

But something could surely be done to fix it, said Lindemann. Not to worry, the theater had capable technicians. Someone would turn on the excellent air-conditioning at any moment. In fact, it had already been done. Up here you could already hear the humming of the machinery. You could feel the rush of air. He turned up his collar. But now it really was blowing terribly. The equipment was astonishingly powerful. He blew on his hands and shifted from foot to foot. It was cold in here, very cold, really very, very cold indeed.

"What's going on?" said Arthur.

"Haven't you noticed?" whispered Ivan. His breath was rising in clouds, his feet had turned numb, and he was having trouble inhaling. Martin's teeth were chattering. Eric sneezed.

"No," said Arthur.

"Nothing?"

"I told you, it doesn't work on me."

But that was not enough, said Lindemann. Over. The end. As he'd already said, he didn't want to waste anyone's time with such tricks. Now he was going to get to something interesting without any further delay, namely, the direct manipulation of the powers of the mind. The lady and the gentleman here on the floor had already been following his instructions for some time. They were happy. Right here and now, in full view of everyone, they were experiencing the happiest moments of their lives. "Sit up!"

Awkwardly, they hauled themselves up into a sitting position.

"Now look," said Lindemann to the woman in the middle.

She opened her eyes. Her bosom rose and fell. There was something unusual about the way she was breathing and the way her eyes moved. Ivan didn't really understand it, but he recognized something large and complex. He noticed a woman in the row in front of him turning her eyes away from the stage. The man next to her shook his head indignantly.

"Eyes closed," said Lindemann.

The eyes of the woman on the stage closed immediately. Her mouth was open, a thin stream of saliva was running out of it, and her cheeks shone in the spotlights.

Alas, said Lindemann, nothing lasted forever, and the best things always ended first. Life could seem immense and miraculous now, but the truth was that nothing lasted, everything rotted away, everything died, without exception. One almost always repressed that fact. But not now, no, not at this particular moment. "Now you know it."

The bearded man groaned. The woman slowly sank backwards and held her hands over her eyes. The other man sobbed quietly.

But, said Lindemann, one could still feel cheerful. Life being a short day between two endlessly long nights, one should enjoy the bright moments even more and dance for as long as the sun still shone. He clapped his hands.

Obediently this trio stood up. Lindemann clapped the beat, slowly at first, then faster. They leapt like marionettes, throwing their limbs this way and that, and spun their heads. There was absolute silence, no one coughed, no one cleared their throat, the audience seemed transfixed by horror. The only sound was the stamping and panting coming from the stage, and the creaking of the boards.

"Now lie down again," said Lindemann. "And dream!"

Two of them immediately sank to the floor, while the man furthest to the left still remained standing, and seemed to grope with his hands—but then his knees also buckled, and he stopped moving. Lindemann bent down and looked at him closely. Then he turned to face the audience.

He said he now wanted to conduct a difficult experiment. Only a handful of practitioners could pull it off, it required the highest skills. "Dream deeply. Deeply, deeper than ever. Dream a new life. Be children, learn, grow up, fight, suffer, and hope, win and lose, love and lose again, grow old, grow weak, grow frail, and then die, it all goes so fast, and when I tell you, open your eyes and none of it will have happened."

He folded his hands and stood there silent for a long moment.

This experiment, he finally said, didn't always work. Certain subjects woke up and had experienced nothing. Others, by contrast, had begged him to erase their memories of the dream because the experience was too disturbing, in order to regain the ability to trust both time and reality. He checked the time. But meantime, in order to occupy themselves while they were waiting, a couple of simple things perhaps? Any children in the audience? He went up on tiptoe. That boy there in the fifth row, the little girl on the end, and this boy in the third row, the one who's the spitting image of the boy right next to him. Come up!

Ivan looked to the right, then the left, and behind him. Then he pointed to himself questioningly.

"Yes," said Lindemann. "You."

"But you said he only calls grownups onto the stage," whispered Ivan.

"Well, I was wrong."

Ivan felt the blood rush into his face. His heart pounded. The other two children were already on their way to the stage. Lindemann fixed him with his eyes.

"Just stay where you are," said Arthur. "He can't order you around."

Ivan slowly got to his feet. He looked around. Everyone was looking at him, everyone in the auditorium, every single person in the entire theater. No, Arthur was wrong, there was no way to refuse, it was, after all, a hypnoshow, and whoever had come had to take part. He heard Arthur say something else, but didn't understand it, his heart was thumping too loudly, and he was already starting toward the stage. He pushed past the knees of the people in the seats and went up the center aisle.

How bright it was up here. The spotlights were unexpectedly powerful and the people in the audience mere outlines. The three grownups were lying motionless, no sign of life, no sign of breath. Ivan looked out into the orchestra but couldn't locate Arthur or his brothers. Lindemann was already right there in front of him, down on one knee, pushing him back a step very carefully, as if he were a fragile piece of furniture, and looking into his face.

"We're going to do it," he said softly.

Up close, Lindemann looked older. There were furrows around his mouth and eyes, and his makeup was sloppy. Anyone painting his portrait would have had to concentrate on the eyes, deep-set and hooded behind the horn-rims: restless, unreadable eyes, giving the lie to the cliché that hypnotists stared so intensely that a subject would lose himself in their gaze. Besides which, he smelled of peppermint.

"What's your name?" he asked in a slightly louder voice.

Ivan swallowed and told him.

"Relax, Ivan," said Lindemann, his voice now loud enough to carry to the people in the front few rows. "Fold your hands, Ivan. Clasp your fingers."

Ivan did so, wondering how anyone was supposed to relax on a stage in front of so many people. Lindemann couldn't mean it seriously; he was just saying it to confuse him.

"That's right." Lindemann was now addressing all three children, loud enough to be heard anywhere in the theater. "Absolutely quiet, absolutely relaxed, but you can no longer separate your hands. They're stuck to each other, you can't do it."

But it wasn't true! Ivan could easily have separated his hands, he felt no resistance and no blockage. But he didn't feel like blaming Lindemann. He just wanted it to be over.

Lindemann talked and talked. The word *relax* kept being repeated, and he kept saying something about listening and obeying. Maybe it was working with the other two, but it was having no effect on Ivan. He felt no different than before, there was absolutely no question of a trance. It was just that his nose itched. And he needed to go to the toilet.

"Try," said Lindemann to the boy next to Ivan. "You can't let go, you can't, try, you won't be able to."

Wild applause erupted, with stamping of feet and calling, as if nothing were more important to everyone than getting Lindemann's wish granted.

Ivan heard a deep rumbling noise; it took him a few moments to realize that it was laughter. The audience was laughing at them. But not at me, thought Ivan, he must have noticed it's not working on me, that's why he's not giving me questions.

"Lift your right foot," said Lindemann. "All three of you. Now."

Ivan saw the other two lift their feet. He could feel all eyes on him. He was sweating. So what could he do? He lifted his foot. Now they'd all think he was hypnotized.

"Forget your name," said Lindemann to him.

He could feel the anger rising in him. It was all becoming truly stupid. If the man asked him again, he'd show him up in front of everyone.

"Say it!"

Ivan cleared his throat.

"You can't, you've forgotten it, you can't. What's your name?"

The problem was the situation, it was so horribly bright and also really hard to stand on one leg in front of all those people, it took all your concentration to keep your balance. It wasn't his memory that was letting him down, it was his voice. It stuck in his throat and wouldn't come out. Whatever anyone asked him now, he'd have to stay silent.

"How old are you?"

"Thirteen," he heard himself say. So by sheer will he could do it.

"What's your mother's name?"

"Katharine."

"Your father?"

"Arthur."

"Is that the gentleman down there?"

"Yes."

"And what's your name?"

He said nothing.

"You don't know it?"

Of course he knew it. He could feel the shape of its contours; he knew where it was in his memory; he felt it, but it seemed to him that the person this name belonged to was not the person Lindemann was asking, so none of all this really hung together, and was completely irrelevant when set against the fact that he was on one leg on a stage with an itchy nose, his hands squeezed together, and he needed to go to the toilet. And then the name came back to him again, Ivan of course, Ivan, he drew and opened his mouth . . .

"And you?" Lindemann asked the boy next to him, "do you know your name?"

Now I've got it, Ivan wanted to shout, now I can say it! But he stayed silent, it was a relief that the whole thing was no longer about him. He heard Lindemann ask the other two something, he heard them answer, he heard the audience laugh and clap. He felt drops of sweat running down his forehead, but he couldn't wipe them away, it would have been embarrassing to move his hands now when they all thought he was in a trance.

"It's already over," said Lindemann. "Not so bad, was it? Separate your hands, stand on both legs, you know your names again. It's over. Wake up. It's over."

Ivan lowered his foot. Of course it was easy, he could have done it the whole time.

"It's okay," said Lindemann softly, putting a hand on his shoulder. "It's over."

Ivan went down the steps behind the other two. He would have liked to ask them what it had been like for them, what they'd seen and thought, how it felt to be genuinely hypnotized. But he was already back in the third row, people made room for him, he pushed past their knees, and dropped into his seat. He let out a breath.

"How was it?" whispered Martin.

Ivan shrugged.

"Do you remember, or have you forgotten it all?"

Ivan wanted to answer that of course he hadn't forgotten anything and that the whole thing had been a silly trick, but then he realized that the people in the rows in front of them had turned round. They weren't looking at the stage, they were looking at him. He glanced around. The whole theater was looking at him. Lindemann had lied. It wasn't over.

"Is that him?" asked Lindemann.

Ivan stared up at the stage.

"Your father. Is that him?"

Ivan looked at Arthur, looked at Lindemann, looked back at Arthur. Then he nodded.

"Would you like to join me, Arthur?"

Arthur shook his head.

"You think you don't want to. But you do. Believe me."

Arthur laughed.

"It doesn't hurt, it isn't dangerous, you might even like it. Give us the pleasure."

Arthur shook his head.

"Not at all curious?"

"It doesn't work on me," called Arthur.

"Perhaps not. Maybe that's right, it can happen. All the more reason for you to come up here."

"Take someone else."

"But I want you."

"Why?"

"Because that's what I want. Because you believe you don't want to."

Arthur shook his head.

"Come!"

"Go on," whispered Eric.

"They're all looking at us," whispered Ivan.

"So what?" said Arthur. "Let them look. Why do children find everything embarrassing?"

"Let's all say it together!" called Lindemann. "Send him up here to me, show him, clap if you think he should come. Clap loud!"

Wild applause erupted, with stamping of feet and calling, as if nothing were more important to everyone than getting Lindemann's wish granted, as if none of them could imagine anything more satisfying than seeing Arthur up on stage. The noise achieved a crescendo as more and more voices joined in: People were clapping and yelling. Arthur didn't budge.

"Please!" cried Eric.

"Please go," said Martin. "Please!"

"Only for you," said Arthur and got to his feet. He worked his way through the howling crowd to the center aisle, walked to the steps, and climbed them. Lindemann made a rapid gesture and the racket ceased.

"You're going to have bad luck with me," said Arthur.

"Possibly."

"It really doesn't work."

"That nice boy. That was your son?"

"I'm sorry. I'm the wrong person. You want someone who feels awkward first of all, and then chats with you and tells you things about himself, so that you can turn him into a joke and make everyone laugh. Why don't we skip all that? You can't hypnotize me. I know how it works. A little pressure, a little curiosity, the need to belong, the fear of doing something wrong. But not with me."

Lindemann said nothing. The lenses of his glasses glinted under the spotlights.

"Can they hear us?" Arthur pointed to the three motionless bodies.

"They're busy with other things."

"And that's what you'd like to do with me too? Give me another life?"

Ivan wondered how his father was managing to let them all understand every word he said. He had no microphone and he was speaking softly, yet he was completely audible. He stood there calmly as if he were alone with the hypnotist and allowed to ask whatever he wanted. Nor did he seem to be absent-minded any more. He seemed to be enjoying himself.

Lindemann, on the contrary, looked unsure of himself for the first time. He was still smiling, but frown lines had appeared on his forehead. Gingerly he took off his glasses, put them on again, took them off once more, folded them up, and pushed them into his breast pocket behind the green handkerchief. He raised his right hand and held it over Arthur's forehead.

"Look at my hand."

Arthur smiled.

The sound of giggling spread through the audience. Lindemann grimaced for a moment. "Look at my hand, look at it, look at my hand. Just my hand, nothing else, just at my hand."

"I don't notice anything."

"Nor should you." Lindemann sounded agitated "Just look! Look at my hand, my hand, nothing else."

"You're focusing my consciousness on itself, aren't you? That's the trick. My attention is focused on my own attention. A slipknot, and suddenly, it's impossible . . ."

"Are those your sons down there?"

"Yes."

"What are their names?"

"Ivan, Eric, and Martin."

"Ivan and Eric?"

"The Knights of the Round Table."

"Tell us about yourself."

Arthur said nothing.

"Tell us about yourself," Lindemann said again. "We're all friends here."

"There's not much to say."

"What a pity. How sad, if true."

Lindemann lowered his hand, bent forward, and looked at Arthur in the face. Everything was very quiet, the only sound was a faint hiss, perhaps from the air conditioning, perhaps from the electrical current to the spotlights. Lindemann took a step back, a board creaked, one of the sleeping bodies groaned.

"What do you do for a living?"

Arthur said nothing.

"Or don't you have a job?"

"I write."

"Books?"

"If what I write got printed, they'd be books."
"Rejections?"
"A few."
"That's bad."
"No, it doesn't matter."
"It doesn't bother you at all?"
"I'm not that ambitious."
"Really?"
Arthur said nothing.
"You don't look as if you'd settle for a little. You might want to believe that of yourself, but actually you don't. What do you really want? We're all friends here. What do you want?"
"To get away."
"From here?"
"From everywhere."
"From home?"
"From everywhere."
"It doesn't sound as if you're happy."
"Who's happy?"
"Please answer."
"No."
"Not happy?"
"No."
"Say that again."
"I'm not happy."
"Why do you stick it out?"
"What else is there to do?"
"Run?"
"You can't just keep running."
"Why not?"
Arthur didn't reply.
"And your children? Do you love them?"
"You have to."
"Right. You have to. All of them equally?"
"Ivan more."
"Why?"
"He's more like me."
"And your wife? We're all friends here."
"She likes me."
"That wasn't the question."
"She earns money for us, she takes care of everything, where would I be without her?"
"Free perhaps?"
Arthur said nothing.
"What do you think of me? You didn't want to come up to the stage, and now you're standing here. You thought it wouldn't work on you. What do

you think now? For example, of me?"

"A little man. Insecure about everything, which is why you are what you are. Because without all this here, you'd be nothing. Because you stutter whenever you're not up here."

Lindemann was silent for some moments, as if giving the audience the chance to laugh, but there wasn't a sound. His face looked white and waxy; Arthur stood very straight, his arms by his sides, stock-still.

"And your work? Your writing? Arthur, what is it with all that?"

"Not important."

"Why not?"

"A hobby. No reason to fuss about it."

"It doesn't bother you that your work doesn't get published."

"No."

"That you aren't any good? It doesn't bother you?"

Arthur took a small step back.

"You think you have no ambition? But maybe it would be better if you did, Arthur. Maybe ambition would be an improvement, maybe you should be good, maybe you should admit to yourself that you want to be good, maybe you should make the effort, maybe you should work at it, maybe you should change your life. Change everything. Change everything, Arthur. What do you think?"

But above all, people were dangerous.

Arthur said nothing.

Lindemann moved even closer to him, went up on tiptoe and put his face close to Arthur's. "This superiority. Why make the effort, is what you've always thought, isn't it? But now? Now that your youth is over, now that everything you do carries weight, now that there's no time to be casual anymore, what now? Life is over very quickly, Arthur. And it gets squandered even quicker. What needs to happen? Where do you want to go?"

"Away."

"From here?"

"From everywhere."

"Then listen to me." Lindemann put a hand on Arthur's shoulder. "This is an order, and you're going to follow it because you want to follow it, and you want to because I'm ordering you, and I'm ordering you because you want me to give the order. Starting today, you're going to make an effort. No matter what it costs. Repeat!"

"No matter what it costs."

"Starting today."

"Starting today," said Arthur. "No matter what it costs."

"With everything you've got."

"No matter what it costs."

"And what just happened here shouldn't bother you. You can think back on it quite cheerfully. Repeat."

"Cheerfully."

"And it really isn't important. It's all a game, Arthur, just fun. A way to pass the time on an afternoon. Just like your writing. Like everything people do. I'm going to clap my hands three times, then you can go and sit down."

Lindemann clapped his hands: once, twice, three times. There was no sign of any change in Arthur. He stood just as he had before, back straight, his neck tilted slightly backward. There wasn't a sound to be heard. Hesitantly, he turned around and went down the steps. Gradually timid applause broke out here and there, but once Arthur had reached his seat, it crescendoed into a thunder. Lindemann bowed and pointed to Arthur. Arthur imitated him with an empty smile and bowed back.

That was what was so wonderful about his métier, said Lindemann when the noise had finally died down. One never knew what the day would bring, one could never foresee the demands that would be made on one. But now finally for the high point, the star turn. With a light touch on her cheek he wakened the sleeping woman and asked what she had experienced.

She sat up, but after a few sentences the excitement took her breath away. She panted, sobbed, gasped for air. In tears, she described a life as a farmer's wife in the Caucasus, and a hard childhood in the winter cold, she spoke about her brothers and sisters, her father and mother, her husband, the animals, and the snow.

"Can we go?" whispered Ivan.

"Yes, please," said Eric.

"Why?"

"Please," said Martin. "Please, let's go! Please."

As they stood up, there was the sound of snickering in the audience. Eric clenched his fists and said to himself that he was only imagining it all, while Martin understood for the very first time that people could be mean-minded and spiteful, taking malicious pleasure in things for no reason at all. They could also be spontaneously good, friendly and supportive, and both these qualities could exist simultaneously in the same person. But above all, people were dangerous. This realization would stay with him permanently, bound up forever with a memory of Lindemann's face looking down from the stage at their departure, as he polished his glasses with the green handkerchief. At the very moment Martin, bringing up the rear, was leaving the theater, he caught Lindemann's expression: eyebrows arched, smiling, wet tongue peeping from a corner of his mouth. Then there was a little click and the door closed behind him.

The whole way home, Arthur beat time on the steering wheel and whistled. Martin sat very straight next to him, while Ivan stared out of one window and Eric out of the other. Twice Arthur asked what on earth had upset them, why they'd wanted to leave, and why in the world children found everything so embarrassing, but when no one replied, he just said there were some things he'd never understand. That woman, he cried, that idiotic story about the Russian farm, all laid on far too thick, obviously she worked in cahoots with the hypnotist, childishly easy to see through, who would believe stuff like that! He turned on the radio, then turned it off again, then on again, and then, not very long afterwards, off again.

"Did you know," he asked, "that the condor flies higher than any other birds?"

"No," said Eric. "I didn't know."

"So high that sometimes it's no longer visible from the ground. As high as a plane. Sometimes so high, that the distance above it is shorter than the distance below."

"What's that supposed to mean?" asked Ivan. "Above it to where?"

"You know, above it!" Arthur rubbed his forehead. For a few seconds he steered with his eyes closed.

"I don't understand," said Martin.

"What's there to understand? I'd rather you tell me about school and how it's going, you never say anything."

"Everything's fine," said Martin quietly.

"No problems, no difficulties?"

"No."

The car stopped by the house long enough to release the boys while Arthur remembered he had to run an errand. It wasn't till a telegram arrived shortly after midnight that their mother got them out of bed and made them tell her all about it. Arthur had taken his passport and all the money in their joint account. There were only two sentences in the telegram: First, he was fine, no need for concern. Second, not to wait for him. He wouldn't be coming back for a long time.

DANIEL KEHLMANN is the recipient of numerous prizes, including the Candide Prize, the Literary Prize of the Konrad Adenauer Stiftung, the Doderer Prize, the Kliest Prize, the Welt Literature Prize, and the Thomas Mann Prize. His novel *Measuring the World* was translated from German into more than 40 languages.

10

THE ATOMISTS HAVE HAD a good run. Since the time of Democritus, scientists have been busy dividing reality into increasingly smaller bits, leaving us today with atoms and quarks, proteins and genes. This has prompted debates about the limits of reductionism, the role of holism, and the importance of emergent phenomena.

But the simplest legacy of this history of division is an exponential explosion in combinatorial possibilities. For as the list of constituent parts has multiplied, so too have their possible interactions, making the boundaries drawn around scientific disciplines increasingly porous. From polymers to parasites, and genes to galaxies, we have learned that our world is replete with wheelers and dealers, and hosts more shotgun weddings than Las Vegas on New Year's Eve. The result is that almost everything around us used to be two or more of something else—the echo of a very long and growing constitutive alphabet.

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ED YONG
"The Unique Merger That Made You (and Ewe, and Yew)" p.70

Mergers & Acquisitions

HOW NATURE COMES TOGETHER

Can Science Breed the Next Secretariat?

How a "speed gene" test is stirring up horse racing and athletics

BY ADAM PIORE & KATIE BO WILLIAMS

ANY TRAINER WITH GOOD horse sense could have told you that Trading Leather was something special before he raced from the pack, overtook Galileo Rock, and galloped to victory in the prestigious Irish Derby in June 2013. All one needed to do was take in the magnificent crevasse of muscle running down the back of his hindquarters, the length and architecture of his limbs, his inimitable dignity of motion.

But the legendary trainer who bred him, Jim Bolger, 72, had an extra reason to believe his prized colt was suited for the mid-distance race on the storied track at County Kildare. Bolger had Trading Leather tested for the "speed gene." He knew, like an expectant mother who has an embryo tested to find out the sex of her baby, what distance Trading Leather was optimally suited to run and at about what age he'd be ready to run it.

Genetics testing has arrived in the world of thoroughbred horse racing. Bolger, whose name is synonymous with success in that fickle game, has called it "the most important thing that has happened to breeding since it began over 300 years ago." The speed gene is now central to the decisions Bolger makes every year when he sits down to pencil out which of his roughly 100 thoroughbreds to mate, and when to begin training his most promising yearlings. Merging specific gene types from his sires and mares, he believes, can result in new lines of lucrative champions. He's so sure of the science behind the speed gene that he opened a company to sell a speed gene test to his fellow breeders and trainers.

Genetic testing has long been a dream of the sports industry. Since the human genome was mapped in 2000, sports scientists have been racing to identify genes that contribute to athletic superiority. The first test purporting to evaluate human athletic potential hit the market in Australia back in 2004 (arriving in the United States in 2008), a year after a team of researchers published a study linking a single gene to a type of muscle fiber involved in producing the explosive, short-duration bursts of energy needed for sports like powerlifting and sprints. This January, Uzbekistan

ILLUSTRATION BY GRACIA LAM

became the first nation to announce a plan to use genetic tests to evaluate future Olympians. The tests of children as young as 10 will be overseen by a team of geneticists who have been studying the genes of the nation's best athletes for two years, and are preparing a report detailing 50 genes that will form the basis of their talent search.

Every new announcement of a "sports gene" seems to stir up a debate about science and culture, nature and nurture. Can genes account for athletic performance? Are they any match for expert training?

In the tradition-bound world of thoroughbreds, some veteran trainers say they hardly need a genetic test to spot a top horse; besides, genetics can never account for the ineffable qualities of a champion. What makes a good horse, these trainers say, is the strength of his courage, his heart, his grit, and determination to win. Heart is Seabiscuit on the backstretch of Pimlico, lathered in sweat, breathing hard, eyeballing War Admiral, and refusing to let him get a head on him. It's the filly Rachel Alexandra, leg-weary but valiantly turning back the boys in the shadow of the finish line at Saratoga.

Tradition (waistcoats and Derby hats) aside, scientific research into thoroughbreds marks a breakthrough in the racing industry and genetics itself. It has isolated the efficacy of a single gene and shown how a slight variation in that gene can influence athletic performance. It is a tale that began with Emmeline Hill, a young scientist from a prominent Irish horse-racing family.

WHEN SHE WAS A CHILD growing up on a horse farm in County Wexford, a couple hours outside Dublin, Hill often spent time with her grandmother, Charmian Hill, known as "The Galloping Granny." The first woman to compete against men in Ireland, Charmian Hill rode horses in competitions well into her 60s and remains forever wedded in lore to Dawn Run, a legend in Irish racing. (Ireland is the largest producer of thoroughbred foals in Europe, and a major force at the elite levels of the sport.) Perhaps foreshadowing the tensions of her future career, Hill was excused from biology class at the age of 12 to watch Dawn Run leap into history in the 1986 Gold Cup.

At 19, Hill spent a summer working in the stables of John Oxx, an industry heavyweight who produced a racehorse named Sea The Stars, one of the most successful champions of the last decade. After choosing to focus on genetics at Trinity College Dublin and pursue a graduate degree, Hill studied human population genetics and sleeping sickness in African cattle. But it was only a matter of time before she found a way to marry her two passions. In 2004, she received

HORSE SMARTS Emmeline Hill at trainer Jim Bolger's farm in Ireland. She identified a genetic type linked to a horse's performance, a potential revolution in breeding.

Genetics testing has long been a dream of the sports industry. It's now a reality.

a grant from Science Foundation Ireland to study the genetics of racehorse performance. She then began collecting DNA samples from thoroughbreds at horse farms around Ireland. It was an opportune time to be in the field of genetics. The human genome had been sequenced in 2000 and completion of the horse genome was a few years away. Around the world, geneticists were making some of the most profound discoveries since Watson and Crick first identified the double helix structure of DNA.

Every horse (and human being) carries a genetic blueprint in every cell of their body. That blueprint consists of about 20,000 different genes, composed of anywhere from 250 pairs to 2.4 million pairs of DNA's core building blocks, nitrogen-containing compounds known as nucleotides that contain one of four bases, cytosine, guanine, adenine, and thymine. The sequence of these base pairs (totaling about 2.4 billion in a horse), referred to by their first letters—"A," "C," "G," and "T"—encodes the instructions for the structure of every single protein that bodies produce. Those proteins in turn determine everything from the height of a thoroughbred to the color of its coat.

Hill knew that many traits in animals are influenced by the interaction of many genes, and wasn't necessarily expecting to find a single genetic determinant of speed in racehorses. But she did know one place to look for clues: in the single gene that encoded the protein myostatin.

Myostatin inhibits the growth of muscle fibers by limiting the proliferation of muscle cell precursors called myoblasts. Since larger muscles require more calories to sustain them, some have suggested the protein would have conferred an evolutionary advantage by ensuring the size of the muscles remains appropriate, and efficient, for the animal's activity level.

In 1997, a team of researchers at Johns Hopkins University studying mice discovered that the less myostatin a mouse had, the larger its muscles grew. Mice bred to lack the gene that codes for it grew almost comically huge muscles. Follow-up experiments revealed this same mechanism was in play in a number of other species, including an uncommonly muscular breed of cattle known as "Belgian Blue," which also carried genetic mutations that interfered with their production of myostatin.

A compelling example of the potential benefits of a myostatin deficiency appeared in a 2007 *PLOS Genetics* paper on racing dogs. A team led by scientists from the National Institutes of Health found that dogs, so-called "bully whippets," with two copies of a gene that interfered with the production of myostatin were so muscle-bound it slowed them down. But whippets with only one copy of the defective gene—which increased their muscle mass to a size between the two extremes—were significantly faster than both those dogs and dogs whose myostatin was perfectly normal. The paper marked the first time researchers had linked a mutation in myostatin to superior athletic performance.

"The idea from a speed standpoint is that you need power, so you need muscle mass," explains H. Lee Sweeney, a physiology professor at the University of Pennsylvania, who made headlines when he created muscle-bound "Schwarzenegger Mice" by genetically manipulating their myostatin levels. Although the mice

NICK BRADSHAW/FOTONIC

"That can't be right!" Hill recalls thinking. "Then I thought, no, this could actually be real. It started to dawn on me, this could be something really big."

weren't capable of doing anything spectacular, their humongous muscles demonstrated to powerful effect the impact of the protein. "Certainly if you have no myostatin, it makes a big mound of muscle that is not good for anything as far as athletics," Sweeney says. "But getting even a little less myostatin can give you a lot more power."

Animal studies on myostatin gave Hill confidence that she had been looking for speed in the right place. "We knew about this in these species, in sheep and pigs, in humans, in fish," she says. "So I asked the question, 'What about in the horse?' We looked in the literature and nobody had published anything."

Hill knew that thoroughbred horses, like racing dogs, had been bred for generations with an eye toward speed. The term "thoroughbred," in fact, refers to a registered racehorse that can trace its ancestry back to one of three original stallions and about 30 original mares entered in The General Studbook in 1791. Driven by a love of sport, humans, in 300 years, had created a unique kind of horse, using the power of selective breeding to produce speed.

To Hill, it seemed axiomatic that traits for which breeders had selected had genetic correlates. Industry professionals had been making judgments based on the pedigree, physical characteristics, and race records of parents and siblings—all in an attempt to engineer what the product of a planned mating will be capable of on the racetrack. Still, Hill wasn't prepared for the simplicity of the results. When she ran her analysis of the DNA she'd collected from 148 thoroughbreds, variants in the horses' myostatin gene stood out. The vast majority of sequences of Cs, Gs, As, and Ts on the gene were identical. But at the same point on the gene, horses can have two Cs, two Ts, or one copy of each letter from each parent. The three genotypes on this part of the gene are specific to horses (rather than humans), and all horses have one of the three types.

Hill wanted to know if one of the genetic types—CC, CT, or TT—was any more common in winning horses. She retrieved the race results of 142 of her tested horses from racing databases. The genetic type, she discovered, did not appear to predict if a horse would win or lose. But Hill knew that champion horses at different race lengths often have noticeable physical differences. Sprinters tended to be shorter, stockier, and more muscular; long distance racers leaner. So Hill ran the numbers to search for correlations between the distance at which horses ran their best races and their genetic type.

When the results scrolled across her computer screen late one night, she assumed there had been a mistake. A statistically significant "P-value"—essentially the probability a correlation is random—is generally accepted as less than 0.05. Hill's analysis had a P-value with a decimal point and 19 zeroes after it—an unusually potent, unassailably strong correlation.

"Holy shit, that can't be right!" Hill recalls thinking. "Then I thought, no, this could actually be real. It started to dawn on me, this could be something really big."

FOR HILL, IT WAS the first step toward determining three types of horses, named for the letters at one position of the myostatin gene inherited from each parent. She found that CCs excel at sprint races, from 1,000 to 1,600 meters, and, if they're to be a champion, are likely

JERRY COOKE/*SPORTS ILLUSTRATED*/GETTY IMAGES

HEART OF A CHAMPION Seabiscuit, holding off War Admiral to win the “Match of the Century” in 1938.

Research into thoroughbreds shows how a slight variation in a single gene influences performance.

to experience their first win, on average, as 2-year-olds. CTs (like Trading Leather) are best suited to races between 1,400 and 2,400 meters and take home their first trophy at around the same age. TTs excel at races longer than 2,000 meters but generally achieve peak performance seven months later than the other two genetic types.

In 2010, Hill published her research in the science journal *PLOS ONE*, showing a correlation between a horse's genetic type and race distance. "Nobody believed there was a single gene that could predict that," Hill says. "But the more science we do, the more it validates it."

Ernest Bailey, a professor in the veterinary science department at the University of Kentucky, and a leading equine geneticist, calls himself a fan of Hill's published research. "One of the things that was remarkable was to discover one gene with such a large effect," he says. "Most of the genes in humans have been uncovered only by looking at hundreds or thousands of individuals because the effects are so small." Sweeney, of the University of Pennsylvania, also looked at Hill's research. Her "correlations look pretty tight—pretty convincing," he says.

Sweeney notes that while it may seem remarkable that single-letter variants in one gene can produce different traits, there are plenty of other examples. In a 2007 *Science* study, a team of researchers compared the DNA of small dog breeds—Chihuahuas, toy fox terriers, Pomeranians—to several larger dog breeds, including Great Danes, St. Bernards, and Irish wolfhounds. They found that a variation in a single gene, which codes for growth factor, was strongly associated with the size of the tiny dogs.

Similar breeding pressures are a factor in domesticated lines of horses. In a study published in *PLOS Genetics* in 2013, a team of researchers at the University of Minnesota, including James R. Mickelson, who runs a canine and equine genetics lab at the university, examined 33 breeds, some of which were bred for sprint races, such as quarter and paint horses. The team, which included Hill, identified single genes associated with coat color that appeared to be selected for, such as the chestnut coat of Belgian draft horses and the dun coloration of the Norwegian Fjord. They also found that across those sprinting quarter and paint horses, the region of the genome that appeared to have been selected for by engineered mating was in fact the part of the genome that coded for myostatin, the speed gene.

Still, questions remain about whether the speed gene makes horses, well, speedier. For one thing, muscle mass, determined by the gene, is by no means the only determinant of speed. The right balance between body type, bone shape, and muscle size is essential. Mickelson explains that a number of factors contribute to athletic performance in horses. They include the efficiency with which a horse's muscles can absorb oxygen, the thickness and morphology of its bones, and the size of its heart (Secretariat was famed for the size of his).

Further, the precise mechanism by which the speed gene variations influence myostatin production and, ultimately, speed, is not known. In the 2013 *PLOS Genetics* study, the University of Minnesota researchers attempted to get to the bottom of that question. They took muscle biopsies from horses and examined the make-up of the muscle fibers—a key factor in athletic performance—associated with each variation. Muscle fibers come in two major types: "slow-twitch" and "fast-twitch." The two types of fibers rely on different forms of the same proteins to produce the contractions that, in the case of horses, allow the muscle to propel it forward. Fast-twitch fibers are capable of contracting in more rapid succession, generating greater force in a shorter period of time. But they also rely on a kind of metabolism to supply energy that is sustainable for short periods of time, explains Mickelson. Slow-twitch muscles, on the other hand, contract at a slower rate, but are more efficient at converting glucose and fatty acids to energy and tire more gradually than their fast-twitch cousins.

An athlete's ratio of slow-twitch to fast-twitch fibers, which is largely genetically determined, can suggest a predisposition to either sprint or endurance sports. Fast-twitch fibers are dominant in a cheetah's leg muscles, while slow-twitch fibers are dominant in a turkey's legs. Mickelson notes that the speed gene mutation "apparently does cause a shift in fiber type and we do know that it is not changing the size of the fibers." And the correlation of fiber types and performance is borne out in horses. Mickelson found that quarter horses—CCs suited to sprint races—had up to 10 percent more fast-twitch fibers than TT horses, those best suited to distance races. To Mickelson, the conclusion is undeniable: Researchers may not entirely understand how the speed gene works, but it clearly has an effect on a horse's athletic performance. If there's a message for human athletics in Hill's work on horses, it's that myostatin is a rich, complex target for research. Indeed, some geneticists have already shown that a slight variation in the human myostatin gene can subtly alter "muscle power" in ways that affect athletic activity.

IN 2009, HILL JOINED Bolger to form Equinome, a biotech company, to sell the speed gene test. The test sells for $750. So far Equinome has sold more than 5,000 tests. In the past two years, Hill and her colleagues have developed another test to measure a horse's performance, based on a set of 80 gene variants, associated with heart function and muscle contraction, that Hill believes are critical to success. Equinome is not the only game in town. There are at least four other private companies offering to test for a variety of genetic traits purportedly linked to a racehorse's performance. They include the Lexington-Kentucky-based Performance Genetics, which used their own genetic tests on the one-time favorite in the 2013 Kentucky Derby, Verrazano, two years before they purchased him.

Many industry professionals, however, are not sold on the tests. "I believe I can look at the catalog and look at the horse, and get it right 98 percent of the time on that simple equation alone, without the expense of a DNA test," says Jon Freyer, Stud Bloodstock Manager for Arrowfield. Arrowfield is one of the leading breeding farms in Australia, and Freyer is a respected voice in the Antipodean racing industry. Freyer says one can identify a "sprinter" or a "stayer" by the records of the particular yearlings' parents and antecedents. "You should not need a $1,000 test to prove something that should be fairly obvious. To identify if a horse is a CC or a TT is pretty clear cut," he says.

Mike Trombetta, owner and trainer at Escape Stables in Maryland, who has trained horses that have run in the Kentucky Derby and the Preakness, says he is also skeptical of a genetic test's value. Even if he did know a horse's genetic type, that would be no substitute for testing the horse in action. "As a trainer, I don't really give up on any individual horse until we try him out at different lengths on different surfaces," he says. "What are you going to do if the test doesn't tell you what you were looking for? Give up on a horse without trying him out?"

Trombetta's rhetorical question is echoed by David Epstein, author of the 2013 book, *The Sports Gene*, which concludes that science has a way to go before genetic testing will be capable of making a meaningful impact on sports. Epstein notes that a much more direct method of evaluating athletic ability would simply be to watch a horse or human run. Why examine the speed gene? "If you know what you are looking for, why not just use a stopwatch?" he says.

Hill, who also heads the Equine Exercise Genomics research group at University College Dublin, admits the test is a tool that could never replace the judgment of thousands of sage industry hands who make their living practicing the art of horsemanship. She acknowledges that the skill and care with which a horse is trained and raised can account for anywhere from 30 to 65 percent of overall performance.

Nevertheless, Hill says, genetic tests offer insights that trainers may be missing, such as the fact that TTs are likely to reach peak speeds at a later age than CCs. She surveyed horses at Irish racing yards and found that trainers were entering the two types of horses in sprint and longer races at the same age. "This suggests trainers are not fully aware of the genetic differences," she says.

On a rainy Tuesday in January, at his farm in Coolcullen, County Kilkenny, Ireland, Bolger said that after all of his years of breeding horses, the speed gene test had revolutionized his approach. He credits the test for a reduction in TT colts, a horse he has traditionally had far less success training and racing. "I know like the back of my hand what type the mares are, and I know how some of the stallions are," he says. "With that knowledge, we have reduced our TT numbers from over 25 percent to around about between 3 and 5 percent."

At the same time, Bolger wasn't quite ready to abandon his experience to genetics. He grew philosophical as he watched handlers lead Trading Leather onto a patch of grass, where the champion stood snorting and bobbing his head. "Breeding horses is a bit like pebble-dashing a wall, throwing at it, seeing if it's going to stick," Bolger said. "Full brothers and full sisters can be very different." He motioned toward Trading Leather. "His full brother that came before him is a TT, and he was no use," he said.

Sometimes when he evaluates a horse, Bolger said, "I don't know exactly what I'm looking at. It's just a feeling." Bolger said genetics has a way to go before it can identify the trait he would most like to test for: "Is he a champion?" Identifying that quality will probably always require the experienced eye of veteran industry hands, along with an assist from the alignment of the stars, Bolger said. But even one of the world's best trainers can use a little help sometimes. "I don't have to wing it as much nowadays," he said. "I have the science."

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“IS IT NORMAL TO HOARD?”
BY YUKO SHIMIZU


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Fig. 101. — encéphale et nerfs

Trying Not to Try

Modern science and Chinese philosophy tell us similar stories about how we think

BY EDWARD SLINGERLAND

IN A FAMOUS STORY from ancient Chinese philosophy, Butcher Ding has been called upon to play his part in a traditional religious ceremony. The ritual, to consecrate a newly cast bronze bell, requires the butcher to sacrifice an ox in a public space, with the ruler and a large crowd looking on. The still-smoking bell is brought fresh from the foundry and cooled with the blood of the sacrificial animal—a procedure that demands precise timing and perfectly smooth execution. Butcher Ding is up to the task, dismembering the massive animal with effortless grace: "At every touch of his hand, every bending of his shoulder, every step of his feet, every thrust of his knee—swish! swoosh! He guided his blade along with a whoosh, and all was in perfect tune." Ding's body and blade move in such perfect harmony that a seemingly mundane task is turned into an artistic performance. When questioned later by Lord Wenhui, the village master, about his incredible skill, Butcher Ding explains, "What I, your humble servant, care about is the Way [Dao]." He then launches into an explanation of what it feels like to perform in such a state of perfect ease:

> When I first began cutting up oxen, all I could see was the ox itself. After three years, I no longer saw the ox as a whole. And now—now I meet it with my spirit and don't look with my eyes. My senses and conscious awareness have shut down and my spiritual desires take me away. I follow the Heavenly pattern of the ox, thrusting into the big hollows, guiding the knife through the big openings, and adapting my motions to the fixed structure of the ox. In this way, I never touch the smallest ligament or tendon, much less a main joint.

The result is that Butcher Ding is not so much cutting up the ox as releasing its constituent parts, letting the razor-sharp edge of his cleaver move through the spaces between the bones and ligaments without encountering the slightest resistance.

It is not all smooth sailing. Occasionally Butcher Ding's effortless dance is interrupted when he senses

ILLUSTRATION BY PEP MONSTERRAT

trouble, at which point his conscious mind seems to reengage a bit, although he still remains completely relaxed and open to the situation confronting him: "Whenever I come to a knot, I see the difficulty ahead, become careful and alert, focus my vision, slow my movements, and move the blade with the greatest subtlety, so that the ox simply falls apart, like a clod of earth falling to the ground." Lord Wenhui clearly sees something in this account that goes far beyond simply cutting up oxen. "Wonderful!" he exclaims. "From the words of Butcher Ding I've learned how to live my life!"

This remark signals to us that we should be taking the story of the ox as a metaphor. The story of Butcher Ding comes from a book called the *Zhuangzi*, an important work of Daoist philosophy, and one that is principally concerned with a value known as *wu-wei*, or effortless action. *Wu-wei* literally translates as "no trying" or "no doing," but it's not at all about dull inaction. In fact, it refers to the dynamic, spontaneous, and unselfconscious state of mind of a person who is optimally active and effective. For a person in *wu-wei*, proper and effective conduct follows as automatically as the body gives in to the seductive rhythm of a song. This state of harmony is both complex and holistic, involving as it does the integration of the body, the emotions, and the mind. Just as Butcher Ding's blade remains razor-sharp because it never touches a bone or ligament—moving only through the gaps in between—so does the *wu-wei* person move only through the open spaces in life, avoiding the difficulties that damage one's spirit and wear out one's body. This is a metaphor that has not lost any of its power. I, for one, can attest that, after 40-odd years of sometimes hard living, my own blade feels a bit nicked and dull.

The preoccupation with how to cultivate *wu-wei* was at the center of early Chinese controversies about how to attain the good life. Characterizations of *wu-wei* in other early Daoist texts, such as the *Laozi*, take the form of concise, cryptic poems rather than stories. They often describe the "Way of Heaven" as a model for how a properly cultivated person should move through the world. In the poems, the Laozian sage attains *wu-wei* by not trying, by simply relaxing into some sort of preexisting harmony with nature. The Daoist poems are characterized by an effortless ease and unselfconsciousness that also plays a central role in early Confucianism. This may come as a surprise, because Confucianism is typically associated with hidebound traditionalism and stuffy ritual—both of which strike us as the opposite of *wu-wei*. It can't be denied that the Confucians do a lot to earn this reputation. In the early stages of training, an aspiring Confucian gentleman needs to memorize entire shelves of archaic texts, learn the precise angle at which to bow, and learn the length of the steps with which he is to enter a room. His sitting mat must always be perfectly straight. All of this rigor and restraint, however, is ultimately aimed at producing a cultivated, but nonetheless genuine, form of spontaneity. Indeed, the process of training is not considered complete until the individual has passed completely beyond the need for thought or effort.

My guess is that we have all experienced this combination of effortlessness and effectiveness at some point in our lives. While we are completely absorbed in chopping and sautéing, a complex dinner simply assembles itself before our eyes. Fully relaxed, we breeze through an important job interview without even noticing how well it's going. Our own experiences of the pleasure and power of spontaneity explain why these early Chinese stories are so appealing and also suggest that these thinkers were on to something important. Combining Chinese insights and modern science, we are now in a position to understand how such states can actually come about.

Colloquially, we often speak of ourselves as if we were split in two: "I couldn't make myself get out of bed this morning," "I had to force myself to be calm," "I had to hold my tongue." Although we use such phrases all the time, if you think about them they're a bit weird. Who is the self who doesn't want to get out of bed, and what is its relationship to me? Does my tongue really have a will of its own, and how do I go about holding it? (And who am I if not my tongue?) Since there is always only one "me" involved, this split-self talk is clearly metaphorical rather than literal. Talk of split selves is certainly not limited to English: we can see it in many *wu-wei* stories from early China that involve a narrative "I" confronting a part of the self that is more or less autonomous.

We can see our autonomous self in action when we walk. We don't worry about how to walk, we don't consciously monitor ourselves while we're walking, we just walk. In fact, actually thinking about walking while trying to walk is a great way to trip. And walking is just one of many things our body knows how to do without any input from our conscious mind. When we reflect upon this, we get a strong sense of being split between a conscious "I" and an unconscious body, which often seems to have a mind of its own.

Recent research suggests that there might be some basis to this idea. Although there is only one me, in an important functional sense we are divided into two beings. There is now general agreement that human thought is characterized by two distinct systems that have very different characteristics. The first and most important of these (tacit, hot cognition, or "System 1") is fast, automatic, effortless, and mostly unconscious, corresponding roughly to what we think of as "the body" and what the *Zhuangzi* calls the "Heavenly mechanism." The second (explicit, cold cognition, or "System 2") is slow, deliberate, effortful, and conscious, corresponding roughly to our "mind"—that is, our conscious, verbal selves.

So if I say that I had to force myself not to reach for that second helping of tiramisu, there is a more than metaphorical struggle going on. My conscious, cold system, which is concerned about long-range issues like health and weight gain, is fighting to control the more instinctive hot system, which really likes tiramisu and doesn't share my cold system's concerns about the consequences. This isn't because hot cognition doesn't take future consequences into account. The problem is that this system's conception of relevant consequences was fixed a long time ago, evolutionarily speaking, and is fairly rigid. "Sugar and fat: good" was for most of our evolutionary history a great principle to live by, since acquiring adequate nutrition was a constant challenge. Today, on the contrary, allowing ourselves to indulge in them to excess has a variety of negative consequences. The great advantage of cold cognition is that it is capable of changing its priorities in light of new information. So another way to think about how the systems differ is that hot cognition is evolutionarily older and more rigid, while cold cognition is evolutionarily newer and more flexible—and therefore more likely to adapt to novel behavioral consequences.

These two systems are even, to some degree, neuroanatomically distinct—that is, they are implemented

Wu-wei literally translates as "no trying" or "no doing," but it's not at all about dull inaction.

The goal is to get these two selves working together smoothly and effectively.

in different parts of the brain. In fact, our first hint that the two systems existed came from clinical cases where selective brain damage allowed researchers to watch one of them functioning without the other. Anyone who has seen the movie *Memento* (2000) is familiar with a condition called anterograde amnesia: Patients afflicted with this condition cannot form new, explicit short-term memories. They remember who they are and the more distant past but are condemned—consciously, at least—to a perpetual forgetting of the present. What's interesting is that, although these patients can't form new conscious memories, at a subconscious level they are able to form new, implicit ones. They cannot consciously recall ever having met the doctor who greets them every day with a thumbtack hidden in his palm, but for some reason they don't want to shake his hand. We see a similar disjunction when it comes to different types of skills: Unconscious "knowing how" seems distinct from conscious "knowing that." As with emotional memories, the two types of knowledge seem to be created and preserved in different parts of the brain. Not only can amnesiac patients "remember" not to shake hands with Dr. Thumbtack, they are also able to pick up new physical skills after a period of instruction without having any conscious memory of the training, even while remaining completely unable to explain how or why they have this new ability.

So although talk of "mind" and "body" is technically inaccurate, it does capture an important functional difference between two systems: a slow, cold, conscious mind and a fast, hot, unconscious set of bodily instincts, hunches, and skills. "We" tend to identify with the cold, slow system because it is the seat of our conscious awareness and our sense of self. Beneath this conscious self, though, is another self—much bigger and more powerful—that we have no direct access to. It is this deeper, more evolutionarily ancient part of us that knows how to spit and move our legs around. It's also the part that we are struggling with when we try to resist that tiramisu or drag ourselves out of bed for an important meeting.

The goal of *wu-wei* is to get these two selves working together smoothly and effectively. For a person in *wu-wei*, the mind is embodied and the body is mindful; the two systems—hot and cold, fast and slow—

are completely integrated. The result is an intelligent spontaneity that is perfectly calibrated to the environment. The ease perceived by observers of his performance mirrors Ding's own internal experience, in which his "spiritual desires" take him away and the ox falls apart effortlessly.

Recall the stages of "seeing" that the butcher describes to his lord: "When I first began cutting up oxen, all I could see was the ox itself. After three years, I no longer saw the ox as a whole. And now—now I meet it with my spirit and don't look with my eyes." These lines appear to describe the act of "seeing" by using different parts of the self. When Butcher Ding is a complete novice, and all he can see is "the ox itself," he is merely looking with his eyes, gazing upon this massive, daunting creature that he must somehow reduce to pieces. Anyone who has ever seen an ox up close—not a common experience in our modern world—can vividly imagine the plight of the neophyte Butcher Ding. There he is, standing in front of this massive wall of hair and flesh, cleaver in hand, with no idea where to begin or what to expect once he makes the first cut.

After three years of practice and training, Butcher Ding reached a point where he "no longer sees the ox as a whole." Perhaps Butcher Ding now looks at the ox and sees, superimposed upon it, something like the charts that hang in butchers' shops, illustrating the different cuts of meat. The ox, for him, is no longer simply a dumb, inert object in his path. Drawing upon his training and analytic mind, Butcher Ding now perceives it in terms of its constituent parts, as a set of cuts that he can make, or a set of challenges to be traversed.

Finally, Butcher Ding reaches a stage where, as he puts it, he no longer looks with his eyes: "My senses and conscious awareness have shut down," he explains, "and my spiritual desires take me away."

But to understand how the deliberate part of his brain shuts down, we need a clear understanding of what effort and consciousness feel like from the inside.

Let's begin with a little exercise. Go down the list of words in the next column, and as quickly as possible read each word silently and then say out loud either "upper" or "lower," depending on whether the word itself is written in upper-or lowercase letters.

UPPER
lower
lower
upper
LOWER

Unless you are an alien cyborg from Alpha Centauri, you were probably cruising along until you reached the last two, where you stumbled a bit and took longer to say "lower" while reading upper, and then "upper" while reading LOWER. That slight catch as you began to talk—that feeling of needing to stop yourself, to not read the word but instead focus on its case—has been referred to as the oomph that is the hallmark of conscious will or effort. A task that presents someone with this kind of mismatch between the meaning of a word and its physical appearance is commonly referred to as a "Stroop task," after the American psychologist who published a paper on the effect in the 1930s, originally using words printed in incompatible colors (for example, the word green printed in red ink). The Stroop task is a classic example of what's called a cognitive control or executive control task—that is, a situation where the cold, conscious mind (System 2) has to step in and override automatic, effortless processes (System 1).

Brain imaging studies suggest that two brain areas in particular are involved in cognitive control: the anterior cingulate cortex (ACC) and the lateral prefrontal cortex (lateral PFC). Together these are the "cognitive control regions" of the brain. There is still some debate about the precise role played by each of these regions, but one plausible characterization is that the ACC is a kind of smoke detector, and the lateral PFC is the fire response team. Like a smoke detector, the ACC is in constant monitoring mode, waiting to detect a whiff of danger, such as an instance of cognitive conflict. In the case of the Stroop task, we've got two automatic processes that are in conflict: the identification of a typeface or color versus the automatic processing of a simple word (assuming you're literate and it's your native language). This conflict alerts the ACC, which then sends out an alarm to the lateral PFC to come deal with the situation.

Butcher Ding's story shows us that many desirable states are best pursued indirectly.

The lateral PFC is responsible for many higher cognitive functions, such as the integration of conscious and unconscious knowledge, working memory (the small spotlight of consciousness that allows us to focus on explicit information), and conscious planning. Most relevantly, when it comes to the case of the Stroop task, the lateral PFC also exerts control over other areas of the brain by strengthening the activation of task-relevant networks at the expense of other networks. By weakening certain neural pathways, the lateral PFC essentially tells them to stop doing what they are doing, which is the neural equivalent of fire-retarding foam.

In the Stroop task presented above, you were asked to read the word LOWER but say the word upper. The ACC lets the lateral PFC know about the conflict between your perception of the word's case and your knowledge of the word's meaning. The lateral PFC then draws upon its understanding of what the task requires—you've been asked to say aloud the case, not read the word itself—and decides that saying "upper" should take precedence. It then sends a signal telling the visual system, which detects case, to get on with its business; this strengthening of the visual system encourages the word recognition system to just shut up. This whole rigmarole is what results in the slight delay and the feeling of effort that you don't get when the word lower is actually printed in lowercase letters. In the latter case, the two regions work together happily, the ACC conflict detector is not activated, and the lateral PFC is not called upon to adjudicate between squabbling sets of neurons. You can also get a sense of what cognitive control feels like internally if you think about the process of learning a new skill (driving, kayaking, whatever). In the early stages, constant vigilance and effort are required (the ACC and lateral PFC are very active), but as you master the skill, control gets passed to subconscious, automatic systems, and your conscious mind is now freed for other tasks.

Armed with this information, we can now see how a brain on *wu-wei* might function. We can even get a reasonably precise picture of it, thanks to some recent neuroscientific work on *wu-wei*–like states. A clever study by Charles Limb and Allen Braun peered into what's happening in the minds of professional jazz pianists in action. They designed a special, nonferromagnetic keyboard that could be taken inside an fMRI scanner, which is basically a huge magnet. The researchers then had them play in two different conditions. In the first, "Scales," they were required to play, over and over, a one-octave C scale. In the "Jazz Improv" condition, they were asked to remain in the same key but improvise a melody based upon a composition they'd previously been asked to memorize.

The researchers' most striking finding was the pattern of activation when the pianists switched into improvisation mode: widespread deactivation of the lateral PFC and increased activity across relevant sensorimotor systems, the ACC, and the frontal polar portion of a region known as the medial prefrontal cortex (MPFC). What this study suggests is that, in a spontaneous yet high-skill situation such as jazz improv, the conflict-detecting ACC remains alert in the background even when the lateral PFC is turned off. This particular neural configuration may correspond subjectively to the kind of relaxed but vigilant mode we enter into when we're fully absorbed in a complex activity. In other words, at least some forms of *wu-wei* appear to involve shutting down active conscious awareness and control while maintaining background situational alertness. When your conscious mind lets go, the body can take over.

The early Chinese ideal of *wu-wei* involves just this sort of effortless action, and the body unleashed is impressive to behold. After all, when Lord Wenhui sees Butcher Ding's performance, he doesn't thank him for teaching him to cut an ox, he makes the bigger claim that Ding taught him how to live his life better. That's the power of *wu-wei*. We have been taught to believe that the best way to achieve our goals is to reason about them carefully and strive consciously to reach them. But Butcher Ding's story—and the science that's beginning to back it up—shows us that many desirable states are best pursued indirectly. Harnessing the power of spontaneity can give us a deeper understanding of how we move through the world and interact with others and can help us to do it effectively, and with ease.

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How the Cold War Created Astrobiology

Life, death, and Sputnik

BY CALEB SCHARF

ASTRONOMY AND BIOLOGY have been circling each other with timid infatuation since the first time a human thought about the possibility of other worlds and other suns. But the melding of the two into the modern field of astrobiology really began on Oct. 4, 1957, when a 23-inch aluminum sphere called Sputnik 1 lofted into low Earth orbit from the desert steppe of the Kazakh Republic. Over the following weeks its gently beeping radio signal heralded a new and very uncertain world. Three months later it came tumbling back through the atmosphere, and humanity's small evolutionary bump was set on a trajectory never before seen in 4 billion years of terrestrial history.

At the time of the ascent of Sputnik, a 32-year-old American called Joshua Lederberg was working in Australia as a visiting professor at the University of Melbourne. Born in 1925 to immigrant parents in New Jersey, Lederberg was a prodigy. Quick-witted, generous, and with an incredible ability to retain information, he blazed through high school and was enrolled at Columbia University by the time he was 15. Earning a degree in zoology and moving on to medical studies, his research interests diverted him to Yale. There, at age 21, he helped research the nascent field of microbial genetics, with work on bacterial gene transfer that would later earn him a share of the 1958 Nobel Prize.[1,2]

Like the rest of the planet, Australia was transfixed by the Soviet launch; as much for the show of technological prowess as for the fact that a superpower was now also capable of easily lobbing thermonuclear warheads across continents. But, unlike the people around him, Lederberg's thoughts were galvanized in a different direction. He immediately knew that another type of invisible wall had been breached, a wall that might be keeping even more deadly things at bay, as well as incredible scientific opportunities.

If humans were about to travel in space, we were also about to spread terrestrial organisms to other planets, and conceivably bring alien pathogens back

ILLUSTRATIONS BY GRACIA LAM

to Earth. As Lederberg saw it, either we were poised to destroy indigenous life-forms across our solar system, or ourselves. Neither was an acceptable option. When he returned to the United States he quickly threw himself into learning all he could about astronomy and rocketry, and began writing urgent letters to the National Academy of Sciences, alerting his colleagues to the imminent danger.

A mission must present no more than a 1 in 10,000 chance of disrupting an alien ecosystem.

By the spring of 1958, Lederberg's warning of a "cosmic catastrophe" was starting to make people sit up and pay attention. But this pot-stirring wasn't just about scaring researchers and policy makers. It also marked the birth of a new type of science that could take place outside the usual bounds of the planet. In his own words, "I was the only biologist at the time who seemed to take the idea of extraterrestrial exploration seriously." His considerable reputation didn't hurt, and in the following years Lederberg managed to place biological investigations squarely on a fledgling NASA's agenda, coining a new term along the way, "exobiology"—the study of life beyond the Earth.

Exobiology profoundly influenced the way space exploration was conducted. Strict protocols were developed for the sterilization of spacecraft, and for quarantines to restrict what they might bring back. NASA built clean rooms, and technicians swabbed and baked equipment before sealing it up for launch. Scientists got to work and hurriedly computed the acceptable risks for biological contamination of other worlds. One of the standards developed stated that a mission must present no more than a 1 in 10,000 chance of disrupting an alien ecosystem, a somewhat arbitrary choice that perhaps says more about our tolerance for messing up planets than anything else.

Later, upon the triumphant return of Apollo 11, instead of being paraded, the astronauts were promptly locked up in a converted Airstream trailer for three weeks of careful isolation. There is a well-known picture of President Nixon grinning at Armstrong, Aldrin, and Collins, all safely behind the trailer's airtight window, and perhaps happier for it. Eventually, after Apollo 14, it became clear that the lunar surface environment was effectively sterile, and so future quarantines were skipped.

Lederberg wasn't finished though. He and the young Carl Sagan had become friends in the early 1960s, and together they helped define the emerging fields of solar system exploration and the search for extraterrestrial life. In 1965, NASA's Mariner 4 spacecraft sped by Mars, sending back the first close-up images of a desolate and cratered world, an arid desert planet. No vegetation, no civilization, barely an atmosphere. It was a pivotal moment, far removed from earlier optimism about life in our solar system, and it made clear how demanding biological exploration was going to be—if there were clues to life out there, they were going to be found with a microscope. In light of this information, Lederberg, Sagan, and others spurred advanced conceptual and experimental work on microbial and chemical assays that would culminate with the spectacular Viking missions to Mars in 1976. These twin landers carried highly sensitive automated wet labs, specifically for incubating and detecting microbial organisms that could be lurking in its red soil—one of the last reasonable refuges for life in this inhospitable place.

However, for all their sophistication, in many respects the Viking missions to Mars also represented the end of Lederberg's brand of exobiology. The landers' attempts to spot microorganisms, or any sort of organisms, didn't pan out. The biological tests gave confusing and unexpected results, now generally considered to be a consequence of the rather fearsome chemistry of the upper soil—full of nasty oxidants akin to substances used in rocket fuel. Viking made it clear that finding life beyond the Earth was going to be vastly more challenging than hoped—or feared.

Partly in response, partly as a natural evolution, the specialized study of exobiology began morphing into a much larger scientific fishing net. It co-opted everything, from terrestrial microbiology and the origins of life, to interstellar chemistry, planetary physics, and even a smattering of cosmology. This wasn't an easy transformation. It was a field with pitifully little data. But much of the impetus of Lederberg's original vision remained; these were profound questions, and appetites had been whetted. In the U.S., NASA stuck to its guns, supporting an unprecedented array of interdisciplinary studies ranging from evolutionary biology to astrochemistry; actively seeking out science that would otherwise fall through the cracks of conventional funding programs.

In the late 1970s and into the '80s, scientists' imaginations were reignited by the discovery of terrestrial organisms living in remarkably extreme environments. Microbes and larger creatures were found supping the noxious super-heated effluvia of volcanic vent systems, kilometers down in the world's oceans. Elsewhere, bacteria were identified that readily survived desiccation, ionizing radiation, and freezing. Carl Woese and other scientists identified the great domain of archaea and provoked a host of new ideas on the origins of life, and Thomas Gold talked about the insinuation of life into subsurface planetary environments. There was a sense that we had overlooked much about life on Earth, and that meant we might have overlooked much about life elsewhere, too.

By the 1990s the term exobiology was barely adequate to convey the scope of scientists' questions, and the effort was re-branded as "astrobiology," a full-on merger of astronomy and biology. It had become the quest to understand life as a truly cosmic phenomenon—a pan-disciplinary adventure that started taking shape just as the first bona fide planets were discovered orbiting other sun-like stars in 1995.

In retrospect, it was an incredibly fortuitous chain of events that led up to this point, beginning with bacteria and Sputnik, and ending with exoplanets. Had the timing been different we could have unwittingly bumbled around contaminating the solar system left and right, far beyond any natural diaspora. In doing so we'd have hindered, possibly squandered, the opportunity to examine the indigenous life that might exist on other worlds.

Instead, we sipped a cocktail of Cold War posturing and paranoia, garnished with Lederberg's quick-witted thinking. This put the superpower space race into a bio-containment lockdown, but it also bought time to look more closely and carefully at other worlds. And had we not quickly sobered up with those early visits to Mars, and even Venus, we'd have missed the deeper implications about life's abundance. Life is not a given, its frequency on the cosmic stage is a vital statistic to learn, but gaining that knowledge is one of the greatest scientific challenges of all time. For these reasons astrobiology is arguably both the luckiest and the unluckiest scientific field of the past hundred years.

The venture can still be a slightly uneasy partnership; biologists and astronomers don't always see eye-to-eye on scientific priorities. But we deal with it, because in many respects Lederberg's original motivation to protect and preserve is also more urgent than ever. We're not just looking to discover life's cosmic abundance, we're also looking to place our own world in proper context, to understand it well enough to try to plot a stable course through the environmental changes that we're carelessly, and probably needlessly, making.

Here too is a hint to the greatest union, the one yet to come. We now know for a fact that Mars has at times been a far more temperate place. We also know that our solar system does not harbor the kinds of planets that may be most numerous in the galaxy, those a little larger than Earth. Such worlds exhibit extraordinary diversity, even when examined with our currently primitive data. Some are dense and rocky, or strange places with gas-rich envelopes. Others perhaps have radically different geochemistry, where carbon, not silicon, is the bedrock. One day soon we'll have to find a way to explain our place within that planetary menagerie, and maybe we'll have to explain our place within an extraterrestrial biological menagerie too. That will be the ultimate merger of knowledge, the placement of Earth's life on the cosmic stage—when astrobiology finally comes out of the cold.

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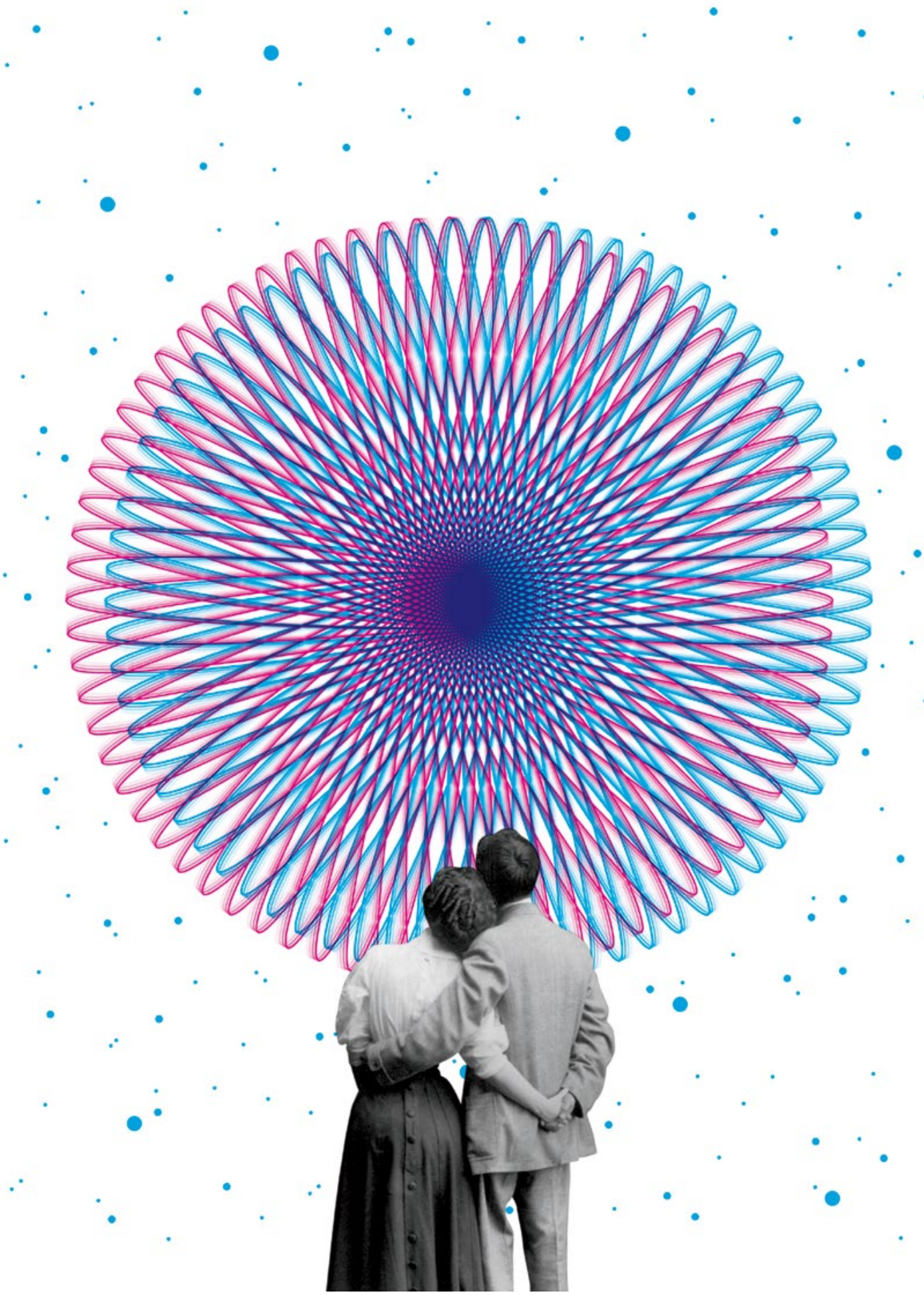

“THE STORIES THAT GALAXIES TELL”
BY MIKEL JASO

The Unique Merger That Made You (and Ewe, and Yew)

All sophisticated life on the planet Earth may owe its existence to one freakish event

BY ED YONG

ILLUSTRATION BY GRACIA LAM

AT FIRST GLANCE, a tree could not be more different from the caterpillars that eat its leaves, the mushrooms sprouting from its bark, the grass growing by its trunk, or the humans canoodling under its shade. Appearances, however, can be deceiving. Zoom in closely, and you will see that these organisms are all surprisingly similar at a microscopic level. Specifically, they all consist of cells that share the same basic architecture.

These cells contain a central nucleus—a command center that is stuffed with DNA and walled off by a membrane. Surrounding it are many smaller compartments that act like tiny organs, carrying out specialized tasks like storing molecules or making proteins. Among these are the mitochondria—bean-shaped power plants that provide the cells with energy.

This combination of features is shared by almost every cell in every animal, plant, fungus, and alga, a group of organisms known as "eukaryotes."

Bacteria showcase a second, simpler way of building a cell—one that preceded the complex eukaryotes by at least a billion years. These "prokaryotes" always consist of a single cell, which is smaller than a typical eukaryotic one and bereft of internal compartments like mitochondria and a nucleus. Even though limited to a relatively simple cell, bacteria are impressive survival machines. They colonize every possible habitat, from miles-high clouds to the deep ocean. They have a dazzling array of biological tricks that allow them to cause diseases, eat crude oil, conduct electric currents, draw power from the sun, and communicate with each other.

Still, without the eukaryotic architecture, bacteria are forever constrained in size and complexity. Sure, they have their amazing skill sets, but it's the eukaryotes that cover the Earth in forest and grassland, that navigate the planet looking for food and mates, that build rockets to Mars.

The transition from the classic prokaryotic model to the deluxe eukaryotic one is arguably the most important event in the history of life on Earth. And in more than 3 billion years of existence, it happened exactly once.

Life is full of complex structures that evolve time and again. Individual cells have united to form many-celled creatures like animals and plants on dozens of separate occasions. The same is true for eyes, which have independently evolved time and again. But the eukaryotic cell is a one-off innovation.

Bacteria have repeatedly nudged along the path toward complexity. Some are very big (for microbes); others move in colonies that behave like single, many-celled creatures. But none of them have acquired the full suite of crucial features that define eukaryotes: large size, the nucleus, internal compartments, mitochondria, and more. As Nick Lane from University College London writes, "Bacteria have made a start up every avenue of eukaryotic complexity, but then stopped short." Why?

It is not for lack of opportunity. The world is swarming with countless prokaryotes that evolve at breathtaking rates. Even so, they were not quick about inventing eukaryotic cells. Fossils tell us that the oldest bacteria arose between 3 and 3.5 billion years ago, but there are no eukaryotes from before 2.1 billion years ago. Why did the prokaryotes remain as simple cells for so damn long?

There are many possible explanations, but one of these has recently gained a lot of ground. It tells of a prokaryote that somehow found its way inside another, and formed a lasting partnership with its host. This inner cell—a bacterium—abandoned its free-living existence and eventually transformed into the mitochondria. These internal power plants provided the host cell with a bonanza of energy, allowing it to evolve in new directions that other prokaryotes could never reach.

If this story is true, and there are still those who doubt it, then all eukaryotes—every flower and fungus, spider and sparrow, man and woman—descended from a sudden and breathtakingly improbable merger between two microbes. They were our great-great-great-great-...-great-grandparents, and by becoming one, they laid the groundwork for the life forms that seem to make our planet so special. The world as we see it (and the fact that we see it at all; eyes are a eukaryotic invention) was irrevocably changed by that fateful union—a union so unlikely that it very well might not have happened at all, leaving our world forever dominated by microbes, never to welcome sophisticated and amazing life like trees, mushrooms, caterpillars, and us.

The transition is arguably the most important event in the history of life on Earth.

IN 1905, THE RUSSIAN BIOLOGIST Konstantin Mereschkowski first suggested that some parts of eukaryotic cells were once endosymbionts—free-living microbes that took up permanent residence within other cells. He thought the nucleus originated in this way, as did the chloroplasts that allow plant cells to harness sunlight. He missed the mitochondria, but the American anatomist Ivan Wallin pegged them for endosymbionts in 1923.

These ideas were ignored for decades until an American biologist—the late Lynn Margulis—revived them in 1967. In a radical paper, she made the case that mitochondria and chloroplasts were once free-living bacteria that had been sequentially ingested by another ancient microbe. That is why they still have their own tiny genomes and why they still superficially look like bacteria. Margulis argued that endosymbiosis was not a crazy, oddball concept—it was one of the most important leitmotivs in the eukaryotic opera.

The paper was a tour de force of cell biology, biochemistry, geology, genetics, and paleontology. Its conclusion was also grossly unorthodox. At the time, most people believed that mitochondria had simply come from other parts of the cell. "[Endosymbiosis] was taboo," says Bill Martin from Heinrich Heine University Düsseldorf, in Germany. "You had to sneak into a closet to whisper to yourself about it before coming out again."

Margulis' views drew fierce criticism, but she defended them with equal vigor. Soon she had the weight of evidence behind her. Genetic studies, for example, showed that mitochondrial DNA is similar to that of free-living bacteria. Now, very few scientists doubt that mergers infused the cells of every animal and plant with the descendants of ancient bacteria.

But the timing of that merger, the nature of its participants, and its relevance to the rise of eukaryotes are all still hotly debated. In recent decades, origin stories for the eukaryotes have sprouted up faster than old ones could be tested, but most fall into two broad camps.

The first—let's call it the "gradual-origin" group—claimed that prokaryotes evolved into eukaryotes by incrementally growing in size and picking up traits like a nucleus and the ability to swallow other cells. Along the way, these proto-eukaryotes gained mitochondria, because they would regularly engulf bacteria. This story is slow, steady, and classically Darwinian in nature. The acquisition of mitochondria was just another step in a long, gradual transition. This is what Margulis believed right till the end.

The alternative—let's call it the "sudden-origin" camp—is very different. It dispenses with slow, Darwinian progress and says that eukaryotes were born through the abrupt and dramatic union of two prokaryotes. One was a bacterium. The other was part of the other great lineage of prokaryotes: the archaea. (More about them later.) These two microbes look superficially alike, but they are as different in their biochemistry as PCs and Macs are in their operating systems. By merging, they created, in effect, the starting point for the first eukaryotes.

Bill Martin and Miklós Müller put forward one of the earliest versions of this idea in 1998. They called it the hydrogen hypothesis. It involved an ancient archaeon that, like many modern members, drew energy by bonding hydrogen and carbon dioxide to make methane. It partnered with a bacterium that produced hydrogen and carbon dioxide, which the archaeon could then use. Over time, they became inseparable, and the bacterium became a mitochondrion.

There are many variants of this hypothesis, which differ in the reasons for the merger and the exact identities of the archaeon and the bacterium that were involved. But they are all united by one critical feature setting them apart from the gradual-origin ideas: They all say that the host cell was still a *bona fide* prokaryote. It was an archaeon, through and through. It had not started to grow in size. It did not have a nucleus. It was not on the path to becoming a eukaryote; it set off down that path *because* it merged with a bacterium. As Martin puts it, "The inventions came later."

This distinction could not be more important. According to the sudden-origin ideas, mitochondria were not just one of many innovations for the early eukaryotes. "The acquisition of mitochondria *was* the origin of eukaryotes," says Lane. "They were one and the same event." If that is right, the rise of the eukaryotes was a fundamentally different sort of evolutionary transition than the gradual changes that led to the eye, or photosynthesis, or the move from sea to land. It was a fluke event of incredible improbability—one that, as far as we know, only happened after a billion years of life on Earth and has not been repeated in the 2 billion years since. "It's a fun and thrilling possibility," says Lane. "It may not be true, but it's beautiful."

IN 1977, MICROBIOLOGIST Carl Woese had the bright idea of comparing different organisms by sequencing their genes. This is an everyday part of modern biology, but at the time, scientists relied on physical traits to deduce the evolutionary relationships between different species. Comparing genes was bold and new, and it would play a critical role in showing how complicated life like us—the eukaryotes—came to be.

Woese focused on *16S rRNA*, a gene that is involved in the essential task of making proteins and is found in all living things. Woese reasoned that as organisms diverge into new species, their versions of *rRNA* should become increasingly dissimilar. By comparing the gene across a range of prokaryotes and eukaryotes, the

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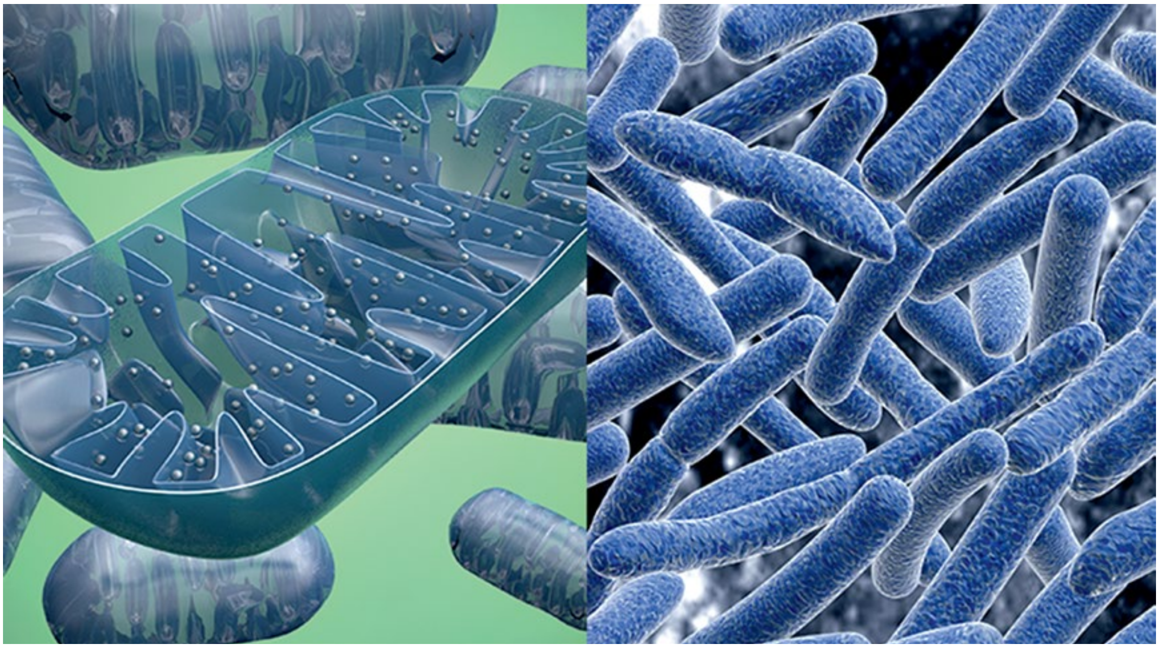


POWERHOUSES Mitochondria (left) are domesticated versions of bacteria (right) that now provide the cells of every animal, plant, and fungus with energy.

branches of the tree of life should reveal themselves.

They did, but no one expected the results. Woese's tree had three main branches. Bacteria and eukaryotes sat on two of them. But the third consisted of an obscure bunch of prokaryotes that had been found in hot, inhospitable environments. Woese called them archaea, from the Greek word for ancient. Everyone had taken them for obscure types of bacteria, but Woese's tree announced them as a third domain of life. It was as if everyone was staring at a world map, and Woese had politely shown that a full third of it had been folded underneath.

In Woese's classic three-domain tree, the eukaryotes and archaea are sister groups. They both evolved from a shared ancestor that split off from the bacteria very early in the history of life on Earth. But this tidy picture started to unravel in the 1990s, as the era of modern genetics kicked into high gear and scientists started sequencing more eukaryotic genes. Some were indeed closely related to archaeal genes, but others turned out to be more closely related to bacterial ones.

"[Endosymbiosis] was taboo," says Bill Martin. "You had to sneak into a closet to whisper to yourself about it before coming out again."

The eukaryotes turned out to be a confusing hodgepodge, and their evolutionary affinities kept on shifting with every new sequenced gene.

In 2004, James Lake changed the rules of engagement. Rather than looking at any single gene, he and his colleague Maria Rivera compared the entire genomes of two eukaryotes, three bacteria, and three archaea. Their analysis supported the merger-first ideas: They concluded that the common ancestor of all life diverged into bacteria and archaea, which evolved independently until two of their members suddenly merged. This created the first eukaryotes and closed what now appeared to be a "ring of life." Before that fateful encounter, life had just two major domains. Afterward, it had three.

Rivera and Lake were later criticized for only looking at seven species, but no one could possibly accuse Irish evolutionary biologist James McInerney of the same fault. In 2007, he crafted a super-tree using more than 5,700 genes from across the genomes of 168 prokaryotes and 17 eukaryotes. His conclusion was the same: Eukaryotes are merger organisms, formed through an ancient symbiosis between a bacterium and an archaeon.

The genes from these partners have not integrated seamlessly. They behave like immigrants in New York's Asian and Latino communities, who share the same city but dominate different areas. For example, they mostly interact with their own kind: archaeal genes with other archaeal genes, and bacterial genes with bacterial genes. "You've got two groups in the playground and they're playing with each other differently, because they've spent different amounts of time with each other," says McInerney.

They also do different jobs. The archaeal genes are more likely to be involved in copying and making use of DNA. The bacterial genes are more involved in breaking down food, making nutrients, and the other day-to-day aspects of being a microbe. And although the archaeal genes are outnumbered by their bacterial neighbors by 4 to 1, they seem to be more important. They are nearly twice as active. They produce proteins that play more central roles in their respective cells. They are more likely to kill their host if they are mistakenly deleted. Over the last four years, McInerney has found this same pattern again and again, in yeast, in humans, in dozens of other eukaryotes.

This all makes sense if you believe the sudden-origin idea. When those ancient partners merged, the immigrant bacterial genes had to be integrated around a native archaeal network, which had already been evolving together for countless generations. They did integrate, and while many of the archaeal genes were displaced, an elite set could not be ousted. Despite 2 billion years of evolution, this core network remains, and retains a pivotal role out of all proportion to their small number.

THE SUDDEN-ORIGIN HYPOTHESIS MAKES one critical prediction: All eukaryotes must have mitochondria. Any exceptions would be fatal, and in the 1980s, it started to look like there were exceptions aplenty.

If you drink the wrong glass of water in the wrong part of the world, your intestines might become home to a gut parasite called *Giardia*. In the weeks that follow, you can look forward to intense stomach cramps and violent diarrhea. Agony aside, *Giardia* has a bizarre and interesting anatomy. It consists of a single cell that looks like a malevolent teardrop with four tail-like filaments. Inside, it has not one nucleus but two. It is clearly a eukaryote.

But it has no mitochondria.

There are at least a thousand other single-celled eukaryotes, mostly parasites, which also lack mitochondria. They were once called archezoans, and their missing power plants made them focal points for the debate around eukaryotic origins. They seemed to be living remnants of a time when prokaryotes had already turned into primitive eukaryotes, but before they picked up their mitochondria. Their very existence testified that mitochondria were a late acquisition in the rise of eukaryotes, and threatened to deal a knockout blow to the sudden-origin tales.

That blow was deflected in the 1990s, when scientists slowly realized that *Giardia* and its ilk have genes that are only ever found in the mitochondria of other eukaryotes. These archezoans must have once had mitochondria, which were later lost or transformed into other cellular compartments. They aren't primitive eukaryotes from a time before the mitochondrial merger—they are *advanced* eukaryotes that have degenerated, just as tapeworms and other parasites

If intelligent aliens did exist, they would probably have something like mitochondria, too.

often lose complex organs they no longer need after they adopt a parasitic way of life. "We've yet to find a single primitive, mitochondria-free eukaryote," says McInerney, "and we've done a lot of looking."

With the archezoan club dismantled, the sudden-origin ideas returned to the fore with renewed vigor. "We predicted that all eukaryotes had a mitochondrion," says Martin. "Everyone was laughing at the time, but it's now textbook knowledge. I claim victory. Nobody's giving it to me—except the textbooks."

IF MITOCHONDRIA WERE SO important, why have they only evolved once? And for that matter, why have *eukaryotes* only evolved once?

Nick Lane and Bill Martin answered both questions in 2010, in a bravura paper titled, "The energetics of genome complexity," published in *Nature*. In a string of simple calculations and elegant logic, they reasoned that prokaryotes have stayed simple because they cannot afford the gas-guzzling lifestyle that all eukaryotes lead. In the paraphrased words of Scotty: They cannae do it, captain, they just don't have the power.

Lane and Martin argued that for a cell to become more complex, it needs a bigger genome. Today, for example, the average eukaryotic genome is around 100–10,000 times bigger than the average prokaryotic one. But big genomes don't come for free. A cell needs energy to copy its DNA and to use the information encoded by its genes to make proteins. The latter, in particular, is the most expensive task that a cell performs, soaking up three-quarters of its total energy supply. If a bacterium or archaeon was to expand its genome by 10 times, it would need roughly 10 times more energy to fund the construction of its extra proteins.

One solution might be to get bigger. The energy-producing reactions that drive prokaryotes take place across their membranes, so a bigger cell with a larger membrane would have a bigger energy supply. But bigger cells also need to make more proteins, so they would burn *more* energy than they gained. If a prokaryote scaled up to the same size and genome of a eukaryotic cell, it would end up with 230,000 times less energy to spend on each gene! Even if this woefully inefficient wretch could survive in isolation, it would be easily outcompeted by other prokaryotes.

Prokaryotes are stuck in an energetic canyon that keeps them simple and small. They have no way of climbing out. If anything, evolution drives them in the opposite direction, mercilessly pruning their genomes into a ring of densely packed and overlapping genes. Only once did a prokaryote escape from the canyon, through a singular and improbable trick—it acquired mitochondria.

Mitochondria have an inner membrane that folds in on itself like heavily ruched fabric. They offer their host cells a huge surface area for energy-producing chemical reactions. But these reactions are volatile, fickle things. They involve a chain of proteins in the mitochondrial membranes that release energy by stripping electrons from food molecules, passing them along to one another, and dumping them onto oxygen. This produces high electric voltages and unstable molecules. If anything goes wrong, the cell can easily die.

But mitochondria also have a tiny stock of DNA that encodes about a dozen of the proteins that take part in these electron-transfer chains. They can quickly make more or less of any of the participating proteins, to keep the voltages across their membranes under check. They supply both power and the ability to control that power. And they do that without having to bother the nucleus. They are specialized to harness energy. Mitochondria are truly the powerhouse of the eukaryotic cell. "The command center is too bureaucratic and far away to do anything," says Lane. "You need to have these small teams, which have limited powers but can use them at their discretion to respond to local situations. If they're not there, everything dies."

Prokaryotes do not *have* powerhouses; they *are* powerhouses. They can fold their membranes inwards to gain extra space for producing energy, and many do. But they do not have the secondary DNA outposts that produce high-energy molecules so the central government (the nucleus) has the time and energy to undertake evolutionary experiments.

The only way to do that is to merge with another cell. When one archaeon did so, it instantly leapt out of its energetic canyon, powered by its new bacterial partner. It could afford to expand its genome, to experiment with new types of genes and proteins, to get bigger, and to evolve down new and innovative routes. It could form a nucleus to contain its genetic material, and it could absorb other microbes to use as new tiny organs, like the chloroplasts that perform photosynthesis in plants. "You need a mitochondrial level of power to finance those evolutionary adventures," says Martin. "They don't come for free."

Lane and Martin's argument is a huge boon for the sudden-origin hypothesis. To become complex, cells need the stable, distributed energy supply that only mitochondria can provide. Without these internal power stations, other prokaryotes, for all their evolutionary ingenuity, have always stayed as single, simple cells.

The kind of merger that creates mitochondria seems to be a ludicrously unlikely event. Prokaryotes have only managed it once in more than 3 billion years, despite coming into contact with each other all the time. "There must have been thousands or millions of these cases over evolutionary time, but they've got to find a way of getting along, of reconciling and coadapting to each other," says Lane. "That seems to be genuinely difficult."

This improbability has implications for the search for alien life. On other worlds with the right chemical conditions, Lane believes that life would be sure to emerge. But without a fateful merger, it would be forever microbial. Perhaps this is the answer to the Fermi paradox—the puzzling contradiction between the high apparent odds that intelligent life would exist elsewhere among the billions of planets in the Milky Way, and our inability to find any signs of such intelligence. As Lane wrote in 2010, "The unavoidable conclusion is that the universe should be full of bacteria, but more complex life will be rare." And if intelligent aliens did exist, they would probably have something like mitochondria, too.

THE ORIGIN OF EUKARYOTES is, by no means, a settled matter of fact. Ideas have waxed and waned in influence, and although many lines of evidence currently point to a sudden origin, there is still plenty of dissent. Some scientists support radical notions like the idea that prokaryotes are versions of eukaryotes that evolved to greater simplicity, rather than their ancestors. Others remain stalwart devotees of Woese's tree.

Writing in 2007, Anthony Poole and David Penny accused the sudden-origin camp of pushing "mechanisms founded in unfettered imagination." They pointed out that archaea and bacteria do not engulf one another—that's a hallmark of eukaryotes. It is easy to see how a primitive eukaryote might have gained mitochondria by engulfing a bacterium, but very hard to picture how a relatively simple archaeon did so.

This powerful retort has lost some of its sting thanks to a white insect called the citrus mealybug. Its cells contain a bacterium called *Tremblaya*, and *Tremblaya* contains another bacterium called *Moranella*. Here is a prokaryote that somehow has another prokaryote living inside it, despite its apparent inability to engulf anything.

Still, the details of how the initial archaeon-bacterium merger happened remain a mystery. How did one get inside the other? What sealed their partnership—was it hydrogen, as Martin and Müller suggested, or something else? How did they manage to stay conjoined? "I think we have the roadmap right, but we don't have all the white lines and the signposts in place," says Martin. "We have the big picture but not all the details."

Perhaps we will never know for sure. The origin of eukaryotes happened so far back in time that it's a wonder we have even an inkling of what happened. Dissent is inevitable; uncertainty, guaranteed.

"You can't convince everyone about anything in early evolution, because they hold to their own beliefs," says Martin. "But I'm not worried about trying to convince anyone. I've solved these problems to my own satisfaction and it all looks pretty consistent. I'm happy."

Ed Yong is an award-winning science writer. His work has appeared in *Wired*, *Nature*, the *BBC*, *New Scientist*, the *Guardian*, the *Times*, *Aeon*, *Discover*, *Scientific American*, *The Scientist*, the *BMJ*, *Slate*, and more.

The Seeds That Sowed a Revolution

Galapagos Finches are famous, yet Darwin learned more about evolution from the plants

BY HENRY NICHOLLS

WHEN THE HMS BEAGLE dropped anchor on San Cristobal, the easternmost island in the Galapagos archipelago, in September 1835, the ship's naturalist Charles Darwin eagerly went ashore to gather samples of the insects, birds, reptiles, and plants living there. At first, he didn't think much of the arid landscape, which appeared to be "covered by stunted, sun-burnt brushwood...as leafless as our trees during winter." But this did not put him off. By the time the Beagle left these islands some five weeks later, he had amassed a spectacular collection of Galapagos plants.

It is fortunate that he took such trouble. Most popular narratives of Darwin and the Galapagos concentrate on the far more celebrated finches or the giant tortoises. Yet when he finally published *On the Origin of Species* almost 25 years later, Darwin made no mention of these creatures. In his discussion of the Galapagos, he dwelt almost exclusively on the islands' plants.

By the early 19th century, there was increasing interest in what we now refer to as biogeography, the study of the distribution of species around the globe. Many people still imagined that God had been involved in the creation of species, putting fully formed versions down on Earth that continued to reproduce themselves, dispersing from a divine "center of creation" to occupy their current habitats. To explain how the plants and animals reached far-flung places such as the isolated Galapagos, several naturalists imagined that there had to have been land bridges, long-since subsided, that had once connected them to a continent. But in the wake of the Beagle voyage, the collection of Galapagos plants suggested an alternate scenario.

Even if there had once been a land bridge to the islands, it could not account for the fact that half of the plant species Darwin collected were unique to the Galapagos, and that most of them were particular to just one island. "I never dreamed that islands, about fifty or sixty miles apart, and most of them in sight of each other, formed of precisely the same rocks, placed

ILLUSTRATIONS BY GABY D'ALESSANDRO

When the botanist began to study the flowers and seeds, he was in for a big surprise.

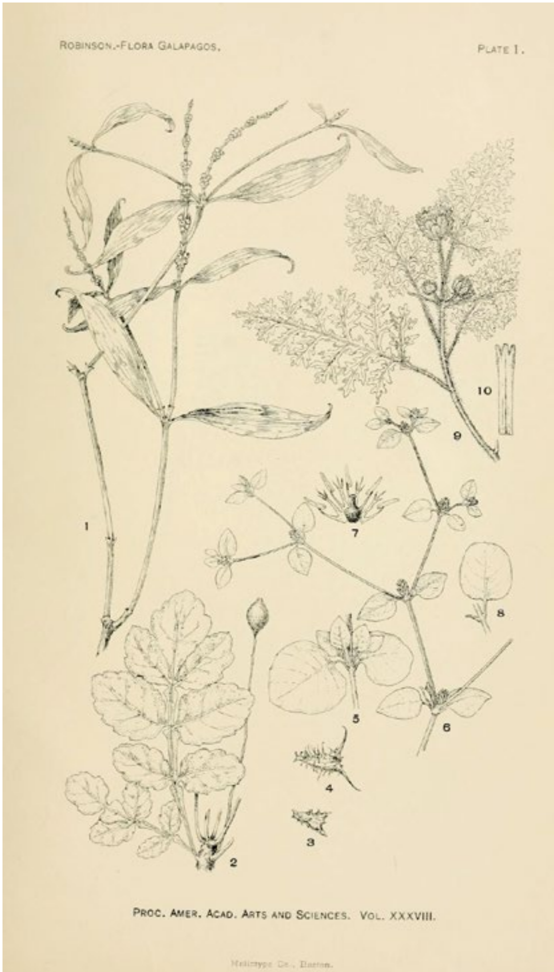
under a quite similar climate, rising to a nearly equal height, would have been differently tenanted," wrote Darwin in his *Journal of Researches*. His observations could be best explained if species were not fixed in nature but somehow changed as the seeds traveled to different locations.

In order to make that conjecture, Darwin needed to classify the plants. Given his limited botanical expertise, he turned to a young botanist named Joseph Dalton Hooker. Darwin was excited to find out the number of different plant species he'd collected and their distribution across the archipelago. At first, Hooker did not anticipate a huge amount of novelty. "The species will no doubt be peculiar but they may not form peculiar genera of more than one or two species." In other words, he expected most of the Galapagos plants to fit into the established botanical framework.

But when the botanist began to study the leaf structure and the flowers and seeds in minute detail, he was in for a big surprise. "The Galapagos plants are far more extensive in number of species than I could have supposed," he wrote to Darwin in great excitement in late 1843.

Although they resembled the vegetation from mainland South America, almost half of the flora appeared to be endemic, found only in the Galapagos. Even more interestingly, Hooker noted that almost every species of flowering plant and fern that he described was confined to just one island. This "most strange fact," wrote Hooker, "quite overturns all our preconceived notions of species radiating from a centre." Rather, each different island had its own similar, yet different flora.

Darwin, in turn, was ecstatic. "I cannot tell you how delighted & astonished I am at the results of your examination; how wonderfully they support my assertion on the differences in the animals of the different islands." In addition to Hooker's insights into the distribution of plants in the Galapagos, his paper *On the Vegetation of the Galapagos Archipelago* contained some very interesting speculation about how plants had got to the islands in the first place. For example, Hooker noted that in comparison to the tropical plants from the continent,



NATIVES Drawings from *Flora of the Galapagos Islands* (1902), a booklet based on expeditions by Darwin, Joseph Dalton Hooker, and other 19th-century botanists.

B.L. ROBINSON

the Galapagos flora contained a far smaller proportion of a particular kind of flowering plant. Perhaps, he suggested, there might have been "obstacles to the transport of seeds from the continent." He went on to suggest four main routes through which plants might have reached the Galapagos. "The means of transport which may have introduced these plants are, oceanic and aerial currents, the passage of birds and man," he wrote.

Hooker guessed that most of the species found near the coast had probably reached Galapagos by floating, their tough seeds helping them "in resisting for some time the effects of salt water." There were also some species beyond the coast with seeds "too large for probable transport by winds" and "no means of attaching themselves to birds" that had probably also taken an oceanic route to Galapagos. Hooker felt that it was only species with small seeds or those "furnished with wings or other appendages" that might have arrived on the wind. Birds, he felt sure, could account for the presence of many of the plant species lying further from the coast. It was known that humans had visited the Galapagos so it was clear that they had brought plants too, for Floreana—then the only inhabited island—was the only one with a significant number of plants that could be exploited as food.

In 1855, Darwin put his mind to testing some of Hooker's predictions. He began by playing around with seeds and seawater at his home in the English countryside south of London. He kicked off with species he could easily get his hands on—cress, radish, cabbage, lettuce, carrot, celery, and onion—just to establish whether seawater kills seeds. It was a question he admitted "might naturally appear childish to many," but one that produced some intriguing results and unexpectedly profound conclusions.

He left the seeds in salt water for a week before planting them in little pots. To his surprise, they all germinated. "It is quite surprising that the Radishes shd have grown, for the salt-water was putrid to an extent, which I cd not have thought credible had I not smelt it myself," he wrote. He went further, buying seeds of still more species and gradually extending the length of time they were immersed in his seawater concoction. By the time he published *On the Origin of Species* in 1859, he had exposed the seeds of 87 different plant species to these hostile conditions. Incredibly, nearly all of them germinated after stewing in brine. Some survived just days, but others still seemed in perfectly good working order after several months.

Suddenly, the vast expanse of salty ocean between South America and the Galapagos did not seem to be such an obstacle. There was, however, a snag: A lot of the seeds he experimented with sank and would have been lost in the oceanic depths long before reaching

the Galapagos. But Darwin had an answer to this, discovering that the condition of the seed affects its buoyancy. "For instance, ripe hazel-nuts sank immediately, but when dried, they floated for 90 days and afterwards when planted they germinated," he wrote in *On the Origin of Species*. Likewise, "an asparagus plant with ripe berries floated for 23 days, when dried it floated for 85 days, and the seeds afterwards germinated."

Even a seed that sinks, Darwin realized, might still be carried on ocean currents if it hitches a ride on a clod of earth attached to the roots of some big tree or is protected inside the carcass of a dead animal. To illustrate this possibility, he fed a pigeon on seeds that would normally be "killed by even a few days' immersion in sea-water." He then sacrificed it and floated its body on salty water for a month. To his great surprise (and, one imagines, satisfaction), the delicate seeds "nearly all germinated."

> *Once a plant had become established in an isolated spot like an island in the Galapagos, Darwin felt that it would eventually result in the origin of new species, a process he termed "natural selection."*

If most seeds could survive weeks in seawater, would they be able to reach remote islands like the Galapagos intact? Darwin hauled A. K. Johnston's *Physical Atlas* from his bookshelf and worked out that the Atlantic currents run at an average of 33 miles per day, fast enough to carry a significant proportion of seeds a very long way before they either sank or succumbed to the salty insult. In the case of the Galapagos, the current that flows out from continental South America runs considerably faster, often around twice Johnston's Atlantic average. So a back-of-the-envelope calculation suggests that a seed—either floating or hitching a ride—could reach the Galapagos in just over nine days. Those species with the most delicate seeds might not make it. But a lot of species would.

Although some Galapagos plants clearly came on ocean currents and others on the wind, it's thought that most Galapagos plants arrived with help from birds. "Living birds can hardly fail to be highly effective agents in the transportation of seeds," Darwin wrote in the *Origin*. Obvious as it might be, he still sought evidence, going out into his garden in search of bird droppings. "In the course of two months," he wrote, "I picked up in my garden 12 kinds of seeds, out of the excrement of small birds, and these seemed perfect, and some of them, which I tried, germinated." He also dug around in the mud and showed it was full of seeds, in one instance a small cupful of sludge from a nearby pond producing more than 500 little plant shoots. "I think it would be an inexplicable circumstance if water-birds did not transport the seeds of fresh-water plants to vast distances," he wrote.

Once a plant had become established in an isolated spot like an island in the Galapagos, Darwin felt that the "preservation of favorable variations and the rejection of injurious variations" would eventually result in the origin of new species, a process he termed "natural selection." "I can see no limit to the amount of change, to the beauty and infinite complexity of the coadaptations between all organic beings, one with another and with their physical conditions of life, which may be effected in the long course of time by nature's power of selection," he wrote in the *Origin*.

Darwin did not go into detail about how the first seeds to reach Galapagos entered into this "struggle for life." Almost 180 years after his visit, however, there is plenty of evidence for such adaptation. One of the most telling observations, made in the 1980s, is that the vast majority of flowering plants in the Galapagos are capable of self-pollination. Darwin would have loved this observation and reveled in the explanation. If you have a fussy reproductive set-up, like a flowering plant that relies on a special insect to carry pollen to a fellow member of your species, the odds of surviving on a remote island in somewhere like the Galapagos are stacked against you. This also accounts for the fact that most flowering plants in the archipelago, with no need to attract insects, are not particularly showy (white or yellow petals are the norm).

In fact, there is evidence of adaptation everywhere in Galapagos. Near the coast, we see plants that are tolerant of dry, salty conditions. The red mangrove, for instance, is able to survive with specialized roots that can draw water from the sea without bringing too much salt on board. The leaves of black mangroves also contain salt glands capable of shifting salt from the inside to the outside of the plant.

Beyond the salty coastal region, the lowest reaches of each Galapagos volcano are dominated by the arid zone, where water—or the lack of it—is the perennial problem. On Santiago, Darwin stuck a thermometer into some brown soil, and the mercury rocketed up to almost 60 degrees Celsius (140 degrees Fahrenheit). It could have been yet still hotter, but Darwin's thermometer only went so far. It takes a certain kind of plant—usually with rather special roots—to survive in such a parched environment. Take the prickly pear cacti of the genus *Opuntia*, for example. These have two kinds of roots: one superficial set of finer roots whose job it is to suck up every last drop of water in the aftermath of a downpour, and a deeper "tap" root, which gives the plant a stronger hold on the rocks and searches out deeper sources of water. Life in the arid zone is also easier if you are capable of storing water, something that cacti are famous for. Their leaves, after all, have been so modified that we call them spines—and these modifications are a perfect way to cut down on water loss.

During the cool season, between June and November, a cool mist hovers at between 500 meters and 1,000 meters above sea level, creating a lush, moist zone, overrun with effulgent flora of an altogether different kind. When Darwin experienced the transition from the arid to the humid zone, it struck him too. Landing at Black Beach on Floreana (where the small town of Puerto Velasco Ibarra now stands), he walked about 8 kilometers inland, where he was thrilled "to find black mud & on the trees to see mosses, ferns & Lichens & Parasitical plants adhaering."

Darwin's collection of Galapagos plants proved to be a vital inspiration for his ideas on evolution by natural selection. In 1837, his bird specimens—particularly the Galapagos mockingbirds—alerted him to the possibility that the Galapagos flora and fauna would be allied with the productions of South America, that there would be an extraordinarily high level of novelty, and that most new species would be confined to a single island. But his failure to record the island of origin for many of his bird specimens meant that they could not furnish him with the robust evidence to support or refute his suspicions.

Darwin's Galapagos plants, however, were fit for purpose. Hooker's initial assessment confirmed that the Galapagos flora was indeed allied to that of South America, that there were lots of endemic species, and that many of these novelties seemed to be confined to just one island. These conclusions reached Darwin in early 1845, just in time for him to weave them into the second edition of his *Journal of Researches*. The chapter on the Galapagos ballooned to accommodate the new material and he became bolder with his conclusions.

"Reviewing the facts here given," he wrote, "one is astonished at the amount of creative force, if such an expression may be used, displayed on these small, barren, and rocky islands." And it was in direct response to Hooker's findings that Darwin reached the following, now-famous conclusion: "Both in space and time, we seem to be brought somewhat near to that great fact—that mystery of mysteries—the first appearance of new beings on this earth."

HENRY NICHOLLS is the author of *Lonesome George*, which was shortlisted for the Royal Society Book Prize, and *The Galapagos: A Natural History*. He lives in London.

How We Make Gods

Taking lessons from the rise and fall of divinity in online games

BY JASON ANTHONY

FROM THE MOMENT he arrived, Egor lived for mayhem. The time was 1982, and the place was the first online game world, called MUD (short for Multi-User Dungeon). Before Egor there had been duels, pranks, and the occasional fire-breathing dragon, all amiably playing out in the MUD world, hosted on the servers of the University of Essex. A rough kind of social contract had held.

Egor was the screen name of a player who set out to test the limits. He learned the shortcuts allowed by the code. He wrote scripts that let his character level up quickly. He discovered a way to fake other players' logins. With a borrowed screen name, he would go on sprees of destruction, and watch with amusement as the real player logged on later to face a raging mob. He "ganked" new players—killed them before they knew which end of the sword to hold.

Thirty years down the road, an online multiplayer scene would grow geometrically from those few hundred players logging into the Essex server. About 618 million people now participate in online worlds; on a given day, the most popular might boast 2 million people playing at the same time. The industry built around these so-called massively multiplayer online games (or MMOs) brings in $14.9 billion in annual revenues, greater than the gross domestic product of Iceland.

Yet that whole massive industry was shaped, in some way, by how the game handled the problem of Egor. At the golden dawn of online space, he brought a snake into Eden. He forced his little world of techno-misfits to answer its first big questions, questions familiar to students of any society and its basic rules: Who's in charge, and by what authority? And how does a community test and affirm its social boundaries?

NEIGHBORS CAN CREATE the ineffable threads of a good society, a point made in the book *The Great Good Place* by sociologist Roy Oldenburg. He argues that for this to happen, a culture needs a place for people to meet informally. He calls this a "third place." It isn't

ILLUSTRATION BY JONATHON ROSEN


reload
tilt
stop
time
round one
game over
attack
level 2
score 4
lives 9
ammo 8
health 90%
stealth 90%

"I am the law!" he would announce, killing 1 in 10 players on his server in a digital plague.

one of practical functions, like a courthouse or an office building. Instead, it encourages the alchemy that happens in unstructured "hanging out." In the past, that's happened in the agora of ancient Greece, or in the cafés of Enlightenment-era France. Chat is common in a third place; so are games.

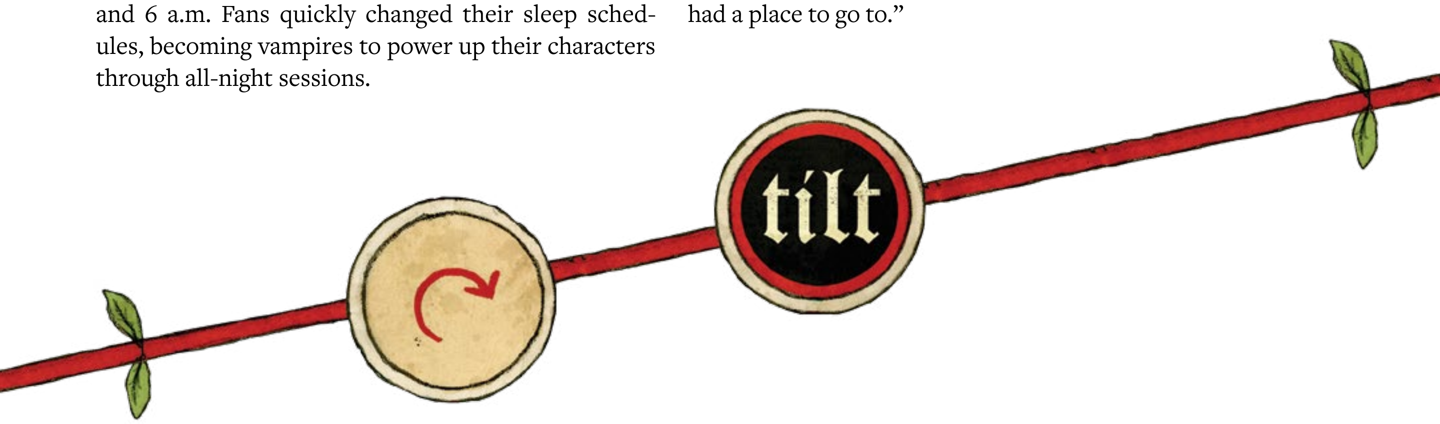
The earliest online communities ticked many boxes of a third place. Until MUD, however, none of them had really been a *place*. Richard Bartle, who designed MUD with Roy Trubshaw in 1980 at the University of Essex, sees this as a signature contribution of his game. MUD was the first game world that could host dozens of players at the same time. A database housed a chain of "rooms" that allowed players to wander from one to the other. If they happened to enter the same "room," they could do things that people did in real life: chat, fight, even kiss.

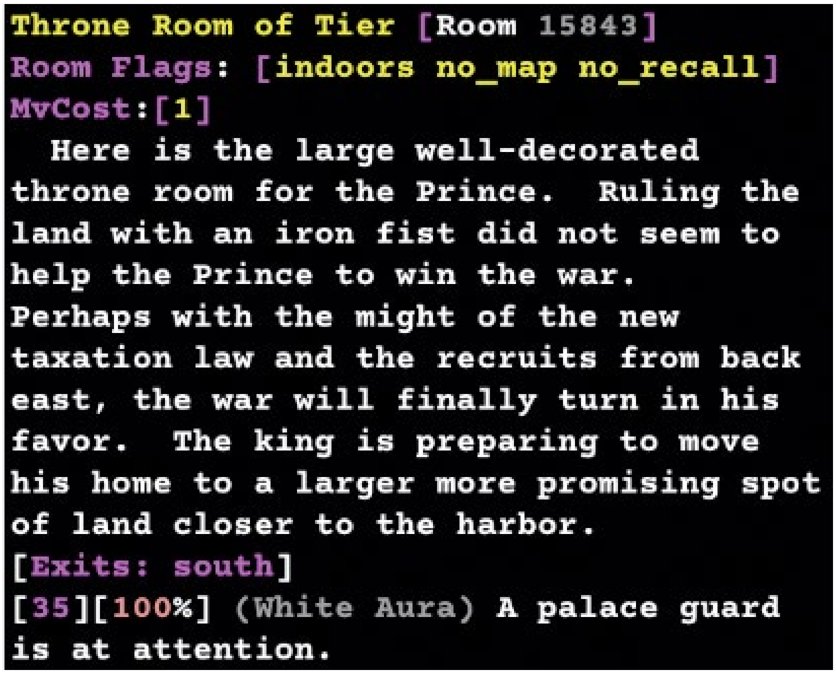
"MUD brought the concept of space to the Internet," says Bartle. "People could feel they were 'there' in a way that they couldn't from chat." That experience proved powerfully addictive. When the university server connected to ARPANET in 1980, the popularity of MUD exploded. In the early days, the University of Essex server would only allow dial-up players to use the network to play between midnight and 6 a.m. Fans quickly changed their sleep schedules, becoming vampires to power up their characters through all-night sessions.

In short, MUD began to operate very much like Oldenburg's third space for a new demographic: the first generation of computer geeks. "On the whole, players were tech-savvy and intelligent; as a consequence, the real world regarded them as nerds, dweebs, whatever," says Bartle. He designed his software as both hangout and a kind of sanctuary. "Players could shed the personality constructed for them in the real world and get to be who they really were."

While a physical sanctuary was a pretty new concept for what was then called the wired world (the Internet would come later), the concept has deep roots in our offline experience, according to anthropologist Tom Boellstorff. Boellstorff spent three years applying real-world ethnographic tools to virtual spaces, which resulted in the seminal 2008 book *Coming of Age in Second Life*. As he finished the book, he couldn't help but note similarities to work he was doing with gay and lesbian populations in Indonesia.

"On the ground I was finding that being gay in Indonesia was less about an identity; it was about a space," he says. Marginalized communities in Indonesia became tied together, he found, by the spaces in local parks where they met. "I found the same thing happening online, in the ways that groups cohered when they had a place to go to."





DECISIONS, DECISIONS A screenshot from the MUD game Act of War.

GARUMIKE/WIKIMEDIA COMMONS

LIKE SPACES IN THE offline world, MUD had to establish its rules, and those were partly shaped by a crisis of social behavior—which brings the story back to Egor.

"For the first two or three years, MUD was played in the spirit of face-to-face games, which is to say 'nicely,' " says Bartle. "Then along came Egor."

Bartle is quick to stress that, offline, the man who played under the screenname Egor was a nice guy. His rampages in MUD simply expressed a nascent hacker ethic: inventive, independent, and inclined to test the limits, qualities that would later come to shape many corners of wired space.

To the first fledgling MUD community, however, Egor posed a clear and present danger. Bartle's response was as elegant as it was ancient. He dug his fingers into the programming of the world he had created. He hard-coded a bolt from the heavens—the Finger of Death—and smote Egor to bits.

Perhaps it's surprising how quickly the wired, technical community populating his game jumped to what looks like theocratic rule—rule by supernatural intervention. "Most users had a disinterest in authority," says Bartle. Part of that came, he says, from the mindset it took to code in the early days. Making computers work was a meritocracy of best solutions and finding better ways to do things. Yet when problems arose, an all-powerful being outside the physics of the game simply made the most sense.

The hierarchy quickly codified. Players were "mortals." With hard work, a player might hope to rise up to "wiz" or "witch." A wiz could be a local administrator, hex players with punishments, or perform other in-game parlor tricks—even smite lower level players. But the game developer, and a handful of chosen ones, served a higher role. Their duty was to resolve any conflicts that could not be met by an in-game meritocracy. To do this, they used their power to change time and space.

At the golden dawn of online space, he brought a snake into Eden.

Bartle called the role he assumed in MUD an "arch wiz," but his later theories elevated that role. He became an evangelist of the term "god" as the technically appropriate word for an MMO designer. They invent physics, yet are not bound by their own laws, he argued. Good gameplay demands that they must also be free of social rules they put on others. In 2011, in a talk at the University of Bristol, Bartle went so far as to say that this role of god was not metaphorical—it was a literal function of those who molded the worlds where millions of people spent countless hours of their lives.

In the games that followed MUD, "wizzes" stayed, but virtual world developers adopted the "god" terminology. By and large they didn't flaunt their power. As in any theocracy, the day-to-day was fielded by a team of qualified administrators, responsible to the players they watched over. Gods might even walk among mortals, under the guise of another character. But when social crises hit, the social contract depended on creators who were on hand to mete out a very personal justice.

Was it possible to entirely wash the theocratic flavor out of a game? A 1985 experiment by the programmer Ben Laurie, called Gods, allowed the players complete self rule, a true meritocracy with no gods or arch-wizzes to step in. High-level players could place their altar in the main square. If others came to them with tribute, they gained godly powers. The idea was that players would have a say about which administrators they felt best suited the game. There was even a playerless god, called Blob, that players could worship while there were no real people to worship.

Gods, however, never became the success that MUD was. Players voted with their virtual feet for worlds run by supernatural entities.

TALES FROM VIRTUAL SPACE, according to Boellstorff and a growing number of researchers, can shine a light on who we are in our offline lives. He goes even further, to say that some part of the human experience has always been virtual. "Since it is human 'nature' to experience life through the prism of culture, human being has always been virtual being," he writes.

What is the nature of our virtuality? Boellstorff argues that we experience it largely through shared symbols—things perhaps like gods and religion. Robert Wright offers a theory about an arc in that virtual conversation in his book, *The Evolution of God*. He suggests religion is supplanted as a tool of power over time, replaced by legal codes.

That pattern echoes the fate of the gods in multiplayer games. Initially, the power of divine rule expanded with the growing player base. A few worlds even became known for deities that were notoriously capricious. An admin named Lorry ruled over the multi-user dungeon MIST in the mid-80s. "I am the law!" he would announce, killing 1 in 10 players on his server in a digital plague. His legendary manifesto preached the virtues of arrogance, ego, and random destruction—and somehow brought his game active converts.

As time wore on, and player populations radically expanded, the gods' power began to ebb. One pivotal episode from the early '90s made the pages of the *Village Voice*. A player named Mr. Bungle had run rampant in the world of LambdaMOO. Community users couldn't turn to the wizards; they had grown tired of settling social arguments in the large world, and forced players to come to collective agreement before they would mete out justice. Enough players wanted to "toad" Mr. Bungle—a variation on the Finger of Death—to get the superpowers who ran the servers' attention, and the sentence was meekly carried out.

Today, gods are almost entirely absent from online worlds, at least in the form of capricious, genius creators who can reverse gravity on a whim. In the more commercial games, like World of Warcraft, the player now signs a terms-of-use covenant that "clearly defines each type of penalty and how each may be used to protect players' enjoyment." The occasional robed "Game masters" offer little more than an in-game help desk. The brief, strange phase of digital gods has largely come and gone.

Nevertheless, digital gods prompt us to consider what we do when we create civilizations unbounded by the constraints of the physical world. Game worlds free us to indulge in atavistic exploration, not only of those worlds, but of who we are. In the space of 30 years, players moved from cults of magic and personality toward a kind of constitutional state, retracing a much longer real-world journey familiar to any historian. What other lessons about the human condition exist in the greatly accelerated experiment that is online gaming?

As for Egor, he eventually gave up griefing other players, discouraged by the Finger of Death. Turning a leaf, he became the youngest wizard of a multi-user dungeon, then a notable game developer himself.

It seems that there's a secret no one tells you about being a griefer, or a wiz, or a god for that matter. It eventually loses its thrill.

"No one wants to be a god," says Bartle. "They want to be a player."

JASON ANTHONY is a writer and game designer. He lectures about games with deep histories, and advocates for games as good spaces for social and ethical conflict.

"BEFORE THERE WERE STARS"
BY JON HAN

11

WHERE DOES THE STORY of life and light begin? Maybe with the fact that most life on Earth runs on sunlight, or that starlight may have set the direction in which all of Earth's biomolecules spiral. Or is it the ancient photosynthetic transformation of our planet? The human fascination with light offers its own set of beginnings: from Paleolithic cave painters creating animation using flickering firelight, to the astrologer's arithmetic, Hipparchus' trigonometry, Newton's rainbows, and the stunning revelations of the double slit experiment.

Plainly put, we love light—or, in the more eloquent words of Robert Grosseteste, the 13th-century Bishop of Lincoln and pioneer of the English intellectual tradition, "Physical light is the best, the most delectable, the most beautiful of all the bodies that exist." Which raises another question: When most of us cannot see the Milky Way, and glowing screens have shifted our circadian rhythms, have we had too much light, and can we win darkness back?

Welcome to "Light."

—MS

"The world has been spending 0.72 percent of its GDP for light for 300 years now."

DIRK HANSON
"Drowning in Light" p.98

Light

FIELDS OF VISION

Drowning in Light

Technology has fed our addiction to light, and might help us end it

BY DIRK HANSON

IN 1996, YALE ECONOMIST William D. Nordhaus calculated that the average citizen of Babylon would have had to work a total of 41 hours to buy enough lamp oil to equal a 75-watt light bulb burning for one hour. At the time of the American Revolution, a colonial would have been able to purchase the same amount of light, in the form of candles, for about five hour's worth of work. And by 1992, the average American, using compact fluorescents, could earn the same amount of light in less than one second. That sounds like a great deal.

Except for one thing: We treat light like a drug whose price is spiraling toward zero. In the words of sleep expert Charles A. Czeisler of Harvard Medical School, "every time we turn on a light, we are inadvertently taking a drug that affects how we will sleep and how we will be awake the next day."[1] Our daily metabolic cycles are not precisely 24 hours long, and this turns out to be a crucial evolutionary glitch in the mammalian circadian system. Circadian rhythms must be reset daily to keep us in behavioral synch with the earth's rotation, so we will sleep when it is dark and wake when it is light. This process is called entrainment, and it is achieved by means of light exposure. In the brain, a region of the hypothalamus called the suprachiasmatic nucleus receives input from the retina, causing specialized "24-hour" cells to oscillate in specific patterns. This affects how we eat, sleep, and work. And in most people, the circadian response is intensity-dependent, meaning the greater the light, the greater the effect on the human circadian system.

To complicate matters, our relationship with light is profoundly psychological as well. In "Psychological processes influencing lighting quality," published in *Leukos, the Journal of the Illuminating Engineering Society of North America* in 2001, Jennifer A. Veitch analyzed the available scientific evidence concerning the manner in which lighting conditions affect mood and behavior in office settings. Veitch found that "preferences for illuminance levels are generally higher than

ILLUSTRATION BY MIKO MACIASZEK

We have hobbled the nighttime thieves, perverts, and pickpockets.

the recommended levels." Researchers in the Netherlands, Sweden, the United Kingdom, the United States, and Canada have all documented the same tendency to "overlight" things.[2] Veitch also referenced studies showing that "people with seasonal affective disorder or the milder, subsyndromal, form of this mood disorder consistently preferred higher room illuminance levels than matched, normal controls."

Veitch's data support the notion of "a common experience of gloom associated with lighting conditions at low adaptation luminances, particularly when the vertical luminances are low." Put simply, people don't feel comfortable in dim workrooms with no wall lighting. See any film noir classic for details.

Our lust for light has transformed our cities. We have hobbled the nighttime thieves, perverts, and pickpockets; the ghosts, goblins, and witches. Greg Gbur, a professor in the University of North Carolina's Department of Physics and Optical Science, reminded me that a wealth of stories—from H. P. Lovecraft's *The Haunter of the Dark* to the movie *Pitch Black*—have focused on the horrible things that come for us when everything goes dark. Many of the first treatises denying the existence of ghosts and witches came from larger cities in the Netherlands and England, which featured some of the earliest and most extensive street lighting in Europe. At roughly the same time, "failure to illuminate" became a 17th-century crime. As Henry David Thoreau concluded: "Men are generally still a little afraid of the dark, though the witches are all hung, and Christianity and candles have been introduced." By the mid-1800s, gaslight had changed everything. Artists, bohemians, and ordinary citizens of every stripe ventured forth into the gaslit night of the city. In the 1850 pocket guide, *New York by Gas-Light*, we are told how to "penetrate beneath the thick veil of night and lay bare the fearful mysteries of darkness in the metropolis."

Today, engineers are greasing the wheels. Lighting prices fall and efficiencies rise with the breathtaking inevitability of Moore's Law in semiconductors. Moore's Law, a prediction made by Intel co-founder Gordon Moore in 1965, says that the number of transistors packed on a chip will double every 18 to 24 months. More than half a century later, Moore's Law still holds, although many experts believe it will run its course in a few more years. The lighting field has its own Moore's Law, an LED counterpart called Haitz's Law. In 2000, Dr. Roland Haitz, then with Agilent Technologies, predicted that the cost of LED lighting will fall by a factor of 10, while "flux per lamp" (what we call brilliance or luminosity) will increase by a factor of 20 per decade. How long that trend will continue is also a matter of intense debate, but solid-state lighting (SSL) technology is based on semiconductor components, so the technology price fix is in, at least for now, and lighting is likely to keep getting cheaper.

As prices fall, our use of light climbs in exact proportion. For several years now, physicist Jeff Tsao at Sandia National Laboratories has been digging into the economic cost-benefit ratios of artificial lighting. Analyzing data sets spanning three centuries and six continents, Tsao and his coworkers at Sandia have concluded that "the result of increases in luminous efficacy has been an increase in demand for energy used for lighting that nearly exactly offsets the efficiency gains—essentially a 100% rebound in energy use."[3] The Sandia group's equations aren't holy writ, but with remarkable consistency, human beings, when faced with the availability of a cheaper and more efficient lighting technology, simply use more of it. We don't bank the savings, but instead fall into what is known as Jevons' paradox, which states that technological improvements can be counterproductive if the resultant savings are spent rather than saved.

Tsao calculates that, as a result, light represents a constant fraction of per capita gross domestic product (GDP) over time; the world has been spending 0.72 percent of its GDP for light for 300 years now. If there are other energy markets that show a constant percentage of GDP expenditure over time, Tsao doesn't know of them. Noted environmentalist Amory Lovins memorably told the *New Yorker's* David Owen in 2010 that improved lighting has always been "a lunch you're paid to eat."[4]

Like any junkie, we don't know when we've had enough. "One thing that evolutionary anthropologists have learned is that humans are not necessarily natural conservationists," says biological anthropologist Carol Worthman of Emory University, who has done field work in developing countries with scant night lighting, such as New Guinea and Vietnam. "We don't have inbuilt mechanisms to step down consumption, even in the best interest of our own physical health." The disruption of circadian rhythms and the disappearing night sky are just a part of the price. We've even tried, and failed, to understand how much we need. "Despite over a century of research," the Sandia group found, "recommended [lighting] levels for comparable spaces still vary by a factor of up to 20."

After centuries of gorging, however, there may finally be darkness at the end of the tunnel. The Sandia group forecasts that "the developed countries are nearing a saturation point in average illuminance, but plausible arguments can be made that the saturation point may yet be a factor of 10 or more higher." Even a factor of 10 is small compared to the distance we've come, and may be reached in the not-too-distant future. "The pace of improvement is still pretty fast," Tsao says, "so I'm not thinking the slowdown happens for another decade at least."

Even if we don't reach saturation, we may decide to control our own usage. Ecological economist Blake Alcott believes that if Jevons got his paradox right, then "business-as-usual efficiency gains must be compensated for with physical caps like quotas or rationing." Alcott did his Ph.D. work on sustainability strategies at the University of East Anglia, after a stint with the Sustainability Research Institute at the University of Leeds. Much of his work has focused on arguments surrounding the energy rebound effect. Alcott thinks we will need braking mechanisms to cap or otherwise limit the expansive growth of lighting in the developed world. "Politically unfashionable though they may be," Alcott wrote in *Ecological Economics* in 2005, "ecological economics should once again take resource rationing seriously."[5]

Here too, technology will come into play. Tsao predicts that the future will be about sensors and network smartness. "It may seem creepy, but when the network knows where you are and where you are looking, the network should be able to figure out lots of ways of saving energy by judicious placement of light." Jack van der Pol, a development manager for smart lighting at NXP Semiconductors in the Netherlands, told the BBC: "The way street light is managed now is so outdated. People want more control."

The researchers at Sandia envision a future in which lighting systems will more closely approximate natural lighting, and see a useful analogy in telephony, where bare-bones telephone service evolved into "smart mobile communications systems with a fusion of communications, computation, and display technologies." Real-time control of the mix of light wavelengths and intensity, as well as real-time control of light placement, are the keys. The Holy Grail is a semiconductor-based distributed array of sensors and controls that would "tailor local illuminances" to match time, place, and people. The goal is to customize light to fit people's preferences, which could cut back on lighting and save energy by ironing out waste. Today's compact fluorescent lamps are expected to give way to SSL LEDs by about 2020, which is when the first rudimentary "smart" lighting will gain ground, say researchers. This may eventually lead to wireless controls for full on/off dimming responses. We will enter an era in which "lighting systems have the information necessary to customize light to user preferences," according to Tsao's 2010 article in the *Journal of Physics D*.[6]

It would be a major change in our way of thinking. As the smart grid grows smarter, resource rationing becomes more technologically feasible. Micro pricing across a smart lighting grid could result in "illumination arbitrage," where various forms of electrical demand can be traded back and forth. But not everyone thinks it'll happen. William Nordhaus tells me, "I can't imagine that we will see light rationing in my lifetime." Nordhaus has some issues with the quality of the large data sets used by Tsao's group, and thinks that saturation is not on the immediate horizon. "I would be surprised if the growth in lumen-hours was as great in the next century as the last, but saturation on a global scale? Almost surely not."

If nothing else, communities may take the matter into their own hands. A recent survey of light pollution around the National Optical Astronomy Observatory on Kitt Peak in Arizona shows that the mountain is only a little bit brighter than it was in 1988, and has essentially stabilized at 1999 levels. Researchers credit local lighting ordinances and outdoor lighting codes designed to save energy, which have managed to offset overall population growth in Arizona's urban centers. Kathryn Neugent and Philip Massey of Lowell Observatory have written that the restrictions, which mandate total lumens per acre and set curfews for outdoor illumination, "have effectively stopped the impact of household, commercial, and outdoor lights on the night sky."

On his deathbed, Goethe is supposed to have demanded more light. Today we are living in a world that has met Goethe's demand beyond his wildest dreams. Sea turtles trundle mistakenly toward seaside condos, fireflies fail to find mates, and two-thirds of Americans in 2008 and 90 percent of the world's population could no longer see the Milky Way with the naked eye. How much light can we take? We're bound to find out. After all, it's practically free.

DIRK HANSON has contributed to *Scientific American, Wired, The Dana Foundation, Scientific American Mind,* and other publications. He is the author of *The Chemical Carousel: What Science Tells Us About Beating Addiction.*

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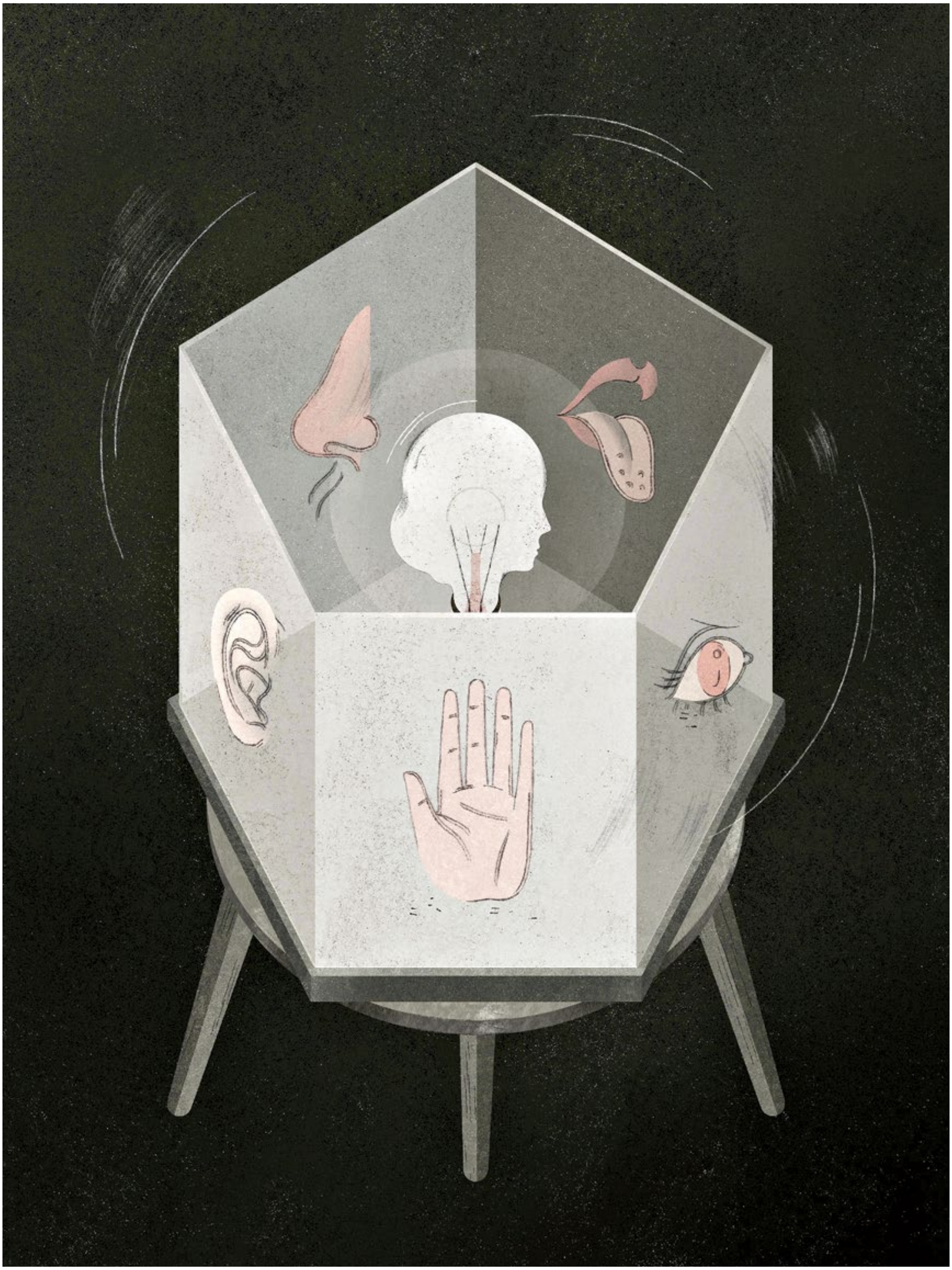

“SOUND AND TOUCH COLLIDE”
BY GRACIA LAM

Take Light, Not Drugs

How light therapy can treat disorders from depression to Alzheimer's disease

BY KATHERINE HOBSON

F**OR RYAN SHERMAN***, a 34-year-old lawyer, something changed eight years ago when he moved from Texas to Europe and then to Boston and New York City: The shorter winter days of the more northern latitudes were like a dead weight on his emotions. "I'd get these depressions," he says. His sleep schedule changed, too, with his bedtime slipping progressively later and early morning wakeups becoming increasingly difficult.

He tried medication to improve his mood—"a Xanax type of thing"—but it didn't make him feel better. Then, while searching online, he discovered the Center for Light Treatment and Biological Rhythms at Columbia University Medical Center in Manhattan. After undergoing a psychiatric consultation and filling out a questionnaire, he was prescribed a light box.

Between October and March, he wakes up at 6:15 a.m. and, so as not to disturb his partner, immediately heads to his living room, where he spends 30 minutes basking in the box's glow. His mood lifted within a week when he started the treatment about two years ago. "It was an overwhelming sense of going from being a pessimist to being an optimist," he says. It's a steady commitment, but a worthwhile one. He can feel the effects when he falls off the light box wagon, as he did recently during a particularly busy time at work. "I felt my mood significantly go downhill," he says. Within three days of returning to his regular doses of light, in combination with a little bit of exercise, he says he felt "a significant transformation."

Light therapy has become standard for treating seasonal depression like Sherman's. The idea that light has a benevolent influence on mood during the dark days of winter instinctively makes sense: As hazardous as sunbathing is, it certainly feels good. Now, research into the circadian underpinnings of chronic depression, bipolar disorder, Alzheimer's disease, and chronic fatigue suggests that light could help these patients, too.

RESEARCHERS HAVE KNOWN FOR decades that light influences animal behaviors; exposing a rodent to light during its usual nighttime, for example, stops its brain's pineal gland from producing melatonin, a hormone that oscillates with day and night cycles. And in 1980, a psychiatrist named Alfred Lewy, then at the National Institute of Mental Health, published a report in *Science* showing that humans were similarly vulnerable to a bright light's effects.[1]

Months before the paper was submitted, Lewy was contacted by Herb Kern, an engineer who had meticulously recorded his severe mood swings for years. Kern noticed that his depressions peaked during the short winter days and then retreated as the days grew longer. He had combed through studies on light and melatonin and wondered if it had any bearing on his sadness.

ILLUSTRATION BY SHANNON FRESHWATER

Lewy and his colleagues asked Kern to sit by a bright light in the winter mornings and evenings to mimic the longer days of spring. Kern responded quickly, his description of light's effects sounding much like Ryan Sherman's. "I began to be bubbly again," he later reflected in a *Science* article. Kern's experience, followed by further research, sparked the first scientific description of seasonal affective disorder, or SAD.[2]

As research into light treatment for SAD continued, it became clear that it wasn't necessary to stretch the day at both ends. "You could get as quick and as effective a response by presenting light in the early morning only and keeping [lighting] dim later on," says Michael Terman, the Columbia University psychologist who treated Sherman and co-author of *Reset Your Inner Clock*, a book about treatments targeting circadian rhythms.

Exactly how light works isn't known, but many researchers suspect that bright lights help SAD sufferers by regulating their sluggish circadian clocks. Those clocks involve the suprachiasmatic nucleus, or SCN, which is a small area of the brain's hypothalamus that dictates the rhythms of a host of bodily functions, including waking, sleeping, body temperature, and alertness. Absent external cues, those rhythms circulate for slightly longer than 24 hours for most people. (They stabilized at 24:30 for a man who lived in a dark cave for two months.) But normally these rhythms are harmonized with the external 24-hour day/night cycle when sunlight hits a cluster of special retinal cells that are sensitive to blue, short-wavelength light.

People with SAD may have problems syncing their internal clocks in the winter, such that darker mornings allow their body's natural rhythms to drift later. Exposure to an artificial bright light in the morning usually improves their moods, says Lewy, presumably by changing the ebb and flow of the stress hormone cortisol or other bodily processes orchestrated by the SCN.

However, circadian rhythms appear to be disturbed in non-seasonal maladies too, which means there is a potential for light therapy beyond SAD, says Anna Wirz-Justice, professor emeritus at the Psychiatric Hospital of the University of Basel. She adds that light therapy has appeal for good reason. When it works, it does so quickly—usually within a week or two. Also, the side effects appear to be mild: Some patients have headaches or slight nausea at the beginning of treatment, and others report agitation. For researchers like Wirz-Justice, the choice to use light rather than drugs for depression and other mood disorders when possible is obvious. "Light is an active pharmacological agent hitting the brain," she says. But does it work?

According to a handful of studies cited by the American Psychiatric Association's (APA) practice guidelines for non-seasonal depression, it may. One of those trials, from 1992, exposed two dozen veterans with major depressive disorder or bipolar depression to bright light treatment ranging from 2,000 to 3,000 lux, and another two dozen to a dim, red light placebo. Those treated with bright light showed declines in three measures of depression during treatment; those exposed to the placebo did not. "In general, bright light therapy is a low-risk and low-cost option for treatment," the APA concludes. They add that it may speed up patients' responses to antidepressants.

HOWEVER, THE TRIALS ON light therapy for nonseasonal depression have been small and generally short-term, the APA notes. And some studies, particularly early ones, had methodological limitations, such as a lack of consensus over the best placebo to use. (For example, if you use dim light as a placebo, patients may not anticipate as much improvement as they would with a brighter light.) The lack of proof may in part explain why so few psychiatrists recommend light boxes for anything beyond SAD. Plus, light therapy might get lost in the grab bag of options for treating depression, such as drugs, psychotherapy, and deep brain stimulation, says David Neubauer, a psychiatrist at Johns Hopkins Medicine in Baltimore, Md.

Then there's the inconvenience of adding anything new. Doctors might not have heard about light therapy in medical school, so it doesn't pop to mind, and some patients accustomed to pills may not be open to the time and logistics involved in sitting beside a light box early each morning.

Light therapy researchers say it's tough to do big, lengthy studies because they lack money for research. In contrast, the pharmaceutical industry has the financial backing to pay for large trials and then get the results in front of physicians' eyes.

A lack of capital may also account for why no light box companies can claim that the boxes treat a disease. For that they need a stamp of approval from the U.S. Food and Drug Administration (FDA), which requires large studies and application fees for filing paperwork. Therefore, people are left to venture out on their own, and to confront an unregulated heap of options ranging in price from less than $100 to $700. However, a Canadian light box manufacturer, The Litebook Company, is seeking FDA approval for a portable device.

Psychiatrists might eagerly turn to light therapy if there were more evidence to back it—particularly when faced with patients who want to avoid antidepressants. With this segment of the population in mind, several studies have kicked off in recent years. In one, published in 2011, researchers treated clinically depressed, elderly participants with an hour of 7,500 lux pale blue light, or a placebo, dim red light, every morning for three weeks.[3] Not only did the group exposed to the blue light report better sleep and a shift in their downcast mood, the effects continued after the therapy ended. According to the study authors, the elderly might be particularly susceptible to the benefits of light therapy because their light perception declines with age, which might be throwing their internal clocks out of sync. Plus, antidepressants aren't always an option for them because the drugs may interfere with some of the medications commonly prescribed to seniors.

Likewise, depressed women often wish to avoid drugs when they're pregnant. A small placebo-controlled trial found that 69 percent of pregnant women treated with light therapy achieved remission from depression after a month, compared to 36 percent in the placebo group.[4] And researchers at the University of Pittsburgh are now analyzing data from a recently completed trial testing the efficacy of light therapy on bipolar depression, which can be difficult to treat with drugs. Light is unlikely to be a silver bullet for complex psychiatric disorders, Terman says, but it may work in combination with other treatments.

SCIENTISTS LIKE MARIANA FIGUEIRO have started to wonder whether light therapy might heal ailments beyond depression by resetting circadian rhythms. Figueiro, a photobiologist at the Rensselaer Polytechnic Institute in Troy, N.Y., has shown that older adults with Alzheimer's disease have disruptions in these rhythms, caused or compounded by the fact that they tend to get outside less often than healthy adults. She's developed light therapy catered to Alzheimer's patients: a "light table" built from a 70-inch flat-screen TV that patients can sit at during the day.

In other ongoing studies, scientists are exploring whether light therapy might reduce fatigue in patients who have recently completed cancer treatment, and treat sleepiness, mood, and motor function in people with Parkinson's disease, who may also have disrupted circadian rhythms.

To Terman, these studies test what he already believes to be true at some level: Light has been woven into human physiology since the beginning. In our artificially lit buildings, we tend to forget that humans once lived under the glowing moon, stars, and sun. Ironically, artificial light may now revive those ancient rhythms from the comfort of our living rooms.

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*Ryan Sherman requested that his real name be concealed.

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Why Physicists Make Up Stories in the Dark

In unseen worlds, science invariably crosses paths with fantasy

BY PHILIP BALL

F**OR CENTURIES, SCIENTISTS STUDIED** light to comprehend the visible world. Why are things colored? What is a rainbow? How do our eyes work? And what is light itself? These are questions that preoccupied scientists and philosophers since the time of Aristotle, including Roger Bacon, Isaac Newton, Michael Faraday, Thomas Young, and James Clerk Maxwell.

But in the late 19th century all that changed, and it was largely Maxwell's doing. This was the period in which the whole focus of physics—then still emerging as a distinct scientific discipline—shifted from the visible to the invisible. Light itself was instrumental to that change. Not only were the components of light invisible "fields," but light was revealed as merely a small slice of a rainbow extending far into the unseen.

Physics has never looked back. Today its theories and concepts are concerned largely with invisible entities: not only unseen force fields and insensible rays but particles too small to see even with the most advanced microscopes. We now know that our everyday perception grants us access to only a tiny fraction of reality. Telescopes responding to radio waves, infrared radiation, and X-rays have vastly expanded our view of the universe, while electron microscopes, X-ray beams, and other fine probes of nature's granularity have unveiled the microworld hidden beyond our visual acuity. Theories at the speculative forefront of physics flesh out this unseen universe with parallel worlds and with mysterious entities named for their very invisibility: dark matter and dark energy.

This move beyond the visible has become a fundamental part of science's narrative. But it's a more complicated shift than we often appreciate. Making sense of what is unseen—of what lies "beyond the light"—has a much longer history in human experience. Before science had the means to explore that realm, we had to make do with stories that became enshrined in myth and folklore. Those stories aren't banished as science advances; they are simply reinvented. Scientists working at the forefront of the invisible will always be confronted with gaps in knowledge, understanding, and experimental capability. In the face of those limits, they draw unconsciously on the imagery of the old

ILLUSTRATION BY MIKO MACIASZEK

stories. This is a necessary part of science, and these stories can sometimes suggest genuinely productive scientific ideas. But the danger is that we will start to believe them at face value, mistaking them for theories.

A backward glance at the history of the invisible shows how the narratives and tropes of myth and folklore can stimulate science, while showing that the truth will probably turn out to be far stranger and more unexpected than these old stories can accommodate.

Occult light

Who now will stand up for the British physicist Edmund Fournier d'Albe, who in 1908 put forward the theory that the human soul is composed of invisible particles called "psychomeres" possessing a rudimentary kind of intelligence? He estimated the mass of these particles in a single soul (about 50 milligrams) and suggested that his hypothesis could account for paranormal phenomena such as ghosts and fairies, perhaps even Moses' burning bush. Sure, it sounds wild, but Fournier d'Albe was a respected researcher in radio telecommunications, and he insisted that, in the light of recent discoveries such as X-rays and the electron, we'd be unwise to discount something just because we can't see it directly.

"We must resolutely combat the tendency to look for the unseen beyond the seen," Fournier d'Albe wrote. "The unseen is all about us… a single octave in the gamut of light-waves impresses our retina, revealing a very small proportion of what would be visible to a more completely equipped intelligence."

In other words, he and his contemporaries insisted, there's more to heaven and earth.

Things that we can't see or touch once belonged to the realm of the occult. This simply meant that they were hidden, not necessarily that they were supernatural. But the occult became the hiding place for all kinds of imaginary paranormal phenomena: ghosts, spirits and demons, telepathy, and other "psychic forces." These things seem now to be the antithesis of science, but when science first began to fixate on invisible entities, many leading scientists saw no clear distinction between such occult concepts and hard science. They invented wonderful stories to link and explain them. Victorian physicists were particularly prone. Some conjectured that there exist intelligent, unseeable beings on the subatomic or the cosmic scale. Others speculated that high-frequency waves outside the visible range could transmit thoughts between minds, or that immortal souls were consistent with the laws of thermodynamics. Anything seemed possible, as it often does when we awaken to our ignorance.

This swerve toward the invisible started with efforts to comprehend the ancient question: What is light? In the early 19th century Faraday introduced the idea of a field—an invisible, pervasive influence—to explain the nature of electricity and magnetism. In the 1860s, Maxwell wrote down a set of equations showing how electricity and magnetism are related. Maxwell's equations implied that oscillations in these coupled fields—electromagnetic waves—would move through space at the speed of light. It was quickly apparent that these waves in fact *are* light.

But where visible light has wavelengths of between about 400 and 800 millionths of a millimeter, Maxwell's equations showed that there was no obvious limit to the wavelength that electromagnetic waves can have. They may exist beyond both the upper and lower limits of the visible range.

These predictions were soon confirmed. In 1887, the German scientist Heinrich Hertz showed that fluctuations of electrical current could give rise to long-wavelength radiation, which became known as radio waves. It took less than a decade for the Italian Guglielmo Marconi to show that radio waves could be used to transmit messages across vast distances.

It's hard to appreciate now how revolutionary this was, not just practically but conceptually. Previously, messages beyond shouting range had to be sent either by a physical letter or as pulses of electricity down telegraph wires. The telegraph was already extraordinary enough, but still it required a physical link between sender and receiver. With radio, one could communicate *wirelessly* through "empty space."

It is no coincidence that these discoveries happened at the height of the Victorian enthusiasm for spiritualism, in which mediums claimed to be able to contact the souls of the dead. The two trends supported each other. The new physics hinted at explanations for thought transference, whether from other people or from spirits; and a widespread belief in invisible influences and intelligences created a receptive environment for ideas in physics that seemed scarcely less incredible. If radio waves could transmit invisibly between a broadcasting device and a receiver, it did not seem so hard to imagine that human brains—which are after all quickened by electrical nerve signals—could act as receivers.

But what, then, of the senders? Scientists, familiarized now to the concept of invisible fields, had begun to speculate about non-material beings that inhabit unseen planes of existence. Maxwell's friends Peter Guthrie Tait and Balfour Stewart, both professors of physics, published *The Unseen Universe* (1875), in which they presented the ether—supposedly the rarefied fluid that carries Maxwell's waves—as a bridge between the physical and spiritual worlds, both of which they considered to be populated with intelligences. Some of the pioneers of the telegraph had already drawn parallels with spiritualism, which they called "celestial telegraphy." Now the wireless spawned a vision of empty space as being alive with the traces of unseen beings. All you had to do was tune in, just as radio enthusiasts scanned the airwaves for crackly, half-heard snatches of messages from Helsinki or Munich. Rudyard Kipling's short story "Wireless" (1902) described a man who, feverish from tuberculosis, becomes a receiver for fragments of a poem by Keats, while elsewhere in the house a group of amateur radio operators picks up broadcasts from a nearby ship. While the spiritual "telegraph line" channeled by the medium in a séance offered the comfort of words from departed loved ones, the wireless seemed instead to make the spirit world a source of impersonal, often meaningless missives cast adrift in an unheeding universe.

The discovery of X-rays by Wilhelm Röntgen in 1895 further stimulated these imaginings. X-rays, it soon became clear, were invisible rays at the other end of the spectrum from radio, with wavelengths much shorter than those of light. Their discovery was an offshoot of experiments on the "cathode rays" found to be emitted from hot metal electrodes, which were themselves found in 1898 to be streams of electrically charged subatomic particles that were named electrons.

What made X-rays so astonishing and evocative was that they not only were invisible but *revealed* the invisible—not least, the bones beneath our flesh, in an unnerving presentiment of death. In the 1890s, people flocked to public demonstrations at shows such as the Urania in Berlin or Thomas Edison's stage spectacles in New York to watch their skeletons appear on fluorescent, X-ray-sensitive screens. X-ray photography seemed a straightforward extension of the "spirit photography" that had become popular in the 1870s and '80s, which claimed to reveal ghosts by faked or genuinely inadvertent double exposures. It confirmed the photographic emulsion as a "sensitive medium" that could render the invisible visible. Others claimed to see evidence of new types of invisible rays recorded in photographs, and even to be able to photograph "thought forms" and souls.

Many leading scientists saw no clear distinction between the occult and hard science.

At the *fin-de-siècle*, invisible "rays" were everywhere, and no claim seemed too extravagant. There were cathode rays and anode rays, wholly spurious radiations such as N-rays and "black light" (although ultraviolet light also acquired that name), and most famously, the "uranic rays" that Henri Becquerel discovered coming from uranium salts in 1896. These streamed in an unchecked and unquenchable flow, suggesting a tremendous hidden source of energy that, through the work of Pierre and Marie Curie, Ernest Rutherford, and others, was eventually traced to the nuclear heart of the atom. The Curies renamed these rays "radioactivity."

There was an old cultural preconception that invisible "emanations" could have life-enhancing agency, whether these were the "virtues" ascribed to medicinal herbs in the Middle Ages or the "animal magnetism" or "mesmeric force" of the 18th-century German physician Franz Anton Mesmer. We shouldn't be surprised,

SPIRITS IN THE LIGHT In the 1870s, to investigate psychic forces, chemist William Crookes invented the radiometer (above), in which delicate vanes rotate when illuminated by light.

HAADE/WIKIMEDIA

then, that radioactivity was widely believed to have miraculous healing powers. "Whatever your Ill, write us," advertised the Nowata Radium Sanitarium Company in 1905. "Testimonials of Cases cured will be sent you." "Therapeutic" radium was added to toothpastes and cosmetics, and spa towns proudly advertised the radioactivity (from naturally occurring radon) in their waters. It wasn't until the 1920s that the health effects of radioactive elements were shown to be quite the opposite: too late to save Marie Curie herself, or some of the Radium Girls—factory workers who had for a decade been licking paintbrushes dipped in radioactive paint for the dials of watches.

Ghost factories

One of the key messages of these discoveries of the late 19th century was that the universe we perceive is only a small part of what is out there. There was a long tradition of "spirit worlds" going back at least to the Middle Ages, when it was a commonplace that invisible, malevolent demons lurked all around us. These beliefs provided the unconscious template for making sense of the new "invisible universe." The respected physicist William Barrett, who co-founded the Society for Psychical Research in 1882, proposed in his book *On the Threshold of the Unseen* (1917) that there exist human-like invisible "elementals."

That was an idea shared by one of the most prominent of the "psychical" scientists of the age, William Crookes. A chemist and entrepreneur who served as the President of the Royal Society between 1913 and 1915, Crookes became famous when he discovered the new chemical element thallium in 1861. Yet he seems to have been particularly credulous of spiritualists' claims, perhaps even collusive with them. He was taken in by several mediums, including the renowned Florence Cook. Like many mediums, Cook was a striking young woman who found it easy to manipulate the judgment of Victorian gentlemen of more advanced years. Crookes was convinced that "there exist invisible intelligent beings, who *profess* to be spirits of deceased people." (He evidently took this to be the skeptical view.) To investigate the "psychic force" that he thought mediums commanded, Crookes invented a device called the radiometer or "light mill," in which delicate vanes attached to a pivot inside a sealed glass bulb would rotate when illuminated by light. Although the reason for the rotation was not, as at first thought, due to the "pressure" exerted by light itself—despite having no mass, light rays can deliver a little kick to surfaces they strike—that pressure is a real enough phenomenon, and the radiometer helped to establish it. Thus, an instrument motivated by a belief in the paranormal prompted useful scientific work on the properties of light.

The same may be said of Crookes' "radiant matter," allegedly a "fourth form of matter" somewhere between ordinary material and pure light. Crookes discovered this stuff while conducting important work with gas discharge tubes, in which charged electrodes ionize a vapor so that an electrical current can pass through it, producing a glow. In 1879 he claimed that radiant matter existed in "the shadowy realm between known and unknown." He suspected that it, like the ether, might be a bridge to the spirit world.

Radiant matter was another figment of Crookes' overactive imagination. But this too bore fruit. He invoked radiant matter to explain a mysterious region inside the discharge tubes called the "dark space." But it turned out that this dark region was instead caused by cathode rays, and Crookes' research on this phenomenon led ultimately to the discovery of electrons and X-rays and, coupled with Marconi's radio broadcasting, to the development of television. Indeed, several of the early pioneers of television were motivated by their paranormal sympathies, whether it was Crookes refining the cathode ray tube, Fournier d'Albe devising his own idiosyncratic televisual technology, or John Logie Baird, usually regarded as the device's *real* inventor, who believed he was in spiritualistic contact with the departed spirit of Thomas Edison.

Both radio communication and television were representative of *all* modern media in that they are ghost factories, forever manufacturing what in 1886 the psychic researcher Frederic W. H. Myers called "phantasms of the living": disembodied replicas of ourselves, ready to speak on our behalf. Radio could conjure the illusion that the prime minister, or a film star, had become manifest, though disembodied like a phantom, in your sitting room. How much more potent the illusion was, then, once you could see such electronic ghosts as well as hear them. It might have seemed natural and harmless enough to refer to the double images of early television sets, caused by poor reception or bad synchronization of the electron beam, as "ghosts"—but this terminology spoke to, and fed, a common suspicion that the figures you saw on the screen might not always correspond to real people. After all, they might already be dead. News reporters flocked to the home of Jerome E. Travers of Long Island in December 1953 to witness the face of an unknown woman who had appeared on the screen and wouldn't vanish even when the set was unplugged. (The family had turned the screen toward the wall, as if in disgrace.)

By appearing to transmit our presence over impossible reaches of time and space, and preserving our image and voice beyond death, these media subvert the laws that for centuries constrained human interaction by requiring the physical transport of a letter or the presence of the persons themselves. We submit to the illusion that the voice of our beloved issues from the phone, that the Skyped image conjured on the screen (now by light-emitting diodes rather than electron-blasted phosphors) is the faraway relative in the flesh.

Who could possibly be surprised, then, that the Internet throngs with ghosts? As folklore historian Owen Davies says, "cyberspace has become part of the geography of haunting." Here too the simulated traces of the dead may linger indefinitely; here too pseudonymous identities are said to speak from beyond the grave. More even than the telephone and television, the Internet, that invisible babble of voices, seems almost designed to house spirits, which after all are no more ethereal than our own cyber-presence.

Time and again we see that technology by itself doesn't banish folk beliefs and superstitions, it

Several of the early pioneers of television were motivated by paranormal sympathies.

The Internet, that invisible babble of voices, seems almost designed to house spirits.

merely creates new environments for them. Maybe that shouldn't be any surprise, as technical advances don't in themselves produce any general advance in people's ability to reason or assess evidence. But surely science still pushes back the dark clouds of ignorance and superstition? Yes, it surely does. That is not to say, though, that scientists today are less prone to flights of imaginative fantasy than their predecessors. And thank goodness, for science needs imagination as much as cold logic. But as in Victorian times, sometimes it's hard to distinguish fantasy from fact when both are couched in the jargon of the day.

Hidden worlds

Take, for example, the Many-Worlds Interpretation of quantum mechanics. There's no agreement about quite how to interpret what quantum theory tells us about the nature of reality at tiny scales, but the Many-Worlds Interpretation has plenty of influential adherents. It supposes the existence of parallel universes that embody every possible outcome of the many possible solutions to the equations describing a quantum system. According to physicist Max Tegmark of the Massachusetts Institute of Technology, "it predicts that one classical reality gradually splits into superpositions of many such realities." The idea is derived from the work of physicist Hugh Everett in the 1950s—but Everett himself never spoke of "many worlds."

At that time, the prevailing view in quantum theory was that, when you make a measurement on a quantum system, this selects just one of the possible outcomes enumerated in the mathematical entity called the wavefunction—a process called "collapsing the wavefunction." The problem was there was nothing in the theory to cause this collapse—you had to put it in "by hand." Everett made the apparently innocuous suggestion that perhaps there is no collapse: that all the other possible outcomes also have a real physical existence. He never addressed the question of *where* those other states reside. But some of his successors build up around them an entire universe, identical to our own in every respect except for that one aspect. Every quantum event causes these parallel universes to proliferate, so that "the act of making a decision causes a person to split into multiple copies," according to Tegmark. (More properly, these alternative universes have always existed, it's just that things evolve differently in each of them.)

But this idea itself collapses into incoherence when you actually try to populate the Many-Worlds with sentient beings. It's not (as Tegmark might be thought to imply above) that there are alternative versions of us in these many worlds—they are *all* in some sense us, but there's no prescription for where to put our apparently unique consciousness. This conundrum arises not (as some adherents insist) as an inevitable result of "taking the math seriously," but simply because of the impulse, motivated by neither experiment nor theory, to make each formal mathematical expression a complete world of its own, invisible from this one. That is done not for any scientific reason but because it is what, in the face of the unknown, we have always done. In the Middle Ages, the tangible evidence for invisible forces like magnetism made invisible beings like demons seem more plausible. The discovery of X-rays, radio waves and radioactivity likewise bolstered beliefs in a populous "unseen universe." The apparent collapse of the wavefunction is indeed a profound mystery—should we then be surprised that one response is to build invisible universes to compensate?

Much the same consideration applies to the concept of "brane" (short for membrane) worlds. This arises from the most state-of-the-art variants of string theory, which attempt to explain all the known particles and forces in terms of ultra-tiny entities called strings, which can be envisioned as particles extended into little strands that vibrate. Most versions of the theory call for variables in the equations that seem to have the role of extra dimensions in space, so that string theory posits not four dimensions (of time and space) but 11. As physicist and writer Jim Baggott points out, "there is no experimental or observational basis for these assumptions"—the "extra dimensions" are just formal aspects of the equations. However, the latest versions of the theory suggest that these extra dimensions can be extremely large, constituting extra-dimensional branes that are potential repositories for alternative universes separated from our own like the stacked leaves of a book. Inevitably, there is an urge to imagine that these places too might be populated with sentient beings, although that's optional. The point is that these brane worlds are nothing more than mathematical entities in speculative equations, incarnated, as it were, as invisible parallel universes.

Dark matter and dark energy are more directly motivated by observations of the real world. Dark matter is apparently needed to account for the gravitational effects that seem to come from parts of space where no ordinary matter is visible, or not enough to explain the tug. For example, rotating galaxies seem to have some additional source of gravitational attraction, beyond the visible stars and gas, that stops them from flying apart. The "lensing" effect where distant astrophysical objects get distorted by the gravitational warping of spacetime also seems to demand this invisible form of matter. But dark matter does not exist in the usual sense, in that it has not been seen and there are no theories that can convincingly explain or demand its existence. Dark energy too is a kind of "stuff" required to explain the acceleration of the universe's expansion, discovered by astronomers observing far-away objects in the mid-1990s. But it is just a name for a puzzle, without any direct detection.

It seems quite possible that dark energy, and perhaps dark matter too, will turn out to be like Crookes' "dark space" and "radiant energy": not exactly stuff, but symptoms of some hitherto unknown physical principle. These connections were exquisitely intuited by Philip Pullman in the *His Dark Materials* trilogy, where (the title alone gives a clue) a mysterious substance called Dust is an amalgam of dark matter and Barrett's quasi-sentient psychomeres, given a spiritual interpretation by the scientist-priests of Pullman's alternative steampunk Oxford University who sense its presence using instruments evidently based on Crookes' light mill.

Scientists, of course, are not just making things up, while leaning on the convenience of supposed invisibility. They are using dark matter and dark energy, and (if one is charitable) quantum many-worlds and branes, and other imperceptible and hypothetical realms, to perform an essential task: to plug gaps in their knowledge with notions they can grasp.

These makeshift repairs and inventions are needed if science is not to be derailed or demoralized by its lacunae. When this happens, it seems inevitable the inventions will take familiar forms—they will be drawn from old concepts and even myths, they will be "mysterious" particles or rays or even entire imagined worlds, replete with inhabitants. These might turn out to be entirely the wrong concepts, but they make our ignorance concrete and enable us to think about how to explore it.

When working at the frontiers of knowledge, pondering questions of time and space that we can hardly intuit or visualize, cold logic and strict adherence to experiment and falsifiability might not be enough. But then the trick is to invent and imagine without losing sight of the fact that this is what we're doing. We'll probably find that our inventions are wrong, precisely because they tend to come from an old canon. But hopefully they'll be wrong in a good way, and illuminate the path to a deeper understanding of the universe.

PHILIP BALL is the author of many books on science and its impacts on the broader culture, including *Life's Matrix: A Biography of Water*; *Universe of Stone*; *The Music Instinct*; *Curiosity: How Science Became Interested in Everything*; and *Serving the Reich*. His book *Critical Mass* was awarded the 2005 Aventis Prize for Science Books. His next book is *Invisible: The Dangerous Allure of the Unseen*.

When the Sky Explained Everything

How ancient astronomy sowed the seeds for science and math

BY KEVIN BERGER

EDWIN C. KRUPP, DIRECTOR OF Griffith Observatory, is in the business of small miracles. "It's a small miracle to turn visitors into observers, to put them eyeball to eyeball with the cosmos," he says. Few observatory directors have been performing small miracles as long as Krupp, 69, who has been the director of the Los Angeles landmark for 40 years.

Nautilus called on Krupp to illuminate the dawn of astronomy, when scientists forged the tools of math and science to make sense of the universe and Earth's place in it. Krupp is an "archaeoastronomer" who has traveled the world studying archeological sites, such as Stonehenge, where ancient people created earthly monuments to the cosmos. His books detail how ancient people organized their lives by the sun, moon, and stars, and crafted calendars, clocks, and legends to live by.

Seated in a conference room in the Griffith Observatory, perched atop Mount Hollywood, Krupp, in conversation, was ebullient, slightly sarcastic with a wonderful tendency to ramble. Central casting couldn't find a better person to star in a movie about an ingratiating astronomer than Krupp, who was wearing a pinstriped gray suit, pink shirt, and pink tie with a photo of Stonehenge on it.

ILLUSTRATION BY MIKO MACIASZEK

How does the story of astronomy begin?

Astronomy is almost nothing but light. And the story of how that light has been perceived and used begins with the eye. Think about what the eye gets from the sky. In the earliest times, you get some information about brightness. You get some information about position. If you watch over a period of time, you get some information about motion, and you get just a little bit of information about color. That's it. And yet, from that information our ancestors contrived tools. They made a tool out of the sky to do things like track the seasons. They kept track of the passage of time because people and things need to be in certain places. Coordinated activity requires both timekeeping and calendars.

Is one of those tools math?

Yes. The path between math and astronomy can be traced back to Mesopotamia, about 4,000 to 5,000 years ago. In terms of human experience on the planet, that's not very much. But math has a power for people that is far more expansive than simply what's happening in the sky and how things overhead work.

Because math was a way to order the universe?

Certainly it was. But if you're looking for the roots of mathematics, it has to begin with, "I've got sheep. How many?" "I've got a family. Is anyone missing?" So counting, numeration, and manipulation of numbers have got to be very archaic skills. We have lots of economic records from ancient Mesopotamia, and it would be easy to argue that the real power of mathematics in ancient Mesopotamia was business.

How did people in prehistoric times relate to the night sky?

Our ancestors in deep prehistoric times had a human connection with the cosmos that is probably deeper, more abiding, and more deeply felt than we have today. They saw the connections between things. They saw light from the sun but they didn't know how it was formed. Nobody was talking about thermonuclear reactions in the core of the sun. But they realized the behavior of the sun had a big-time effect on the earth—on what the animals did, the plants did. The earliest calendars may have kept track of stars that appear in the predawn, or just after sunset. When a group of stars is visible, it means this animal is going to do this, the salmon are going to run, the deer are going to rut. Now we know the universe is operating on scales beyond ordinary human experience, and according to physical laws that don't make common sense and have to be examined mathematically. Maybe now we have a far less integrated relationship to the cosmos.

Give us an example of how ancient people read the stars.

We know the Quechua people in the Andes used astronomical observations to predict the weather. During the summer solstice the community would go out and look at the Pleiades star cluster to decide what their planting strategy should be. The reason is because the Pleiades vary in their appearance from year to year. Sometimes the stars seem very bright and tight. Sometimes they seem a little muddier. And you think, "What is going on here?" The stars are not controlling the weather. But now we know from satellite observations what these folks have been doing for centuries. They are tracking the effects of an El Niño, which is part of the great change of temperature of the Pacific Ocean basin. An El Niño creates cirrus clouds, which are fundamentally invisible, but they alter the appearance of stars in the sky. So the Quechua were observing what El Niño is doing and making decisions based on average temperatures and rainfall. People in the Andes still do.

What's your astrological sign?

I happen to be Scorpio.

Today we make fun of astrology because it's not science, but how did it lead to astronomy?

It's certainly appropriate to say astrology was merged closely with astronomy. Even in antiquity, if you could separate them out, you would say both are just the basic gathering of the data and the manipulation of data to reach broader conclusions. As we've discussed, people saw the seasonal behavior of the sun and stars, the tidal behavior of the moon. So it's understandable that people in antiquity would come to the conclusion that what's happening in the sky has an effect on Earth. But this is what's interesting. You can go to ancient Maya, whose people practiced astrology, to the Mediterranean, where astrology was rooted in Mesopotamia, which picks up stuff from Greece and Egypt, and then to China. Every one of those cultures puts astrological rules together in a different way. It's the same sky but they read it completely differently. So if you could be a cross-cultural astronomer 2,000 years ago, you would know right away that the jig is up because all these guys can't be right. And they aren't right. The rules of astrology are not physical laws. You have to recognize that for people today who invest in astrology, this is a matter of belief. Astrology is truly a matter of faith and I don't believe terribly in criticizing people's religion.

You've said, "If Galileo had never pointed a telescope to the sky we wouldn't have cell phones." What did you mean?

Galileo turns out to be one of those personalities who actually did stuff. He didn't just talk about it. He experimented and didn't take for granted the things that were said to be true. He tested. The heart of science is testing your knowledge. You understand your

Astrology is truly a matter of faith and I don't believe in criticizing people's religion.

knowledge is limited. You understand that what you might successfully discern today could be overtaken by subtler discoveries later on. The scientific revolution is rooted in a mentality that doesn't rely on authority. Galileo had that. When he made a telescope, he did this remarkable thing. He used it to look at the sky. It was a military device for gosh sake, used to look at ships in the distance. He pointed it at the moon, at Venus, at Saturn. It was like the universe was a whole new place. Ultimately, you have to link Galileo's celestial observations to the laws of motion, to Kepler and Newton, who was able to define the mathematical way the forces work to make all this happen. So it's really a short jump from Newton's laws, to putting satellites in orbit around the earth, to smart phones.

You seem very inspired by Galileo. Was he an inspiration for you?

I'm inspired by anybody who makes a jump and does the unusual, who insists on pursuing an inquiry to wherever curiosity and compulsion lead.

Early Humans Made Animated Art

How Paleolithic artists used fire to set the world's oldest art in motion

BY ZACH ZORICH

S**TONE STEPS DESCENDED INTO** the ground, and I walked down them slowly as if I were entering a dark movie theater, careful not to stumble and disrupt the silence. Once my eyes adjusted to the faint light at the foot of the stairs, I saw that I was standing in the open chamber of a cave.

Where the limestone wall arched into the ceiling was a line of paintings and drawings of animals running deeper into the cave. The closest image resembled a bison, with elongated horns and U-shaped markings on its side. The bison followed several horses painted solid black like silhouettes; above them was an earthy-red horse with a black head and mane. In front of that was a very large bison head that was completely out of scale with respect to the other images.

It was the summer of 1995, and in the dim glow, I gazed at the ghostly parade just as my ancestors had roughly 21,000 years ago. Radiocarbon dates from Lascaux cave suggest the art is from that period, a time when wooly mammoths still roamed across Europe and people survived by hunting them and other large game. I stood in silence as I tried to decode the work of ancient people who had come here to express something of their world.

When Lascaux cave was discovered in 1940, more than 100 small stone lamps that once burned grease from rendered animal fat were found throughout its chambers. Unfortunately, no one recorded where the lamps had been placed in the cave. At the time, archeologists did not consider how the brightness, movement, and the location of lights altered how the paintings would have been viewed. In general, archeologists have paid considerably less attention to how the use of fire for light affected the development of our species, compared to the use of fire for warmth and cooking. But now in Lascaux and other caves across the region, that's changing.

ARTISTS AT LASCAUX USED fire to see inside caves, but the glow and flicker of flames may also have been

ILLUSTRATION BY MIKO MACIASZEK

integral to the stories the paintings told. "Today, when you light the whole cave, it is very stupid because you kill the staging," says Jean-Michel Geneste, Lascaux's curator, the director of France's National Center of Prehistory, and the head of the archaeological project I worked on that summer. Worse yet, most people only see cave paintings in cropped photographs that are evenly lit with lights that are strong and white. According to Geneste, this removes the images from the context of the story they were meant to tell and makes the colors in the paintings colder and bluer than Paleolithic people would have seen them.

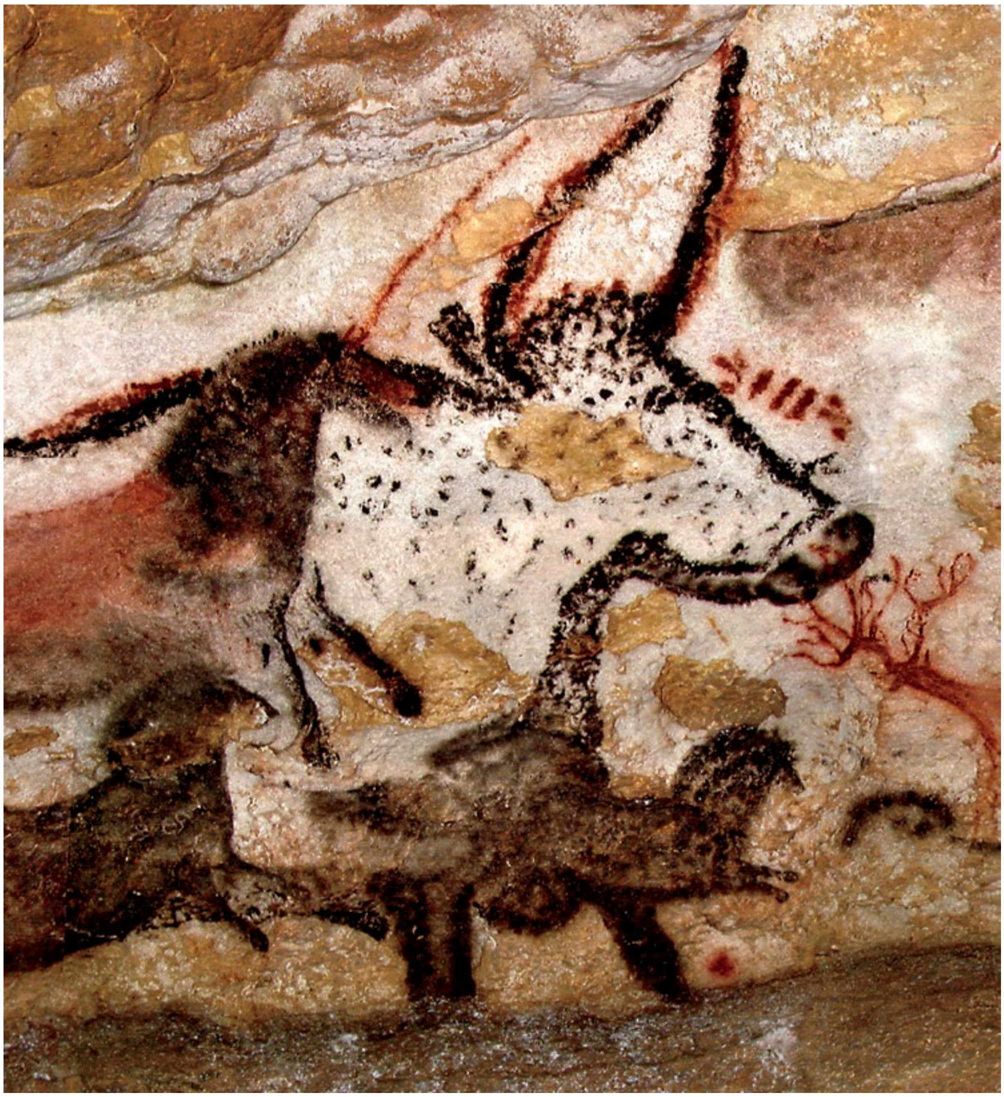
"When you light the whole cave, it is very stupid because you kill the staging."

Reconstructions of the original grease lamps produce a circle of light about 10 feet in diameter, which is not much larger than many images in the cave. Geneste believes that early artists used this small area of light as a story-telling device. "It is very important: the presence of the darkness, the spot of yellow light, and inside it one, two, three animals, no more," Geneste says. "That's a tool in a narrative structure," he explains. Just as a sentence generally describes a single idea, the light from a grease lamp would illuminate a single part of a story. Whatever tales may have been told inside Lascaux have been lost to history, but it is easy to imagine a person moving their fire-lit lamp along the walls as they unraveled a story step-by-step, using the darkness as a frame for the images inside a small circle of firelight.

Geneste supports his hypothesis by pointing to the various sizes of animals. "If you want to have several animals in a narrative relationship it is necessary to have them small," he says. "If you want only one animal, you make them big." If Geneste is right, the paintings I saw in the Hall of Bulls could have been read like a comic strip, as a series of frames: first the bison, then two black horses, more horses, a focus on the bison, and so on down the length of the chamber.

What's more, a flickering flame in the cave may have conjured impressions of motion like a strobe light in a dark club. In low light, human vision degrades, and that can lead to the perception of movement even when all is still, says Susana Martinez-Conde, the director of the Laboratory of Visual Neuroscience at the Barrow Neurological Institute in Phoenix, Ariz. The trick may occur at two levels; one when the eye processes a dimly lit scene, and the second when the brain makes sense of that limited, flickering information.

Physiologically, our eyes undergo a switch when we slip into darkness. In bright light, eyes primarily rely on the color-sensitive cells in our retinas called cones, but in low light the cones don't have enough photons to work with and cells that sense black and white gradients, called rods, take over. That's why in low light, colors fade, shadows become harder to distinguish from actual objects, and the soft boundaries between things disappear. Images straight ahead of us look out of focus, as if they were seen in our peripheral vision.



NORBERT AUJOULAT

ANCIENT HERD Running horses, cattle, and deer line the walls in the Hall of the Bulls at Lascaux cave.

FREEZE FRAME Five stag heads in the Nave region of Lascaux cave might represent a single stag in different stages of motion.

NORBERT AUJOULAT

The end result for early humans who viewed cave paintings by firelight might have been that a deer with multiple heads, for example, resembled a single, animated beast. A few rather sophisticated artistic techniques enhance that impression. One is found beyond the Hall of Bulls, where the cave narrows into a long passage called the Nave.

High on the Nave's right wall, an early artist had used charcoal to draw a row of five deer heads. The images are almost identical, but each is positioned at a slightly different angle. Viewed one at a time with a small circle of light moving right to left, the images seem to illustrate a single deer raising and lowering its head as in a short flipbook animation.

Marc Azéma, a Paleolithic researcher and filmmaker at the University of Toulouse in France, has studied dozens of examples of ancient images that were meant to imply motion and has found two primary techniques that Paleolithic artists used to do this. The first is juxtaposition of successive images—the technique used for the deer head—and the second is called superimposition. Rather than appearing in sequence, variations of an image pile on top of one another in superimposition to lend a sense of motion. Superimposition can be seen in caves across France and Spain, but some of the oldest examples come from Chauvet cave in France's Ardèche region. Burned wood and charcoal streaks along Chauvet's walls indicate that it was lit by campfires and pine torches.

At 32,000 years old, some paintings at Chauvet cave are about 10,000 years older than those at Lascaux, but they are no less accomplished. One of the most extensive images in the cave is the "Grand Panneau," a large panel that shows lions, rhinoceroses, bison, horses, and a wooly mammoth. Azéma explains that the panel may relate two separate narratives of lions stalking prey. Near the center of the panel is a charcoal drawing of a rhinoceros that seems to have seven or eight horns, as well as several backs. The rhinos look as if they are piled on top of one another, but Azéma has teased apart each section of the image to show that it could in fact be one rhino in varied positions. In this superimposition, he says, the rhino raises and lowers its horn. Azéma refers to these images as the beginning of cinema because they depict both narrative and motion.

DURING MY VISIT, THE LIGHT inside Lascaux shined steady and just strong enough for me to make out the colors in the rock walls and the paintings. We were only permitted to stay for about 20 minutes, which was enough time to see all the images except for a few that are difficult to reach. Preserving the artwork there has been a constant battle. Intermittently since 2001, Lascaux has been closed due to infestations of molds and fungus that threaten many of the paintings. One type of black mold even seems to feed on the light that people bring into the cave.

I had stood in the Nave with barely enough room to turn around without brushing against the walls. Looking at the art felt like reading a partially translated language. The shapes of the animals were familiar, but their meaning was obscured by the distance between my mind and those of 21,000 years ago. Paleolithic art may have been spiritual—prayers for a successful hunt—or maybe they related specific events—the time when a pride of lions hunted a large rhinoceros. Or perhaps it was like modern-day art, and fulfilled a variety of roles that aren't easily put into categories. Even though the images were mostly of animals, what the art conveyed to me was humanness. The images were an attempt to express a reaction to a dynamic environment. Now that we live in a halogen and LED lit world, it's easy to forget that the way we illuminate the world affects how we see it.

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


Nordgren

Falling In Love with the Dark

One astronomer has taken to U.S. National Parks to rekindle an old romance

BY TODD PITOCK
ILLUSTRATION BY TYLER NORDGREN

IF YOU SEE A car along that road," Tyler Nordgren warned me, "don't look at the headlights. It'll ruin your night vision for two hours." Nordgren and I had pitched our tents under the brow of Mount Whitney in the Alabama Hills, a field of boulders near Death Valley. We watched it get dark, and on the nighttime horizon, the sky was perforated by stars and streaked by the Milky Way. Or, to put it in scientific terms, it was probably a 3 on the Bortle Scale, the 9-level numeric metric of night sky brightness.

Even so, we could still see domes of hazy light from 200-odd miles south in Los Angeles and 250 miles east in Las Vegas. That encroaching urban glow was like a highlighter calling attention to the issue that Nordgren, a prophet whose cause is light pollution, wanted to illustrate for me.

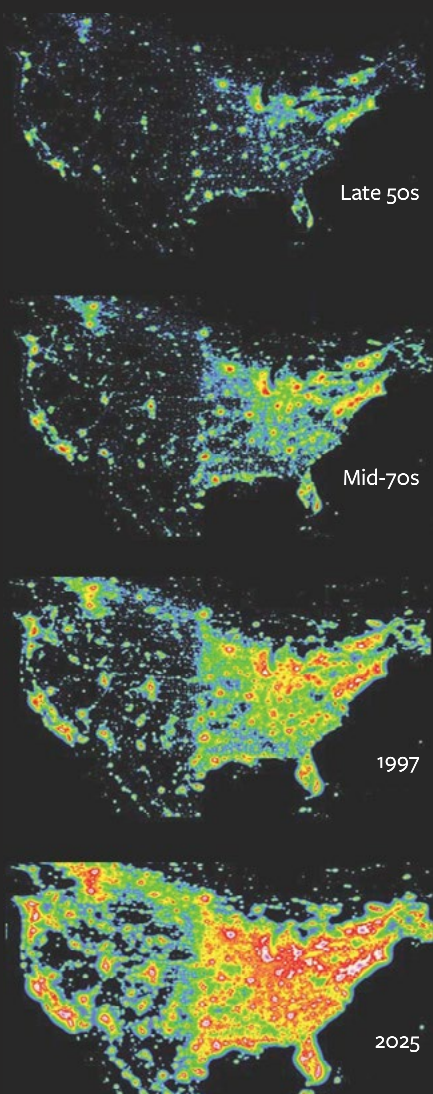
"We're losing the stars," the 45-year-old astronomer told me. "Think about it this way: For 4.5 billion years, Earth has been a planet with a day and a night. Since the electric light bulb was invented, we've progressively lit up the night, and have gotten rid of it. Now 99 percent of the population lives under skies filled with light pollution."

Nordgren is an affable, engaging, and quotable Cassandra, an enthusiastic and patient teacher who loves his subject and wants you to love it, too. Those attributes, along with a book for a lay audience, *Stars Above, Earth Below: A Guide to Astronomy in the National Parks*, have pushed him to center stage of a small but impassioned movement to preserve natural night skies. When he is not lecturing at the University of Redlands, a California liberal arts college, Nordgren is a much

ART AFTER DARK As a complement to his nighttime talks and stargazing programs, Nordgren has developed a poster campaign in conjunction with the National Park Service. Shown to the left is his poster for Sleeping Bear Dunes.

Artificial Skies

The brightness of the night sky at zenith at sea level, over time. Black represents a natural night sky, and pink represents enough artificial light to prevent any stars from being visible. Green represents where you lose sight of the Milky Way.



sought-after itinerant preacher intent on bringing people revelation of the stars they have, almost everywhere, lost sight of.

Almost the entire eastern half of the United States, the West Coast, and almost every place with an airport large enough to receive commercial jets, are too lit up to get a good view of stars. The phenomenon is illustrated by the First World Atlas of Artificial Night Sky Brightness. Based on spacecraft images of Earth in 1997, it shows a spectrum from black, representing the natural night sky, to pink, in which artificial light effectively erases any view of the stars at all. Green is where you lose visibility of the Milky Way. The map of the contiguous 48 states—and much of Europe—looks like a video-game screen showing a carpet bombing, the map a splash of green, yellow, red, and pink.

For roughly the past two decades, at least two-thirds of the U.S. population have not been able to see the Milky Way at all, and it will get worse before it gets better. The dawn of light-emitting diode (LED) lighting is expected to significantly lower costs and spur consumption. In addition, LED lighting produces light with a bluer cast, which is more effectively scattered by the atmosphere. "This has the potential to be the nail in the coffin for seeing stars in most communities," Nordgren told me.

Nordgren wears his hair in the style of a naval officer, cropped on the sides, and I sense that he probably looks much like the boy he once was, who had his sights on becoming an astronaut. Poor vision forced him to settle on becoming a mere astronomer. He wrote his doctoral thesis at Cornell on dark matter in spiral galaxies, graduating in 1997. Carl Sagan, whose popular TV series *Cosmos* had inspired Nordgren to begin with, was there at the time, and Nordgren still regrets that whenever he was in the presence of his idol he would lose his capacity for speech. He couldn't even find the courage to introduce himself, and when he finally did, Sagan said, "I know who you are."

THE LIGHT POLLUTION ISSUE first came up in 1992 when Nordgren went to Cal Tech's Palomar Observatory near San Diego. At the time it had the world's largest telescope. Already, though, the night glow from the surrounding area was forcing astronomers to go elsewhere.

"In 2005, I went back to Palomar to do some work on Adaptive Optics, looking at storm clouds moving atop Uranus and Neptune, and it was really a shock," Nordgren recalled. "Giant housing, casinos, resorts. In '92, you were like, 'Look how bad this is!' Then in '05 we were just an island in a sea of lights."

Light pollution was threatening to pull down the curtain on future research for astronomers, Nordgren said, making existing observatories useless and efforts to build new ones in the U.S. more difficult, as they had to be built in places that put astronomers in conflict with environmentalists and Native Americans.

The light pollution problem grew significantly during a period that was, courtesy of the Hubble Space Telescope, a golden age for astronomy. Hubble went into orbit in 1990 and sent back images of space, unencumbered by backlighting, that would have made Galileo's head spin. But Hubble, despite its marvels, somewhat confused the issue, leading people to assume that astronomy would proceed apace even if astronomers were being shown to obstructed-view seats. The trouble is that Hubble isn't sustainable. Its costs are, as it were, astronomical. It requires space shuttle missions to maintain, and there are no more of those, so Hubble will be gone in a few years. The next project to replace it is over budget and far behind schedule. The long-term solution will rely on terrestrial observatories.

Finding places to put these, though, isn't easy. As astronomers lose the functionality of existing observatories to light pollution, and move to places like Mount Graham in Arizona and Mauna Kea, the location of the W.M. Keck Observatory in Hawaii, they've been protested, sued, and made to feel like wanton intruders, wreckers of the environment, and defilers of sacred spaces. Really ambitious observatory projects, therefore, look overseas. When the Square Kilometer Array Telescope came up for bidding, a process like hosting the Olympics, the U.S. wasn't in the race. With foreign observatories, though, come concerns about long-term political stability.

The question of light pollution gripped Nordgren. Like Sagan, he decided that educating the public was key. When he got his first sabbatical in 2007-2008, he decided he'd spend the time normally reserved for lab work and writing to travel to national parks to give talks. He knew from experience how visitors to the national parks wanted to reconnect to the stars above. But almost all national parks programs were about things on the land. He wanted to remind visitors that the parks, as the last preserves of natural night, were also about the skies. He devoted three weeks in each of a dozen places, among them Rocky Mountain National Park, Grand Teton, Glacier, Acadia, and Great Basin.

Tyler helps participants understand the cultural value of the nighttime sky. "It's one thing all of humanity has in common."

"I was reluctant to tell other astronomers what I wanted to do," he said. "There's a view that astronomers should be in observatories. I remember one guy at Cornell saying, 'Tyler, if you do education, you're wasting your Ph.D.' " This was something Sagan had run into, people who assumed he wasn't a serious scientist because he was on television. "But Carl was a good scientist," Nordgren said. And when Nordgren did share his plans he got a warm reception. "Some people said, 'I wish I'd thought of that!' " The park rangers themselves were mostly very receptive, with some exceptions.

"There were some who had no idea what to make of what I was doing," he said. "I remember folks at the Great Smoky Mountains, when I said I wanted to work with astronomy and night skies, the ranger said, 'We call it 'The Great Smokies.' We don't do a lot of astronomy here.' He was baffled. And then I'd run into people in management for whom it was a 9-to-5 job. When it got dark they went home, so they never saw firsthand the night sky programs, and this was 2007-2008, when budgets were very tight."

In addition to his night skies curriculum, Nordgren created an arts program called See the Milky Way. It's gone on for five years, with poster designs for 30 parks,

SEARCHING FOR THE STARS "People are so stunned when they see the night sky photos they think they're fake," says Nordgren. "Maybe this will be the impetus of a night sky environmental movement." Shown are three of his photographs.

monuments, and dark skies preserves.

The national parks odyssey also resulted in *Stars Above, Earth Below*, his guide which, though it sold out of a relatively modest 3,000-copy first print run and sells now through print-on-demand, found an enduring and loyal audience among rangers.

One of them was Kelly Carroll, a National Parks ranger at Great Basin. He invited Nordgren to keynote the annual astronomy festival he organized and was immediately won over.

"Every once in a while a scientist comes along who knows how to speak about science to the general public," Carroll told me. "Tyler has a way of speaking about light pollution and the aesthetics of the issue. He helps make the connection of what it means to us to lose the night skies as human beings."

Carroll, who was a geologist with the U.S. Geological Survey prior to joining the National Parks Service, told me that the need for someone like Nordgren is great.

TYLER NORDGREN

People are barely aware that "we've had an incredible part of our humanity taken away from us, but it's been so gradual they don't feel the loss," he said.

Rangers tell Nordgren that the night programs get more attendance than all other programs put together. One great success story is Great Basin National Park which, in 2009, put on three night skies programs that drew 300 people. The following year they did 20 that were well-attended, so they instituted it as a primary offering. Since then overnight attendance has increased to about 9,000 a year. And while traditional daytime programs average about 25 to 30 people, the astronomy programs, which are mainly interpretive programs about night skies, typically pull in 150 to 175.

"The first time people come out for dark skies, and we get Bortle Class 1 and 2 here, it affects them deeply," Carroll said. "They're blown away. The connection with the stars is inside all of us, but it has been sequestered away."

Christian Luginbuhl, an astronomer who worked with Nordgren at the Naval Observatory Flagstaff Station, explains to me that Tyler helps participants understand the cultural value of the nighttime sky. "It's also one thing all of humanity has in common," he tells me. "It's the same sky in the Sahara as it is over Philadelphia. It's also the same sky as Native Americans gazed up at 10,000 years ago. People think of light pollution as an astronomer's concern, but Tyler helps establish this broad value, that it matters to everyone."

I trained my eyes straight upwards, to the zenith, and settled in as Nordgren used a laser pointer to explain what we could see in the night sky: giant clouds of interstellar dust and plumes of vaporized debris, some the size of the Earth. He talked about the surface of Titan, a moon of Saturn with Earth-like features, where under a smoggy orange layer it all looks like Minnesota's Land of 10,000 Lakes, with fractal shores and frozen methane raining out of the sky.

"We're 25,000 light years from the center of the galaxy," Nordgren said. "We're way on the fringe of our own galaxy."

"What is 25,000 light years in the other direction?" I asked.

"Then you'd be in an intergalactic area."

"What would it be like if you were moving through it?"

"Nothing. It would be nothing."

"But what's nothing?" I said. "There can't be nothing."

He considered the matter. "No one knows," he said. "I guess it would be like being in an inky blackness. I don't know if you would have a perception of moving. You'd see like six stars. You know what it would be like? It would be like being in Los Angeles."

He meant a night sky in Los Angeles.

We spend some time taking photographs, fiddling with camera settings, a lesson in shooting in the dark to augment my brief alfresco astronomy class. "Over the last decade there has been a revolution in photography," Nordgren told me. "Everyone has a camera now. In the 1950s, Ansel Adams went to photograph the national parks. Some feel that started the modern environmental movement. We're there again. People are so stunned when they see the night sky photos they think they're fake. Maybe this will be the impetus of a night sky environmental movement."

After a cold but pleasant night by Mount Whitney, the view near dawn was splendid, the pale blue night above brightening to a spray of colors in the horizon. It wasn't, though, the sunrise I took it to be. It was Zodiacal light, or false dawn. The beauty of a life in astronomy, at least as it's described by Nordgren, is that every moment, it seems, is a phenomenon described in a way that's both precise and lovely in its description.

"What you're seeing," Nordgren explained, "is that in the plane of our solar system, in the disk the planets orbit the sun in, there are grains of dust that float in there, in the same plane. Those grains of dust reflect and scatter sunlight. It's exactly like the sunbeam you'd see in your house."

Morning glory.

"The stars are still out there," Nordgren told me. "They're just waiting for us to pay attention again."

TODD PITOCK has written for *Discover, The Atlantic* and *The New York Times*, among others.

Lights, Camera, Acrimony!

Physicists and engineers face off over how to make room for more data

BY MARK PEPLOW

A **CROWD OF THOUSANDS HAD** gathered at St. Mark's Square in Venice, drawn by the prospect of witnessing a telecommunications revolution. In the warm summer evening of June 24, 2011, they watched a video, projected onto the wall of the medieval Doge's Palace, explaining a new technology that promised to multiply the volume of data carried by radio waves at a stroke.

Some 442 meters across the lagoon, a pair of unusual antennas had been mounted on the lighthouse on St. George's Island. At the flick of a switch, a signal leapt from the antennas, accompanied by a rifle shot—the same signal used by Guglielmo Marconi to confirm the first radio transmission in 1895. An instant later, the message reached its destination and was flashed onto the palace's gothic facade. "*Segnale Ricevuto*," it read. "Signal received."

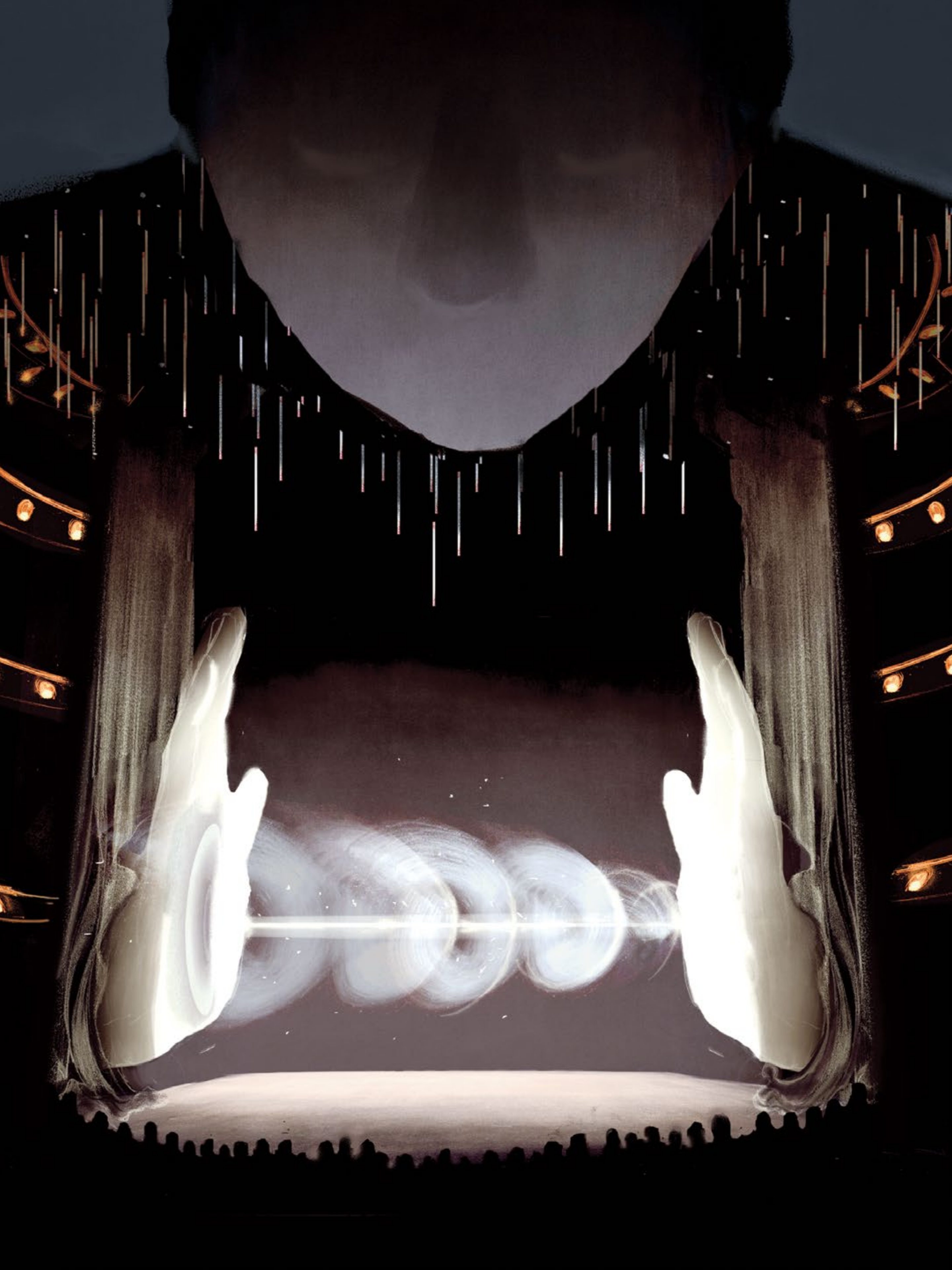
The crowd, already whipped up by a light show and an increasingly hysterical commentator, broke into wild applause.

Fabrizio Tamburini and Bo Thidé, the scientists who orchestrated the Venice demonstration, triumphantly wrote up their results. The transmission, they explained, used two radio beams, one of which had been carved into a helix shape. Even though the beams had the same wavelength, the twist meant that receivers could distinguish between them—as if the beams were separate data channels. In principle, the scientists said, many more beams could be added, each with different degrees of twist in the helix, to provide even more channels. Tamburini was soon being styled by the Italian media as "*il nuovo Marconi*."

More data channels are exactly what the telecommunication industry desperately needs. With the growing burden of images, movies, and online gaming, mobile devices have become voracious consumers of bandwidth. Telecom company Cisco predicts that by 2018, global traffic will reach 2.7 gigabytes per smartphone per month, totaling 15.9 exabytes (15.9×10^{18} bytes), all carried over finite radio spectra and straining wireless networks.

The Venice experiment promised a solution, potentially multiplying the data capacity of a single frequency at a stroke. But rather than global acclaim, their

ILLUSTRATION BY MIKO MACIASZEK



paper was met with skepticism—even outrage—from other researchers who argued that their technique was not new, and would do nothing to boost communication capacity. "This will not allow us to increase the spectral efficiency of wireless communication," says Julien Perruisseau-Carrier, an electrical engineer at the Swiss Federal Institute of Technology in Lausanne. "What is sure: we have a new 'cold-fusion' subject that will survive for years or decades," says Laszlo Kish, a physicist at Texas A&M University, College Station.

"I don't understand how it ended up being so acrimonious," says Miles Padgett, a professor at the School of Physics and Astronomy at the University of Glasgow who has pioneered research into the helical light.

The grandstanding, misunderstanding, acrimony, and accusation that characterize this episode harken back to the days before professionalized science, when showmanship was an integral part of advancing a research agenda.

But on closer examination, the story of Tamburini and helical light transmission also highlights the latent burden of specialization, offering a revealing glimpse of how science works when fields collide. Working at the borders of physics and electrical engineering, Tamburini and his critics almost speak in different languages when describing these phenomena. With scientists sometimes talking past each other, passionate rhetoric can boil over into invective. Throw in the prospects of huge profits from solving one of the biggest conundrums in telecommunications, and tensions are stoked even higher.

Contrary to appearances, science and engineering do not always proceed in an orderly, rational stepwise fashion, but can have just as much showmanship as a circus—and, consequently, as much acrimony as a courtroom.

THINGS COULD HAVE TURNED out very differently for Tamburini, an astrophysicist at the University of Padua, in Italy. While studying physics as an undergraduate, Tamburini moonlighted as an Alfa Romeo test driver—a tempting career option. But then he met Dennis Sciama, a father figure of modern cosmology, who persuaded Tamburini to abandon his cars and study the stars.

Starlight is packed with information, if you know how to read it. Its color can reveal a star's temperature, its composition, or even its distance; polarization of the light can signal the presence of magnetic fields or vast interstellar dust clouds. In 2003, Cornell University astrophysicist Martin Harwit suggested another way to squeeze more data from starlight. He predicted that the matter around pulsars, or the rapid rotation of certain black holes, could imbue the light with something called orbital angular momentum (OAM).

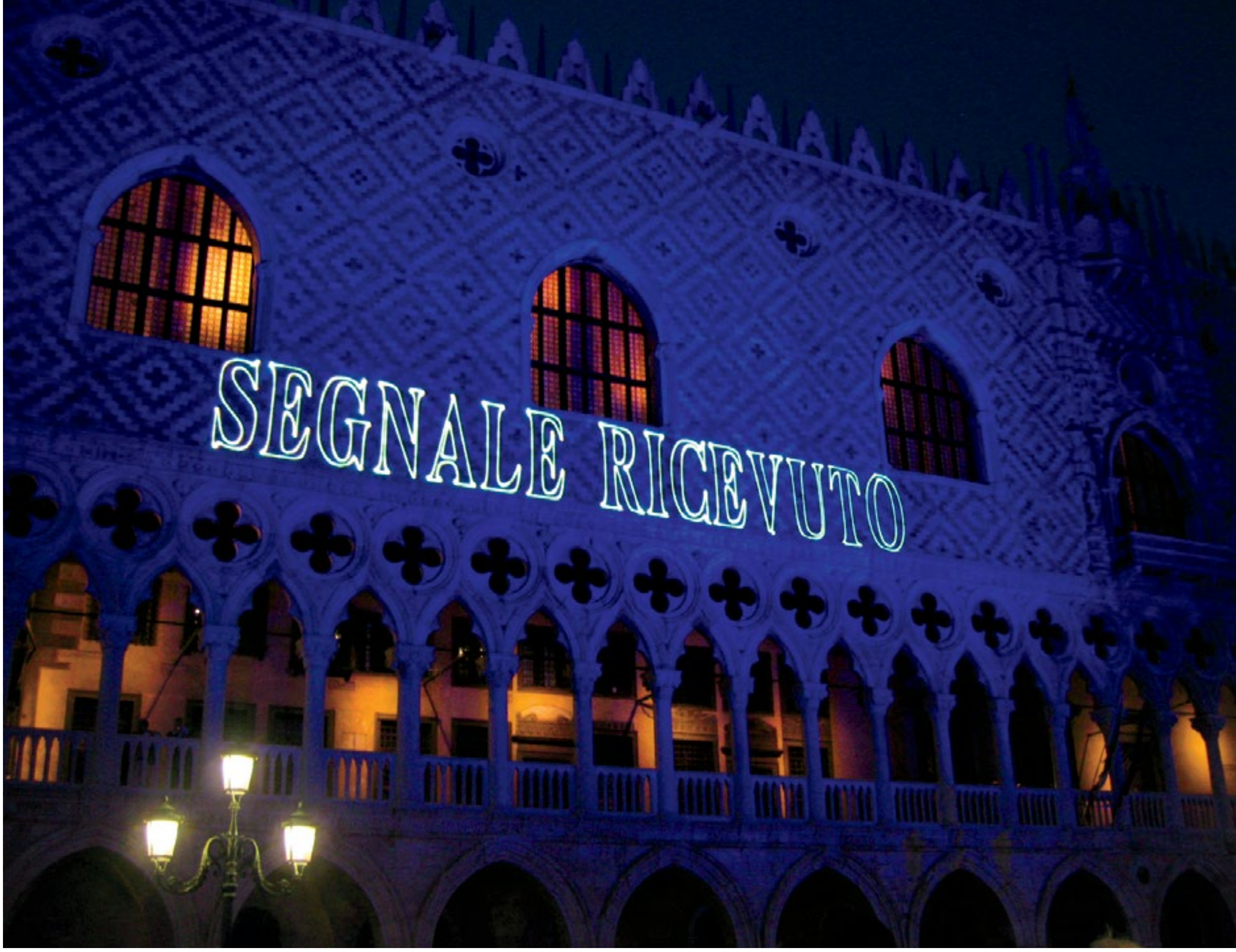
Beams of light typically travel in straight lines, and the energy that they carry follows the same trajectory. But it is also possible for the energy to trace out a corkscrew path around the beam's direction of travel, which gives the light orbital angular momentum. This staggers the electromagnetic waves in the beam, so that their peaks collectively trace out the shape of a helix. Add more momentum and it becomes a double helix, and then a triple helix—the shape of fusilli pasta. In theory, there is no limit to the amount of twist you could give to a beam.

Even single photons can have orbital angular momentum. As quantum entities, it's impossible to define their position and their momentum at the same time—but if you were able to freeze a movie of a "twisted photon" in flight, its momentum would appear to be angled away from its direction of travel. Advance the photon's journey frame by frame, and the arrow representing its momentum seems to rotate around the line of flight—almost as if the light itself were spiraling around an axis. "The energy moves like a tornado," says Juan Torres, physicist and telecommunications expert at the Institute of Photonic Science in Barcelona, who works with twisted light.

Light beams carrying orbital angular momentum are a remarkably recent discovery, considering that a related property, spin angular momentum, has been known about for more than a century. Spin angular momentum arises when light is circularly polarized, so that each wave's electric field rotates as it travels. In 1936, Richard Beth at Princeton University measured that spin angular momentum for the first time by passing circularly polarized light through a quartz disc hung from a fiber—he found that the lens started to rotate as the light transferred its momentum.

Yet it was only in 1992 that scientists realized that twisted laser beams could be made quite easily in the

SIMONETTA SOGLIO



SIGNAL RECEIVED With echoes of Marconi, Tamburini and Thidé lit up the wall of the Doge's Palace in Venice. They projected the words "Segnale Ricevuto" when two radio waves, one of which was twisted, were transmitted across 442 meters and received by two separate channels.

lab. Three years later, a team of Australian scientists used twisted light to make floating microscopic particles orbit around the beam's axis.

One way to give light a twist is to pass it through a fork-shaped pattern in a liquid crystal. As the light waves diffract through the pattern, they interfere with each other in just the right way to give the light orbital angular momentum; changing the diffraction pattern produces different amounts of twist. Shining light through a clear plate with one face shaped into a spiral can also twist light in a similar way.

Harwit's prediction that black holes could imbue light with orbital angular momentum offered a potential route to the first observational evidence that black holes can spin, just as the theory of general relativity predicts. Inspired by this idea, Tamburini paired with Thidé, a physicist at the Swedish Institute of Space Physics in Uppsala, to search for starlight with non-zero orbital angular momentum. In 2010, the pair proved that man-made radio waves could carry such modes, using a bowl-shaped transmitter twisted into a very shallow helix. But they could not get funding to test their technique on astronomical radio signals—so they decided to apply it to terrestrial communication. "A star is just like a mobile phone," says Tamburini. "So if we can't get funding with pure physics, let's go applied."

The target was a rich one. If each orbital angular momentum mode could be used as a separate data channel, it might be possible to add dozens, even hundreds, of extra channels to the same radio frequency.

Solve the capacity problem that modern telecoms are facing, and the rewards could be huge.

After some successful trial runs, Tamburini and Thidé started to plan the Venice demonstration. "It's like having a nicely-colored race car—it was for advertising," says Tamburini. "We were trying to grab the attention of private investors—and it worked." In 2012, the scientists founded a company called Twist-off srl to develop the technology in partnership with SIAE Microelettronica, one of the oldest telecom companies in Europe. The deal is worth €5m (about $7 million), with payouts dependent on meeting key milestones, Tamburini says.

"As telecommunication engineers, we were astonished the first time we saw this," says Piero Coassini, microwave laboratories director at SIAE, who now leads a small team working with Twist-off srl. SIAE specializes in point-to-point communication systems, particularly between mobile phone towers, and Coassini says that OAM radio is a blue-skies project for the company. Nevertheless, he is optimistic that after three years of development work, short-range communication links might begin to incorporate OAM—perhaps wirelessly streaming high-definition video to a display screen. "OAM is a new dimension in electromagnetic communication," he says.

In September 2013, Francois Rancy, Director of the Radiocommunications Bureau at the International Telecommunications Union (ITU), which develops international regulations and standards on spectrum use, visited Padua to see the system in action. This time the experiment used three transmitters—one a clockwise helix, one a conventional bowl, and the third a counterclockwise helix—to generate three OAM modes, all carried by 17 gigahertz radio waves over 150 meters. The three transmissions used quadrature amplitude modulation, showing that OAM could be compatible as an add-on to existing communication

TAMBURINI'S FERRARI Tamburini's work on orbital angular momentum helped him realize a childhood dream: owning a classic Ferrari. This specimen is a Ferrari 208 Turbo GTB with 400 bhp, a racing kit, and an adjustable wheel-chassis setup. "I went crazy to find one as brand new," Tamburini told me. "It looks like the Ferrari of Magnum P.I."

systems. "I was very impressed by what I saw." Rancy concluded. "It shows that this technique could multiply the spectrum by three or more."

Two of the ITU's specialist committees will be taking a closer look at OAM radio—modeling what would happen to networks if a significant number of these antennas were deployed, for example. "This has the potential to bring considerable change to the world of communications," says Rancy. "But we have to avoid being too optimistic and raising false expectations."

FALSE EXPECTATIONS IS EXACTLY what many scientists believe have been raised by the Venice demonstration. "This claim sounded like an amazing discovery," says Perruisseau-Carrier. Yet he was convinced that this "breakthrough" was nothing of the sort, and that Venice was a publicity stunt that would draw public funding toward a technological dead end. So he and his colleagues wrote up a critique of Tamburini's paper, joining two other ripostes that had just been published.

One of their main objections is that although orbital angular momentum can indeed carry information in radio waves, it won't make for a useful technology. "It does not offer a practical means to increase communication capacity", says Ove Edfors, an information technology researcher at Lund University who wrote one of the papers.

Beams of light, or radio waves, are typically brightest at the center. But the reverse is true in beams carrying orbital angular momentum—they have a dark spot at their heart, surrounded by a ring that contains most of the beam's power. Since the beam spreads out as it travels, the hole is magnified to enormous proportions over long distances. A receiver might capture a readable signal if the antennas were just meters apart, and aligned very precisely. But over miles, the signal's power would be dissipated across a huge ring that could only be captured by an impractically vast receiver dish. Even worse, adding more twist to the beam also makes the hole grow bigger, and harder to receive reliably. So much for an unlimited number of extra channels.

Also contentious is that Tamburini and Thidé transmit each mode through separate antennas. Perruisseau-Carrier and others argue that this is merely a form of multiple-input multiple-output (MIMO) communication, already used to increase wireless capacity, and therefore not new. MIMO uses several antennas set up so that signals take different paths—bouncing off buildings and trees, for example—so that they reach their destination at slightly different times. This means they can use the same wavelength yet be read separately, as if each signal was traveling along its own "virtual wire." "Each OAM mode in the Venice experiments plays the role of an antenna in MIMO. If someone tells you this isn't MIMO, they're wrong," says Perruisseau-Carrier.

The ensuing discussions have grown increasingly irate. "These people are not telecommunication engineers, and unfortunately they haven't taken the time to fully understand what else has been done in the field," says Perruisseau-Carrier. Tamburini and his colleagues have retorts for each of these complaints. "They can call it MIMO, MIMO-OAM, Joe, Zorro, or whatever else one wants. We do not care," retorted Tamburini in an email to me last year on the topic of whether his approach was new. "What is important is that it is working and we make money out of it."

Perruisseau-Carrier says he's had a lot of support from the telecommunications community, who all agree with his objections. Thidé refutes that, arguing

Science and engineering do not always proceed in an orderly, rational stepwise fashion, but can have just as much showmanship as a circus.

NICOLETTA STACCO

"A star is just like a mobile phone."

that they only have a handful of critics, and that they get far more positive than negative feedback. Late last year, Thidé presented their work at the Wireless World Research Forum in Vancouver, Canada, and says that he satisfied delegates' queries about the technology. "I went away from Vancouver with a good feeling," he says. "Finally we are getting the message through."

Torres points out that some criticisms share a common assumption: that the twisted beams are being detected in a region known as the "far field." As the waves emitted by an antenna fan out, they form a curved wave front. But eventually, the fan grows so large that its front is essentially flat, and looks like an infinite plane to any receiver. At this range, a receiver would not be able to distinguish any twisty structure in the waves.

But far-field means more than being far away, says Torres: "Indeed, a receiving antenna can be hundreds of meters or even tens of kilometers away from the emitting antenna and still be in the electromagnetic near field." As long as the receiver is big enough, it should still be able to discern the structure of the radio beam, he says. Some of the deepest objections to using OAM for free-wave radio communications, including a claim by Texas A&M's Kish that it violates the second law of thermodynamics, appear to make this mistake, Torres says.

And as for the hole-in-the-middle problem, SIAE's Coassini says it is not a fundamental barrier—it's just another engineering issue to solve, perhaps by stopping the beam from spreading out so much. Keeping the beam tight would also ensure that the required receiver was not too large. Even if technological fixes cannot overcome the "donut hole" problem, the technology could still be used to boost capacity over a few hundred meters, says Torres, perhaps handling the sudden surge of calls when a cruise ship docks in port, or when a football team scores in a packed stadium.

Tamburini adds they are already well on the way to developing a solution to the donut problem, and expect a practical demonstration within a year. "It's a very smart idea," he enthuses. Now that he is working with SIAE, though, he cannot reveal the breakthrough (although he may publish once a patent is granted). That commercial secrecy means that Tamburini's promises are unlikely to cut much ice with detractors, leaving the debate hanging unresolved.

TAMBURINI WAS CLEARLY PLAYING on Marconi's legacy when he staged his Venice demonstration. But the parallels with the wireless communication pioneer go much deeper than he anticipated.

Marconi began his work on radio waves in Italy, before traveling to England in 1896 to present his system to potential buyers from the Navy, Army, and Post Office. But it took a public show at Toynbee Hall in London to really cement his reputation. The newspapers were overawed by the showmanship of his demonstration, calling his equipment "Signor Marconi's magic box." The publicity undoubtedly helped him to commercialize the technology.

But it also generated a lot of ill-feeling. "There was an element of suspicion about Marconi seeking publicity," says Elizabeth Bruton, a historian of science at the University of Leeds, and Marconi expert. "It definitely annoyed quite a lot of scientists." Marconi had some training in physics, but he was very much an outsider to the telecommunications field. "They felt like here was a jumped-up Italian, who didn't have the right background, who hadn't engaged with the community," says Bruton.

Similarly, Perruisseau-Carrier is clear that if Tamburini's light show in Venice hadn't attracted so much publicity, he probably would have ignored the research. "It's not the first time I've read an article I thought was incorrect," he says. But the extraordinary nature of Tamburini's claim and the uncritical press coverage that followed prompted him to speak out.

Public demonstrations like Marconi's—and Tamburini's—were once an integral part of science, says Iwan Morus, historian of science at Aberystwyth University. But by the 1930s, when science had become much more professionalized, "the notion that you publicize a new discovery by staging a performance starts to look more dubious," says Morus. "The notion grows that this is disreputable, beneath the dignity of science."

"It's a shame that we now have a scientific culture that doesn't regard that sort of thing as part and parcel of scientific life," Morus adds. "I think we have lost something—in the 19th century there was a more immediate connection between science and its publics."

The developments in communication technologies in the 19th century were also accompanied by heated debate between physicists and electrical engineers, about how telegraph wires work, for example, with one side arguing from theory, the other from practice. As those fields have become more specialized, the potential for culture clashes at their borders has grown, according to Morus. "I think it does lead to more disputes," he says.

Tamburini sees the communication breakdown as a result of people only being trained in the language of their own narrow fields. "It's a problem of super-specialization," he says. Torres agrees that people from physics and engineering backgrounds have tended to talk past each other on twisted radio waves. "This can create confusion," he says. "In physics they are more interested in the fundamentals," he adds. "For electrical engineers, they're just interested in the channels they get."

Echoing Marconi's outsider status, Tamburini also wonders if some critics are annoyed that the idea came from radio astronomy, rather than their own field. Thidé agrees: "I can't help but feel these are sour grapes feelings—'shit, why didn't we think of that.' "

It's telling that while the debate around radio OAM has been colored by antagonism, it has been positively cordial at higher frequencies, in the infrared part of the spectrum. Alan Willner, an electrical engineer at the University of Southern California, is twisting beams of laser light to combine data streams and increase the amount of data carried through free space or down optical fibers. "But it's not clear to me there are many fundamental differences," he says.

There are big differences, however, in how Willner has approached his research. As a communications expert, Willner says that he has benefitted from working closely with physicists studying twisted light, including Padgett. "We come at it from a different perspective, and everyone benefits. You get physicists to think about engineering systems, and engineers have to think about fundamental physics," he says. "There's a blurring of the lines."

As well as reaching across the disciplinary divide, Willner also has an impeccable scientific pedigree: He is vice president of the Optical Society, the leading professional association in optics and photonics. And while the work has been published—with all the requisite caveats—in leading scientific journals, there have been no dazzling public light shows.

Even some of Tamburini's critics say that Willner's technology could have potential in these circumstances. "If we get to really high frequencies—light rather than radio—the orbital angular momentum communication concept makes more sense and may be a viable solution in some special situations," says Edfors.

BACK IN ITALY, RESEARCH and development work on twisted radio waves is progressing independently of the debate. And it has already helped Tamburini realize a childhood ambition. "I finally own the classic Ferrari I dreamed of since I was a boy," Tamburini wrote to me in December. A few weeks later, a photo followed—the scientist, looking relaxed in yellow shirt and brown loafers, his hand resting proprietorially on a gleaming red sports car. "I've had two heart attacks—I must be calm," he says. "But I still drive racecars."

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12

WHEN SPEAKERS AND MICROPHONES began to appear onstage together in the 1920s, they brought with them an unwelcome guest. Place your pickup too close to your speakers, and an ear-rending screech would take the stage. Directing output into input, we learned, was an inherently unstable and dangerous thing to do.

But it wasn't long before feedback was adopted by musicians as a new tool. The Beatles used it in their 1964 song "I Feel Fine," and within a decade musicians like Jimi Hendrix and Lou Reed had turned it into a near-science. Placing your instrument at the border of control and chaos was cool, demonstrating mastery over a startling detail of sound that seemed to come from nowhere.

This musical journey paralleled a scientific one. At first, scientists and engineers carefully avoided feedback in electronic circuits, but they would soon realize that controlled feedback offered important new capabilities, from precision oscillation to amplification. Today, the numerical study of feedback is standard fare for many undergraduates.

This issue, we cast our gaze onto the feedback loops that regulate, control, and sometimes destabilize the world around us.

Welcome to "Feedback."

—MS

"Drebbel's furnace was a technological marvel created by a magician on a quest to uncover the vital secrets of nature."

STEVEN ASHLEY

"The Vulgar Mechanic and His Magical Oven" p.148

Feedback

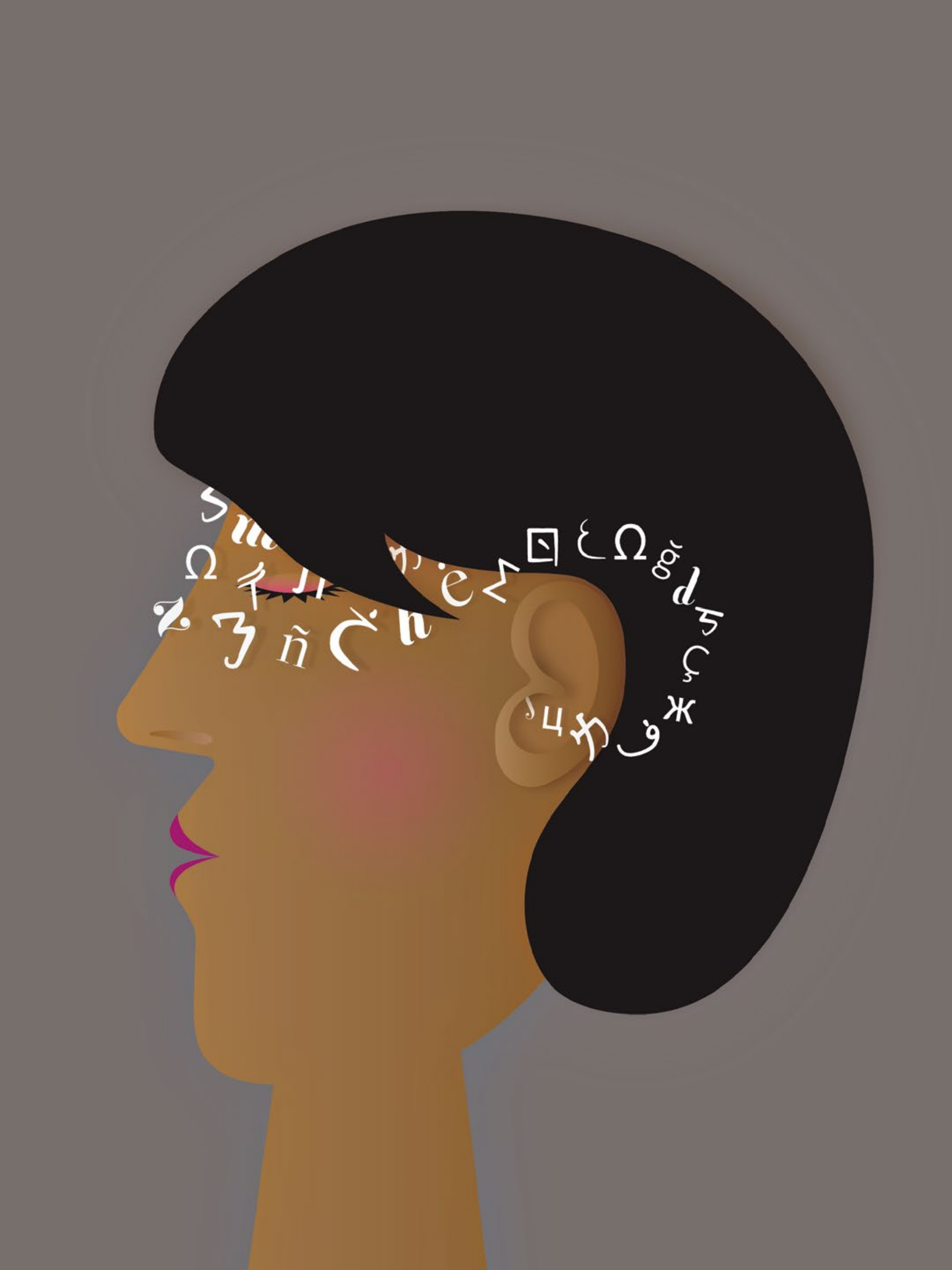
WHAT GOES AROUND COMES AROUND

Secret Military Test, Coming Soon to Your Spanish Class

A powerful, precise language aptitude test is entering civilian life

BY MICHAEL ERARD

ILLUSTRATION BY FRANCESCO IZZO



IMAGINE A TEST THAT could tell you how good you can ultimately get in any foreign language, from Hindi to Welsh, from Igbo to Spanish, before you've even learned how to say "hello," or "please pass the butter." *Très alléchant*, *non*? Most adults have to put in 10 years or more of dedicated work to find out if they have what it takes to end up with the vocabulary, accent, and grammatical sensibilities of a near-native speaker. This test could direct them from the *début*.

And it may be coming your way soon.

Called the Hi-LAB (or "High Level Language Aptitude Battery"), it was developed by University of Maryland researchers working on a government contract in order to predict a person's ability to learn a language to a very high level. Since its release in 2012, the Hi-LAB has been rolled out to government agencies and military training schools and will eventually be available for civilians as well. (Details of the Hi-LAB were only recently released to the public.) In the same way that America's space program and the Cold War created spin-off products and technologies that altered civilian life, the Hi-LAB could become one of the first civilian benefits to come out of America's war on terror.

Scientists who study second language acquisition have long been fascinated by the difficulty that adults have in becoming native-like in a language they begin learning after puberty. Most adults have no problem picking up modest amounts of vocabulary and grammar, assuming they're motivated to put in sustained effort. But to become highly skilled in a second language, simply devoting the 10,000 hours of practice that Malcolm Gladwell made famous in *Outliers* isn't enough. It turns out that a person needs high-performing cognitive hardware, too.

The Hi-LAB provides feedback about who has this ability from the get-go, before the government invests any money in them. Cathy Doughty, the director of the team that developed the Hi-LAB, says "research has shown both focused motivation and personality factors to be necessary… [but they] don't guarantee success, because the outcomes are limited by aptitude." Will education eventually follow this model, too?

THE PATH TO THE HI-LAB began in the aftermath of 9/11, when investigators discovered that a translation backlog at the FBI and NSA had left relevant communications in Arabic untranslated. Then the wars in Afghanistan and Iraq created a huge need for military, diplomatic, and intelligence personnel who knew languages like Arabic, Dari, Pashto, and Urdu. These events underscored a problem that language experts in Washington, D.C. had warned about for decades: There weren't enough trained language experts. The U.S. needed to increase the number of such experts available, and quickly.

At the time, language training facilities relied on aptitude tests that were designed to predict only short-term achievement. Such tests have existed since the 1930s; the most widely used, the Modern Language Aptitude Test, was first published in 1959, and an adaptation, the Defense Language Aptitude Battery (DLAB), was developed in the late 1960s specifically for the Defense Language Institute in Monterey, Calif., where military personnel go for language training.

The Defense Language Institute used the aptitude test scores to match students with languages—the higher their aptitude, the harder the language they could be directed toward. Score really well on the DLAB and you'd be headed for Chinese, Arabic, Japanese, and Korean classes. Score lower, and you'd be tracked into languages that are more similar to English, such as Romance or Germanic languages. The issue, says Doughty, was that the aptitude test could not predict who could progress past a certain point; many language professionals would get "'stuck' at basic proficiency."

He knew what Russians talked about: the jokes, slang, curses, idioms. He could pass for a native speaker.

As a result, the armed services were short of people with native-like language expertise, and their results-oriented culture chafed at the inefficiency. "We can train a helicopter pilot in four months; it takes a year to train a linguist. What's up with that?" one general was known to gripe.

In developing a better test, Doughty and her fellow researchers were faced with a very particular challenge: understanding how a monolingual adult could successfully learn a second language. Most specialists assumed that by the time a person was an adult, the circuitry for language learning had been set in place and that to learn a second language they would have to employ other parts of their brains. But since the 1960s theories of cognition have expanded, allowing scientists to propose ways that cognitive abilities are connected to the learning of both first and subsequent languages.

In the 1970s, Alan Baddeley devised the notion of working memory, showing how it was the crucial mechanism in a range of mental tasks. Working memory is often called "the brain's workbench." It allows you to keep information in your mind while you work on it. It makes possible the "phonological loop," which is the ability that allows you to keep a phone number in your head for a moment before you write it down, or to keep a phrase that you just heard in your mind while you figure out how to pronounce it. It also allows you to keep words in mind while you're changing them, such as adding inflections, or monitoring what you're about to say to make sure it's correct.

Then, in the 1980s and 1990s, Peter Skehan proposed a theory of second-language acquisition based on cognitive abilities that included working memory.

Military Trial

CASL performed a battery of tests on military and other employees to develop the Hi-LAB test. Here are just a few:

- Listen to a series of consonants, with three presented every second, and recall the last six consonants you heard.
- Watch a series of one- or two-syllable-length nonsense words. When prompted with another set of words, indicate whether or not the items in the second set had been present in the first.
- Learn 20 pairs of words, one English and the other in a nonsense language. Several minutes later, when you are presented with the nonsense word, type its corresponding English word.
- Listen to a list of five words. Then, when presented with two other words that are synonyms with words on the list, select which word corresponds with the largest number of words on the list. Both the time it takes to make a selection and whether or not you choose correctly are measured.
- Distinguish between two consonants in a language like Hindi or Russian that, to English speakers, sound the same.

Also important was something called "implicit learning," which babies use to extract meaningful patterns from sounds without explicit instruction, and "associative memory," which links stimulus and response, or native and foreign words. These were general skills that could be retained into adulthood. At a time when aptitude research had fallen by the wayside, Skehan's ideas opened new doors for understanding what made language learners tick.

The Center for the Advanced Study of Language at the University of Maryland (CASL) was founded in 2003 with the goal of turning this kind of research into a better language test. Because they were part of the Washington language establishment, CASL researchers had access to many talented language learners, which they used to their advantage.

The sort of learner they zeroed in on is exemplified by a former soldier named Charlie Cole. In 1966, after he completed basic training, he was sent to the Defense Language Institute at age 19 to learn Russian. After 18 months he was deployed to Europe and did classified intelligence work before returning to Monterey to become a legendary teacher. Cole's colleagues said that he was the archetype of the student they wanted to produce. His pronunciation was impeccable, he knew the grammar, and he knew what Russians talked about: the jokes, the slang, the curses, the idioms. He could pass for a native speaker. Searching for what made someone like Cole tick, CASL researchers assembled a group of around 500 employees from federal agencies. Some were like Cole, with high levels of proficiency in a language they'd begun learning as an adult. These were called "high attainers." Others, who were good at one skill, were "mixed attainers." Both groups were given a series of tasks (see Military Trial).

CASL researchers wanted to see which of the tested abilities (like short-term memory, acoustic sensitivity, and ability to avoid distraction) were most prevalent among the high attainer group. These turned out to be the abilities to learn patterns, manipulate strings of sounds in working memory (phonological loop), and associate new information with already known information. The result of these three experimental tasks alone could predict with 70 percent accuracy who was a high language attainer. So the researchers bundled the tasks and labeled them the Hi-Lab. It was the first experimental identification of the skills that would ensure long-term language learning success.

AS OF 2012, THE HI-LAB has been given to military and civilians looking to advance their careers with additional language training. Although it's too early to say whether this has helped the government produce more Charlie Coles, many inside have expressed confidence in it, and employees are eager to take the Hi-LAB to find out how they can improve their language performances.

Hi-LAB might also become a powerful tool in the educational sphere. Because it identifies a person's learning strengths and weaknesses, the test results could grease a student's instructional path by showing how they learn best, whether it's through reading or talking to people, through explicit grammar lessons or watching movies. CASL executive director Amy Weinberg said that a partnership is in the works with IBM to develop a learner management system that would deliver the appropriate language learning material to people based on their test results and other factors.

"By 2022, tablet–like and smartphone-like devices will have the power to produce a language learning 'app' [that] could [customize] training material according to a student's individual learning style," Weinberg says. Imagine that after you take the Hi-LAB, your smartphone simply adjusts the apps you use to train in Arabic, Korean, or French. One potential use would be to support rapid language learning by people who are involved in massive one-time international events like the World Cup or the Olympics.

Anything that can help people know in advance how to channel their time and energy would be an effort well spent. After all, as Weinberg notes, the percentage of Americans studying a foreign language is so small that even a good familiarity with another language and its culture can make a big difference. "We cannot be competitive in a world," she said, "where only 18 percent of our children even take a foreign language."

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The Vulgar Mechanic and His Magical Oven

A Renaissance alchemist pioneers feedback control

BY STEVEN ASHLEY

BY THE TIME CORNELIS DREBBEL built an oven with a simple thermostat, one of the first manmade feedback mechanisms in history, he was regarded in 17th-century Europe as a magisterial, if not mad, inventor. He had already enchanted royalty and common people alike with elaborate clocks, projected-light spectaculars, fireworks displays, and a submarine. One modern scholar says Shakespeare used Drebbel as a model for Prospero, his noble sorcerer, who rules the mysterious island in *The Tempest*.

The comparison fits. Like the Bard's wise duke, Drebbel was a Renaissance man whose inventions seemed to bend nature to his design. Drebbel appeared to have such uncanny mastery over the elements that some suspected him of sorcery. Constantijn Huygens, diplomat and friend of Galileo and Descartes, warned his son Christiaan to steer clear of the charismatic man "whose magic might come from the Devil."

What's remarkable about Drebbel today, other than the fact that the bewitching Dutch genius is so little known, is how much he has to teach us about the birth and progress of science. He built his oven at a time when a "vital" worldview, in which inanimate objects contain living energy, forged a prelude to the mechanical age.

"Drebbel's circulating oven," as historians of science now call it, included an early thermometer with a heat scale. It regulated itself with a feedback-control device that is a progenitor of the ubiquitous systems that regulate the air we breathe in homes, offices, trains, planes, and automobiles. His oven is one of the earliest devices that gave human control away to a machine and thus can be seen as a forerunner of the self-deciding automaton, the thinking robot.

It's an ironic tale because Drebbel's oven also embodies a vitalist spiritual philosophy. He was a master craftsman, but strictly mechanical inventions weren't his goal. Drebbel always claimed to have drawn his wisdom from nature, declaring that he never read Latin or the classical authors, or enriched his writing

ILLUSTRATIONS BY JONATHON ROSEN

with ancient wisdom. He regarded inventions like his oven as demonstrations of the elemental forces of nature—earth, water, air, fire.

Bert Hall, a retired historian of technology at the University of Toronto, compares Drebbel to Issac Newton. "Alchemical types of the period like Newton—the great magus—want everything to make sense; they want absolutes," Hall says. "There can't be anything extraneous. That's one of the differences between pre-modern and modern thinking." "As Above, So Below," summarizes the alchemical belief that everything in the macrocosm of the universe is related to everything in the microcosm of humanity. This was the philosophy that guided Drebbel as he forged his furnace. His thermostatic oven gave the world an early feedback mechanism. But it was a grander feedback that Drebbel was after.

DREBBEL WAS THE SON of a farm-owning family in North Holland. He was an apprentice, then journeyman artisan with relatively little schooling. Huygens said he "looked like a Dutch farmer." The young maker fabricated engravings, maps, clocks, and lenses for eyeglasses and telescopes. From an early age he was steeped in the arcane lore of alchemy, which aimed at producing the philosopher's stone, a magical substance that could convert base metals to gold—the *magnum opus.* The Dutch master-engraver, Hendrik Goltzius, who taught Drebbel, lost an eye to an alchemical experiment gone wrong, and the apprentice Drebbel married one of Goltzius' sisters.

In 1605, Drebbel and his budding family settled in England. In no time, he was embraced by James I, King of England and Scotland, and became a favorite entertainer at court. The reticent inventor, known for his talents, sly wit, and heavy Dutch accent, entertained the court with light projections and fireworks. Later, during his second stint at court, Drebbel unveiled his "living instruments," the most prominent being a "perpetual-motion machine," a cosmological clock containing a circular glass tube with a little bead of liquid that mysteriously stayed in near-continuous motion.

Drebbel's wonders never ceased. One hot midsummer's day, the King found himself cooling his heels in the Gothic splendor of London's Westminster Abbey when Drebbel managed to cause the Great Hall's vast, vaulted space to grow unnaturally cool. It was a compliment to the royal personage, who, it seems, had a chronic skin condition and suffered cruelly from the heat. Like any good magician, Drebbel didn't reveal how he turned summer to winter, however. (One chemist speculates that the crafty Dutchman probably placed vats of ice in the balconies above and then melted it with salt, allowing the cool air to cascade down to the cathedral's floor.) Not long after he chilled the church, Drebbel caused a sensation by demonstrating on (and under) the Thames River what is arguably the first navigable submarine, a rowboat with oars that he'd turned into a kind of mobile diving bell by erecting a leather-covered sunroof that sealed out water. Onlookers packed the shorelines to watch the vessel mysteriously vanish, and waited anxiously for it to reappear.

Drebbel's fame was a twin-headed beast. Many deemed him a mere "Engeneere," a high-end laborer who executed tasks for his betters. Not a few Oxford and Cambridge men considered him what Isaac Newton later termed a "Vulgar Mechanick," certainly no philosophical gentleman of the learned academy, only a royal sponger, unlettered mountebank and chancy charlatan. It didn't help that the man persisted in peddling his inventions like any Dutch tradesman, dressed poorly, and chain-smoked to boot.

Yet Drebbel intended to challenge the elites, notes Vera Keller, a historian of science and noted Drebbel scholar at the University of Oregon. "Drebbel cast his reticent style as part of a spiritual and social attitude toward knowledge and to whom it belonged," Keller writes. He "contrasted himself with those who sought fame by setting themselves up as greater authorities than others through the writing of books. Aren't we all brothers? When we test ourselves, we find that we have all been created by God as kings with all of nature as our inheritance."

AN OVEN MIGHT HAVE seemed like a mundane development for the spiritual sojourner. But it was a manifestation of his ambitions in alchemy. "He devoted himself to alchemy, in which he claims to have uncovered miraculous things, and inventions of wonderful furnaces, among them that will maintain the fire at any

His oven is one of the earliest devices that gave human control away to a machine.

degree of heat desired, whether hotter or colder," wrote Nicolaus Claude Fabri de Peiresc, one of Drebbel's correspondents, in 1624. Indeed, writes Keller, "Drebbel's ideas about motion were developed primarily in an alchemical context, to which he applied mechanics."

Amazingly, Drebbel's thermostat-equipped furnace functioned according to modern feedback control concepts, in which a sensor detects changes in the output of a system and then modifies the input to correct for those changes and bring the system back to its original state. Did Drebbel know he had created a feedback loop? "He sort of did, but he didn't articulate it," says Hall. "Call it embedded knowledge."

Drebbel never publicly described the mechanical underpinnings of his circulating oven from the 1620s. He might have been protecting his product, since, back then, nothing like real patent or copyright law held sway and plagiarism was rampant. Secrecy was standard alchemical practice in any case, as all the important transmutation formulae were encoded in arcane symbols.

In the 1970 book, *The Origins of Feedback Control*, Smithsonian historian Otto Mayr suggests that Drebbel had seen a widely circulated manuscript that contained a diagram of an ancient Greek feedback device, built by the mechanician Ktesibios around 250 B.C. This gadget closely resembled the oven's float valve, as well as the valves in our modern toilets. Water will

Not a few Oxford and Cambridge men considered him a "Vulgar Mechanick," a royal sponger, unlettered mountebank, and chancy charlatan.

flow into a toilet bowl until the rise of the float ball and attached lever arm trigger a valve that shuts down the inflow. In this case, the position of the float ball senses the height of the water, enabling the float regulator to automatically meter out the same exact volume or weight of water time and again.

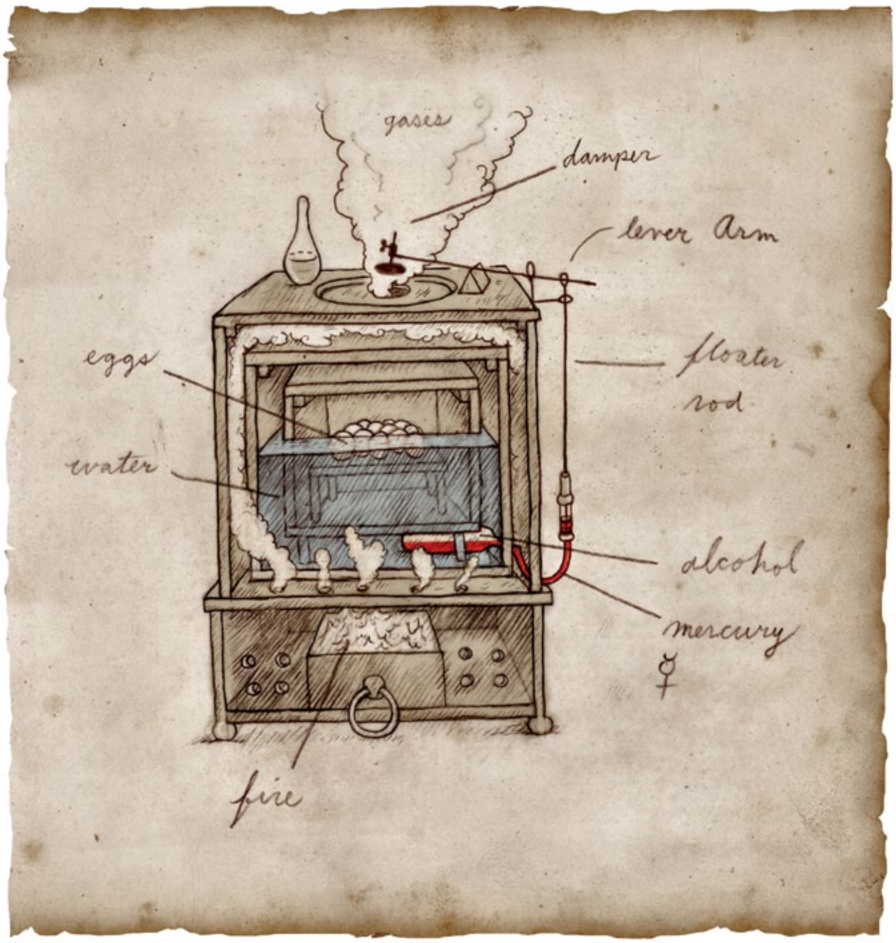
Drebbel may have reasoned that a similar principle could apply to heat flow, so that he could build a device that meters out the same heat repeatedly. The analogy may have been a natural one for Drebbel, since alchemy held that the four elements transform into each other in a cycle, rarifying and condensing through heat and cold, and producing such movement in nature as winds, storms, and the cycle of life.

This natural philosophy would have been matched by the master craftsman's observations. He must have seen how heat ripples through objects as they warm and cool, and that hot materials expand and cold ones contract. One of his diagrams showcases a phenomenon of transference through heat. In it, a piece of glassware whose mouth opens into a bath of water surrounding the vessel is warmed at its base. This causes air to shoot out of the mouth and bubble through the water. Then, when the vessel cooled, the water rose within the tube far above the level of the bath.

With these observations, Drebbel created the first thermostat. It was an L-shaped glass tube filled with alcohol that was topped off by mercury. A metal rod floated in the quicksilver. When the heated alcohol expanded, it pushed up the quicksilver, and the rod rose in the tube. The rising rod then pressed on a lever arm, which adjusted the size of a vent at the top of the furnace. As a chimney designer, Drebbel would have known how flue vents control fires. Flames in an oven can be controlled by the size of the aperture above, which determines the draft. Likewise, the fire that heated Drebbel's furnace was tempered by the size of the vent hole at the top of the oven, which was in turn managed by the rising and falling rod.

The oven comprised three metal boxes that were nested like Russian matryoshka dolls, with a fire below them. The outer box enclosed a chimney-like passage that swept around the other two and exited out a vent at the top. The next box held water, a heat buffer to protect the center box, which contained a sample to be heated. The base of the thermostat, or "feeler," slipped into the water-filled box. It registered the fire's heat and responded to changes by automatically adjusting the valve in a way that curtailed or boosted the heat of the fire. What's more, a person could set the desired temperature, and the oven would oblige.

ALTHOUGH HE TOUTED ITS use as an egg incubator, Drebbel probably built the oven to transmute base metals into gold; apparently many alchemists thought it might be feasible if an initial metallic mixture were heated at a moderate, constant temperature for an extended time. They also thought that using an egg-shaped crucible for the mystical purification process would help it function like a real egg—a static,



Cornelis Drebbel's Oven

In this artist's rendering, Drebbel's circulating oven incubates eggs. The oven consists of three nested metal boxes atop an enclosed fire. Fumes from the fire rise up through vents into the outer box, and out of an opening at its top.

The middle box contains water, which provides a buffer between the high heat circulating in the outer box and the center box containing eggs, or alchemical metals (not shown here). The thermostat sits in the water just touching the center box. It is an L-shaped glass tube filled with alcohol and mercury.

A metal rod floats in the mercury. When the heated alcohol expands, it pushes up the mercury, and the rod rises in the tube. If the heat of the fire rises beyond a set point, the floating rod elevates high enough to lower the damper, cutting off the air that feeds the fire. The fire would then diminish, as would the temperature in the center box. If the heat falls too far, so does the rod, with its lever opening the vent to admit air. Drebbel ensured that the floater rod was adjustable with machined screw threads that let users set the desired heat level.

supremely symbolic object within which a magical metamorphosis takes place. No wonder alchemists sometimes called their crucible the *ovum philosophicum*, the philosophical egg. In placing an actual egg inside the incubator, Drebbel may have intended to demonstrate that his machine could transmute matter. Balthasar de Monconys, a 17th-century French diplomat, magistrate, and natural philosopher, wrote that the inventor considered the oven as important as the *magnum opus*, the transformation of metal to gold.

Drebbel's achievement was astonishing: Informed by a piece of ancient plumbing, he invented an iconic first feedback device. His thermostat provided a seminal example for feedback-control devices of the 18th century, when inventors came up with all manner of float valves, pressure regulators, and centrifugal governors to manage steam engines. Today, feedback loops and automatic control are greatly amplified by the recursive power of digital logic and computers.

Of course, the 17th-century inventor could not have predicted his retrospective fame. Drebbel was never a practical man. Despite his success, Drebbel could never make enough money. At the end of his life, the aging Dutch master ran an alehouse. He passed away in 1633, practically a pauper, according to some reports. His children and in-laws sold a 14-year patent for his ovens, and during the 1640s and 1650s it was the subject of widespread interest. It was used as an egg incubator, a natural science demonstrator for drawing rooms, and as lab furnaces across Europe and even in New England.

Drebbel's circulating oven came at a pivotal time in the history of science, at the still-indistinct beginnings of a paradigm-changing revolution, one that would bring about the mechanical age and enormous advances in technology. From today's viewpoint, Drebbel's furnace was a technological marvel created by a magician on a quest to uncover the vital secrets of nature. His story shows us how a bit of serendipity, a belief in magic, and some craftsman's smarts helped spark early science. Perhaps it's all just part of what Drebbel meant when he advised, "Practice your gifts rightly."

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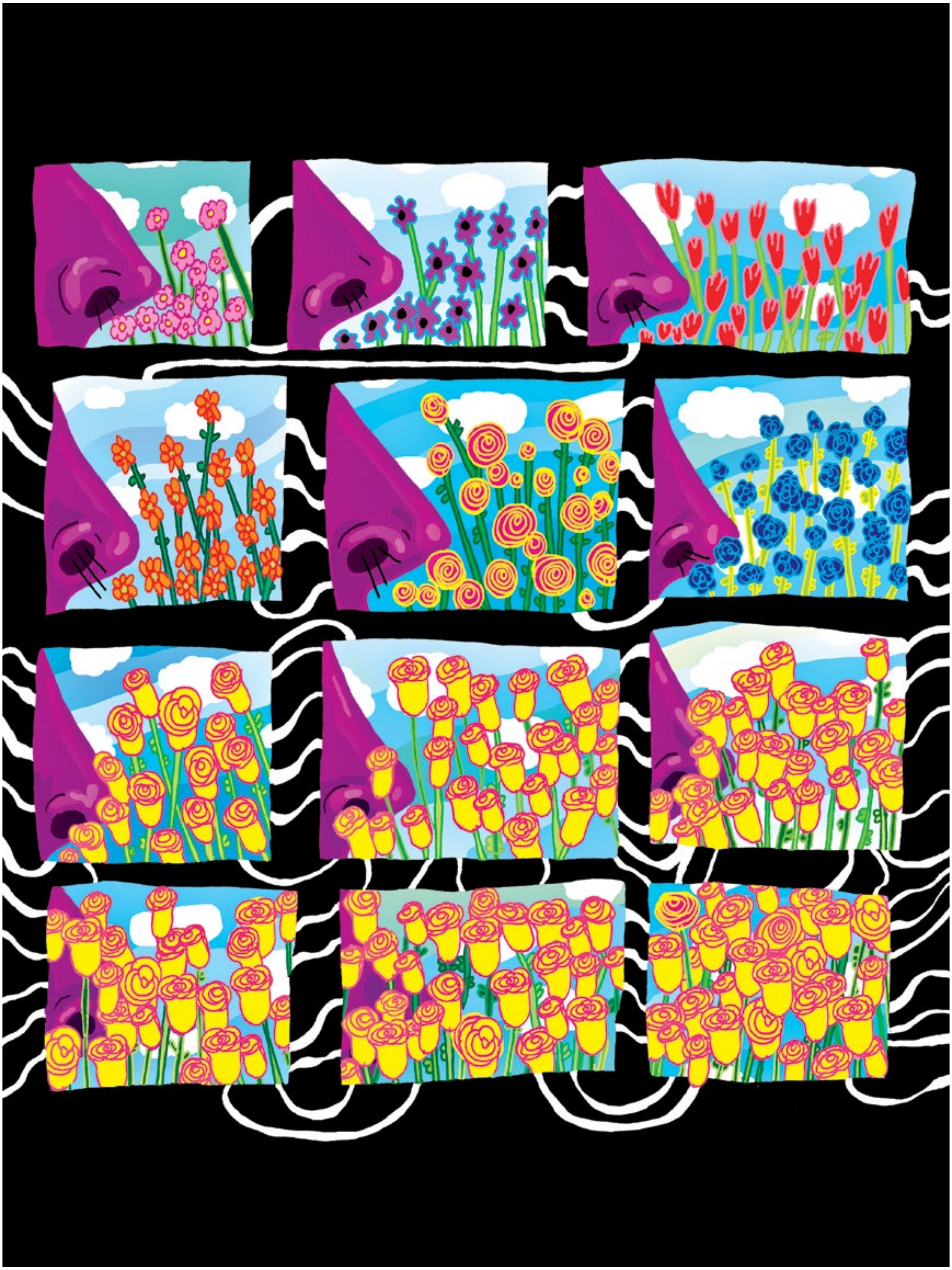


"BUILDING THE PERFECT PAINKILLER"
BY ANA BENAROYA

Why Aliens and Volcanoes Go Together

Life on other planets may rely on plate tectonics

BY STEVE NADIS

THE NOVELIST WILLIAM GOLDING suggested to James Lovelock that he name his now-famous hypothesis after the Greek goddess of the Earth, Gaia. It was a good fit: Lovelock believed that the living and inanimate parts of the Earth formed a single, interacting, and self-regulating system. Lovelock's work grew, in part, out of research he had done for NASA, and published in a 1965 *Nature* paper, about the signs of life we might look for on other planets.

Forty-six years later, NASA's Kepler Space Telescope discovered the planet Kepler-22b. It was one of the first planets outside of our solar system confirmed orbiting a sun-like star at a distance that would allow for liquid water to exist on its surface. The availability of liquid water, which is essential to every form of life that we know of, would raise the chances that the planet harbors life.

Now, scientists are beginning to understand the importance of another characteristic of any planet likely to support life, and it is one that fits squarely into Lovelock's view of Earth as a dynamic participant rather than a passive backdrop: active plate tectonics. On the face of it, the connection between life, with its relatively brief cycles and dizzying complexity, and plate tectonics, with its much slower cycles and ostensibly simpler interactions, appears tenuous. But on Earth, at least, that connection is direct and deep.

Earth's continents move because they sit on separate plates, composed of the crust and upper mantle, which float like islands on a "sea" of hot, fluid-like rock below. The motions of these plates are part of a giant machine that constantly shuttles water, carbon dioxide, and other ingredients vital for life from the deep interior to the terrestrial surface and atmosphere, and back again. Thanks to plate tectonics, "the elements on the periodic table are continually being resupplied to the land, lakes, and oceans," notes Stanford geophysicist Norman Sleep. Life depends on these cycles in countless ways.

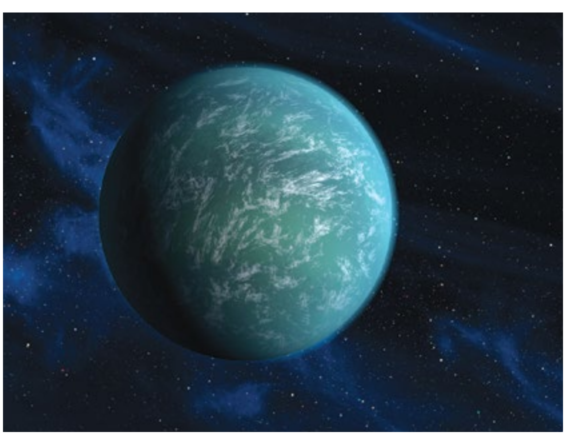
Without plate tectonics, our planet wouldn't have a climate stable enough to support life over the billions of years it's been evolving. That's because plate

ILLUSTRATION BY JONATHON ROSEN

tectonics is an essential part of a crude planetary thermostat called the "carbonate-silicate" cycle.[1, 2] Carbon dioxide in the atmosphere dissolves in rainwater to form carbonic acid, which dissolves silicate rocks. The byproducts of this erosion, or "weathering," are carried to the oceans where they are ingested by organisms—such as tiny planktonic foraminifera—and incorporated into limestone (calcium carbonate) shells. When those creatures die, they fall to the bottom of the ocean and pile up as sediments.

At plate boundaries, some of these sediments are carried down even further through subduction (when one plate slides under another). Under the conditions of higher temperature and pressure found in the deep earth, carbon dioxide gas is released, eventually making its way to the atmosphere through volcanoes, thereby completing the cycle.

When the Earth's temperature increases, more water evaporates from the surface, leading, in turn, to more precipitation, which washes more carbon dioxide out of the atmosphere and sends it deep underground through tectonic pathways. This diminishes the greenhouse effect, leading to global cooling. Conversely, when the Earth cools, less carbon dioxide rains out and atmospheric concentrations build up from volcanoes and other sources, leading to a strengthened greenhouse effect and eventual warming. Tilman Spohn, who directs the Institute of Planetary Research at the German Aerospace Center in Berlin, calls plate tectonics "the most efficient known mechanism for recycling" of this sort.



A LIKELY CANDIDATE An artist's conception of the planet Kepler-22b. It's thought to be an ocean-like world with a composition unlike Earth's.

Remarkably, the dependence of life on plate tectonics is reciprocal: Scientists have come to realize that plate tectonics relies on life just as much as life relies on it. "Life may stabilize plate tectonics, which, in turn, may stabilize the habitability of a planet," says Spohn.

An important part of the feedback from biology to geology stems from the "deep water" cycle, which is closely tied to weathering. Life on the Earth's surface contributes to weathering in a variety of ways, from bacterial acid secretion that breaks down rocks, to the growth on rocks of lichens, moss, and trees. "The sedimentation rate is a function of the activity of the biosphere," Spohn claims. In other words, the more life there is on a planet, the more weathering there will be.

The sediments that result from this process accumulate on the ocean floor, and contain up to 40 percent water by weight.[3] When subduction occurs at plate boundaries, they are conveyed down into the mantle, about 62 miles (100 kilometers) beneath the Earth's surface.

The water tied up in these subsurface strata in turn serves as a kind of lubricant that makes plate motions possible. Water can break the bonds that hold rocks together, making them more malleable and fluid-like. "If a planet doesn't have water in its mantle," Spohn explains, "it wouldn't have plate tectonics, which involves the slow movement of mantle rock up towards the surface. Instead you'd have a stagnant layer of rocks on top." That's what we see on Mercury and the moon.

Increasing the water content of rock also lowers its melting point. Delivering more water to the mantle will therefore generate more molten material, leading to more volcanic eruptions. "The outflow of this volcanic rock is basically the stuff that makes continental crust," which mainly consists of granite, says Spohn. "The more of this melt that you produce, the more the continents are growing." Given that a thriving biosphere can result in more water reaching the mantle, he surmises, it can also contribute to the growth of continents.[4]

In 2013, Spohn, Dennis Höning, and two other colleagues imagined what Earth might look like without plate tectonics. They used computer simulations to spin out two very different scenarios—one with an

NASA/AMES/JPL-CALTECH

active biosphere in the mix and one without. In the "biotic" case, biological weathering contributed to enhanced sedimentation, resulting in about 300 parts per million of water in the mantle. This, in turn, led to more frequent volcanic outbursts and continents covering about 40 percent of the Earth's surface, roughly comparable to the world we see today.

Removing life from the equation led to a very different-looking planet. Reduced sedimentation resulted in lower concentrations of water in the mantle (only about 40 parts per million) and a correspondingly diminished production of continental crust. A lifeless Earth, the model predicts, would essentially be a water world with little landmass—constituting perhaps as little as 3 percent of the surface.

"We can't say which came first, plate tectonics or life," Spohn says. "What we can say is that they basically stabilize each other. If we suddenly switched off plate tectonics, it wouldn't be very good for us. And if we switched off life, it wouldn't be good for plate tectonics."

The idea that plate tectonics makes life more likely is beginning to steer the search for extraterrestrial life. Northwestern University astronomer Nicolas Cowan and his colleagues recently demonstrated a technique for detecting the presence of oceans and continents on an exoplanet. So far they've only tested out the approach on Earth, using a telescope on NASA's Deep Impact spacecraft that was tens of millions of miles away when it made its observations.[5] The basic idea is to see how the color of a planet changes over time as it rotates on its axis.

After looking at the Earth for 24 hours with Deep Impact's small telescope, Cowan's team was able to make a map of the planet that had three colors: blue corresponding to the oceans, orange corresponding to the land, and gray corresponding to clouds.[6] Longer-term observations would show the gray patches (or clouds) moving around, so that the scientists could get a more refined picture of where the oceans and continents lie.

This technique has not yet been applied to remote planets, but Cowan believes it might soon help astrobiologists decide which exoplanets to focus on. "If a planet has large continents and large bodies of water, it's hard to make that without plate tectonics," he says. And plate tectonics are less likely to exist without life.

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When Theft Was Worse Than Murder

Hundreds of years of trial documents reveal our changing attitudes to violent crime

BY SIMON DEDEO

THE RECORDS OF THE Old Bailey, London's central criminal court, tell the tale of one John Randal, who was tried on Sept. 9, 1674. He was charged "with two Indictments, one for Felony for stealing several pieces of Plate, and other Goods..., and the other for Murder, Killing his House-Keeper."

That his theft and his murder were described and tried together was natural for a world where the protection of property was a virtue at least on par with the promotion of human happiness. Nearly a hundred years later, in 1769, William Blackstone argued that it is quite reasonable to execute someone convicted of stealing "a handkerchief, or other trifle, privately from one's person," even though other crimes that involve goods of higher value are punished less severely.

Blackstone was writing the fourth and final volume of his *Commentaries on the Laws of England*, whose goal was to justify British justice using the most up-to-date moral reasoning found on the Continent.[1] His conclusion was that 18th-century British law was "so highly finished, it is hard to speak with that praise, which is justly and severely its due." Two hundred and fifty years later, though, it seems to us a savage thing, preoccupied with property and violent retribution, including both torture and death, rather than any process of intervention, education, or rehabilitation.

It is the responsibility of the historian to reveal the nature and causes of those changes which, although imperceptible in real time, can shift our moral compass so dramatically over centuries. This work has always been done with the help of quantitative reasoning, from chronologies and maps to tabulations of the sizes of armies and the prices of goods.

In the case of the British justice system, where records are particularly abundant, quantitative analysis is now closely approaching the border of what we normally consider the sole domain of human intuition and reason. This convergence received a powerful boost with the Old Bailey Online, a multi-year project

ILLUSTRATION BY MELINDA BECK

It amounts to a completely different kind of historical scholarship than has existed before.

that digitized a remarkable corpus of transcripts from the 17th to the 20th centuries and made them available to the public.

The Old Bailey has tried serious crimes in both London and (later) the whole of England since the Middle Ages.[2] It is the stage-set on which both Blackstone (and his more liberal critics, like Jeremy Bentham) would have observed the actual practice—rather than the theory and justification—of English law. The documents digitized by the Old Bailey Online project were originally created and circulated for reasons both noble (government transparency) and otherwise (cashing in on popular demand for details of sensational trials).[3] They track the day-to-day operation of the court and provide a more-or-less exact record of what was spoken in the courtroom itself.

My colleagues Tim Hitchcock and Sara Klingenstein and I picked up the thread of this story starting in the same decade that Blackstone published his *Commentaries*, looking at the Old Bailey data from 1760 through to the eve of the First World War.[4] The Old Bailey's records allow us to cross a timespan that includes the American revolution and the French one, as well as the latter's violent aftermath in the Napoleonic Wars, and the industrial revolutions that turned Britain from a nation of traders and cottages to an industrial, urbanized state.

Our work required the analysis and manipulation of tens of millions of words, spoken by hundreds of thousands of different people, over the course of 150 years. While the extent of this data is familiar to the exact sciences—our file sizes would impress neither the cosmologist nor the molecular biologist—it amounts to a completely different kind of historical scholarship than has existed before.

To "do history" with such a set of documents, we must read in two completely different ways. The first is to read as we were taught in school—for sense and context. To read a trial in this way is to reconstruct in our imagination both the original scene and the various psychologies of the participants. Reading thus, we might ask, "Is the defendant lying? Is the prosecutor vindictive? Is the witness afraid?" Reading through a trial for sexual assault, we might ask whether the men responsible for the prosecution have empathy. Or, in a trial for theft, we might look for the ways in which a prosecutor attempts to arouse the indignation of a court, or a defense attorney (a reasonably recent innovation at the start of our data) tries to undermine and humiliate a witness.

By contrast, we also need to "read" a trial by tracking its movements statistically. The records of the Old Bailey allow us to track the shifting kinds of crime prosecuted and the likelihood that they concluded with a conviction. But the digitized transcripts are also records of language, of how people spoke about what they and others did.[5] Reading these trials in this second sense we ask, in a particular context—say, a trial for assault—"is the occurrence of this word unexpected?" Or, "are these patterns of speech novel?" We ask, too, whether distinctions of fact and particular "hot button" words influenced the outcome of the trial; whether this kind of witness with this kind of language was more or less likely to lead a jury to convict; and what contextual clues modulate these effects.

Undertaken in part by machine, this second kind of reading is blind to the subtleties—emotional tone, inconsistency of logic, implausibility of description—obvious to readers of the first kind. But reading in this second way allows us to track a completely different spread of effects that are otherwise invisible to even the most dedicated human reader.

When we read the Old Bailey, we find a system undergoing continuous development. Far from being the perfected system that Blackstone saw, needing only repair from the "decays of time" and the "rage of unskillful improvements in later ages," everything appears in constant flux: from the conviction rate (rising from around 60 percent in 1800 to 80 percent a century later) to the range of things people were convicted for and the ways in which they, their prosecutors, victims, and judges, talked about the crime, and the distinctions they made in doing so.

Most interesting among these changes was an evolving attitude toward violence. Over time, discussions in the Old Bailey of violent crimes—what is said, and how it is said—become increasingly distinct from discussions of non-violent crimes. This pattern, at the level of the language itself, accumulates over a century of development. These patterns are not always easily interpreted; many appear to us as subtle and accumulating fluctuations, traces of hidden stories whose effects are apparent but whose origins remain obscure.

By contrast, some stand out clearly as both mathematical effects and historical narratives. At the end of the 18th century, for example, fisticuffs or drawn knives amount to an acceptable background of violent behavior—that a victim was beaten or even stabbed might be mentioned in passing, for example, in a trial for theft. As we move to the beginning of the 20th century, such discussions are found increasingly concentrated in trials for assault and murder, tracing both a decreasing tolerance for uncivilized behavior and an

The Science of Feedback

The idea of feedback emerges as a word (if the Oxford English Dictionary is to be believed) in the 1920s, in the magazine *Wireless Age*. The radio equipment obsessively dissected in that magazine was the first mass-produced system with what we call functional modularity. The different tasks that a radio needed to accomplish were more or less isolated in separate systems, or modules, like Lego bricks.

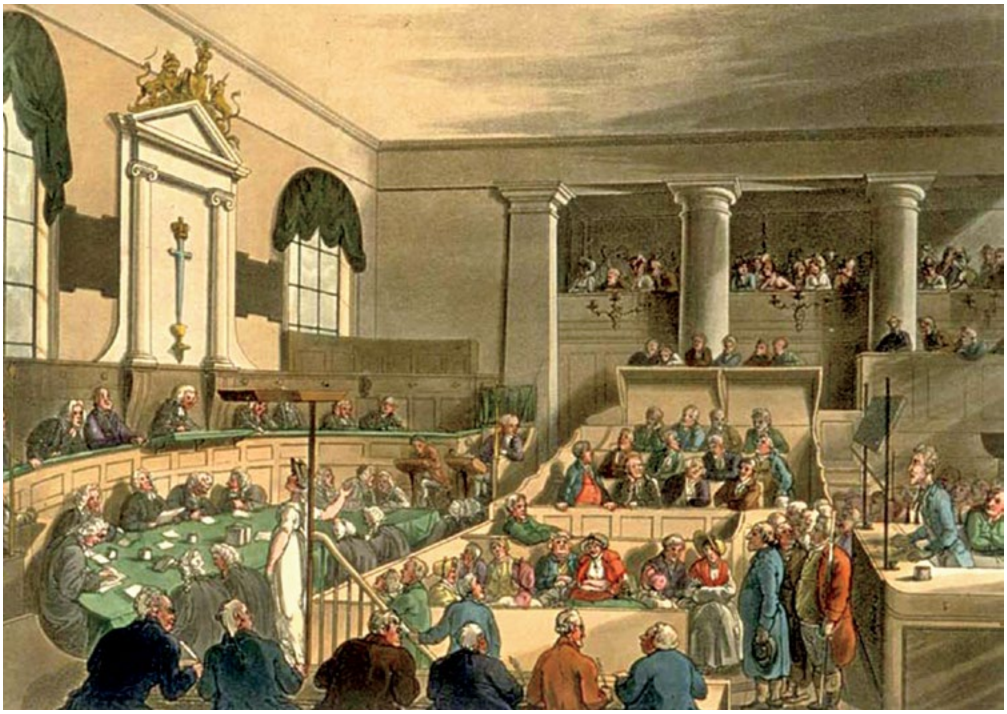
Functional modularity is a powerful aid to imagination: Once it is in place, an observer can imagine the same tasks in a new sequence. When the enthusiasts, tinkerers, and hackers of the radio era were given this freedom, they took the first steps into what today we understand as complex systems science; and one of the first things they discovered was the trick of feedback.

"Feedback" as the tinkerers of *Wireless Age* understood it, was a trick, more or less reputable, for pushing an off-the-shelf construction beyond its rated abilities, strengthening a signal by feeding the output of an amplifier back in to its input.

These feedback loops had effects that were often unpredictable if you worked from the behavior you observed before they were created. While at one extreme, a damped negative feedback leads to perfect stasis, the effects of feedback loops range, depending on configuration, from oscillations to growing instabilities, to what one reader described as a "rushing sound."[8]

The more thoughtful the hacker or engineer who encountered these loops, the more uses they were put to: not just positive feedback, a way to amplify signals, but (its natural

(*continued on p.165*)



THE OLD BAILEY A trial at the Old Bailey in London as drawn by Thomas Rowlandson and Augustus Pugin for Ackermann's "Microcosm of London" (1808-11).

THOMAS ROWLANDSON AND AUGUSTUS PUGIN, WIKIMEDIA COMMONS

increasing concern of the state with enforcing such newly-emerging norms. This shift—one of a wide spectrum of changes of widely-varying size—tracks the emergence of a world in 1910 that is not just technologically distinct from 1780, but also, in crucial ways, morally and culturally distinct.

Most remarkable was the consistency of the rate of this change over 150 years. Rather than an oscillating cycle of changing fads, or something promoted in fits and starts by top-down control, we see an almost-linear[6] emergence of a new social and bureaucratic category as the system increasingly refines its treatment of violence.

Such an apparently orderly and long-term drift poses its own challenges to historians, and frustrates explanations that rely on the influence of one or two men. Even the most powerful and hale of jurists cannot live long enough to guide the Old Bailey over a timespan that includes both the childhood of Jane Austen and the marriage of Virginia Woolf. The gigabytes of data that run from one end to the other outlast both kings and queens.

Indeed, on the scales that the Old Bailey changes, not only does the individual fade away, but so do coteries and cabals, "pivotal moments" and influential books, fashions, and movements. The hundred-thousand-odd cases that came before the court between 1760 and 1913 involved, conservatively, a million

At the end of the 18th century, for example, fisticuffs or drawn knives amount to an acceptable background of violent behavior.

individuals, from the police, prosecution, and judges to the defendants, lawyers, and juries. Such a collection of a million people across the social spectrum would, in the normal run of things, be nothing more than random noise—a tapping into a collective id, or thousands of games of telephone, each 150 years long. That is, except for the exceptional structures, both engineered and evolved, which allowed the Old Bailey to observe itself, in part through the very records which form the basis of our research.

What explains the development of the Old Bailey over the centuries is, I would argue, the thing that one imagines would keep it the same: tradition. The fact that the patterns of behavior and traditions of the Old Bailey were visible to the people responsible for its re-creation, the fact that individuals could perceive what had come before (and, indeed, over the decades were increasingly *able* to do so—in part by creating the data that Sara, Tim, and I can use today) amounted to feeding the output of the Old Bailey the day before to the input of the Old Bailey the day after.

Such feedbacks were not, of course, all that happened. But it is only when one includes these effects of self-observation, I would argue, that one can explain the even and centuries-long evolution that we see. Where the words unearthed a trend, the numbers unearth a mechanism that is stable and self-driven over the lifetimes of many people and many governments.

Such mathematical accounts, that form the basis of a series of papers from our group, are a part of a new

(*continued from p.163*)

counterpart) negative feedback which, in the form of the phase-locked loop, enables the transmission of radically higher-fidelity and bandwidth FM radio.

Thirty years after *Wireless Age*, these scientific extensions of a hacker's toolkit finally achieved a clear formulation with the publication of Norbert Wiener's *Cybernetics* in 1948. Now given an explicit name—from the Greek work for helmsman, or the steerer who both commands his vessel and feels its response to those commands—the field underwent rapid elaboration in both the seminar room an the laboratory.

Today we understand that we can find feedback not just in the things we engineer, or in the biological cells and tissues that evolved without our intervention, but in the systems that lie somewhere in the middle: half-engineered, and half-evolved, the mass democracies that saw their first expressions in the middle of the 18th century.

form of scholarship that is essentially interdisciplinary, computer-enabled, and amenable to cross-cultural comparison. In advancing our understanding of politics and society they continue a process of correcting the intuitions of an earlier view of history. Where Machiavelli imagined a world dominated by the effects of a prince's character, by the time we reach Hobbes' *Leviathan* we see a different picture: individuals reacting not just to their leaders, but to each other, and reacting to the reactions of others. Though he comes before the time of urbanization and mass democratization, Hobbes, at least, sets forth the essence of problems that define both the scholarship of modern society and the task of its citizens. When one sees how such feedback loops are closed, science and scholarship begin.[7]

SIMON DEDEO is a professor in the School of Informatics and Computing at Indiana University and a research fellow at the Santa Fe Institute.

FOOTNOTES

1. Blackstone was not the first to do this, but he was, perhaps, the most influential, being the first to lecture on the "common" (as opposed to church) law, and having published his four volumes in time to influence the development of legal thinking in the American colonies.

2. The Old Bailey is the central criminal court for London. The name refers not only to a particular building (built in 1907), but to an institution whose existence stretches back centuries, copied from location to location and originating in a medieval courthouse that burned down in the Great Fire of London. Today, nearly 2 billion people live in systems fully or partially governed by the common law system that originated there.

3. Sounding simultaneously medieval and modern, for example, the cover of the June, 1682, edition advertises, "Tryal of many Notorious Malefactors, for Murders, Fellonies, Burglary, and other Misdemeanours, but more especially the TRYAL of JANE KENT for Witch-Craft. ... As likewise some Proceedings in Relation to the Persons that Violently took the Lady out of the Coach on Hounslow-Heath."

4. There are many lovely things to say about my research partnership with Tim and Sara, that begun in 2011, and with Sara's move to Kyoto last year is now, like the British Empire, "a collaboration upon which the sun never sets." What I write here is (naturally) a personal and informal view of a small fraction of the questions we've considered; it is both (1) deeply indebted to many conversations with Sara and Tim over the years, and (2) without any guarantee that they would agree in the slightest.

5. I learned to understand mathematical analysis as a kind of reading from the literary scholar Franco Moretti, who has argued for this in a series of influential articles and books, most recently *Distant Reading*.

6. In particular, almost-linear in the bits of information available for discrimination between categories; see our article in *Entropy* **15**, 2246-2276 (2013) for how one can quantify these kinds of processes by reference to information theory.

7. One might add only that scholarly battles, once won, do not stay won. The possibility (and the obligation) to tell a story beyond the scale of a single human life must be rediscovered and re-argued for: most recently, in Armitage, D. & Guidi, J., Return of the Longue Durée, *Annales. Histoire, Sciences Sociales* **69** (2014).

8. The mysterious and uncanny world of the wireless hobbyist is beautifully described in a recent article of the Cambridge Literary Review, Vol. II, No. 5, by David Hendy, "Danger in the air: the covert cultures of early radio."

“ONE PERCENTERS CONTROL ONLINE REVIEWS”
BY EDA AKALTUN

Ants Swarm Like Brains Think

A neuroscientist studies ant colonies to understand feedback in the brain

BY CARRIE ARNOLD

DEBORAH GORDON SPENT the morning of Aug. 27, 2013 watching a group of harvester ants foraging for seeds outside the dusty town of Rodeo, N.M. Long before the first rays of sun hit the desert floor, a group of patroller ants was already on the move. Their task was to find out whether the area near the nest was free from flash floods, high winds, and predators. If they didn't return to the nest, departing foragers would know it wasn't safe to go search for food.

When the patrollers returned and the first foragers did leave, they scattered in all directions, hunting for the fat-laden, energy-rich seeds on which the colony depends. Other foragers waited in the entrance of the nest for the first wave to return. If lots of food were nearby, foragers would return and depart quickly, creating a massive chain reaction. If food was scarce, however, the second group of foragers might not leave the nest at all.

"It's a brilliant system. The ants can take advantage of sudden windfalls of food but they don't waste energy and resources if there's nothing there," said Gordon, who is an ecologist at Stanford University.

The behavior of each individual in the group is set by the rate at which it meets other ants and a set of basic rules. Its behavior alters that of its neighbors, which in turn affects the original ant, in a classic example of feedback. The result is astonishing, complex behavior. "Individually, an ant is dumb," Gordon says. She gazes off into the distance and inhales sharply. "But the colony? That's where the intelligence is."

About 110 miles from Gordon's offices in Palo Alto, Calif., Mark Goldman studies a different kind of complex, emergent behavior. Goldman is a neuroscientist at the University of California, Davis. For most of his life, he was never particularly interested in ants. But when he traveled to Stanford in 2012 to plan some experiments with a colleague who had recently

ILLUSTRATION BY JONATHON ROSEN

attended one of Gordon's talks, something clicked.

"As I watched films of these ant colonies, it looked like what was happening at the synapse of neurons. Both of these systems accumulate evidence about their inputs—returning ants or incoming voltage pulses—to make their decisions about whether to generate an output—an outgoing forager or a packet of neurotransmitter," Goldman said. On his next trip to Stanford, he extended his stay. An unusual research collaboration had begun to coalesce: Ants would be used to study the brain, and the brain, to study ants.

Each of the brain's 86 billion neurons can be connected to many thousands of others. When a neuron fires, it sends a signal to nearby neurons that changes the probability that they will also fire. Some neurons are excitatory, and increase the chances that other neurons will fire. Others are inhibitory, and reduce this chance. A combination of inputs from a given neuron's neighbors will determine if it fires. If two neurons make each other fire often, the synapse between them (a small gap across which chemical or electrical signals are passed) will strengthen, so that they can more readily provide feedback to each other.

"This is where you get the saying that 'Neurons that fire together, wire together,' " says Dmitri Chklovskii, a neuroscientist at the Howard Hughes Medical Institute. But what is often not appreciated about this adage is that wiring also requires the second neuron to send a message to the first that it, too, has fired.

"The only way the upstream neuron knows that the second neuron fired is that it produces a feedback spike. This helps the synapse make the decision to get stronger," Chklovskii says. Feedback is where the similarity with ants begins. "Feedback loops are everywhere on every level. They allow the system to realize that what it used to be doing isn't working anymore, and to try something new."

Both ants and brains actually rely on two types of feedback, held in a delicate balance: negative (or inhibitory) feedback, and positive (or excitatory) feedback. "Negative feedback tends to cause stability. Positive feedback tends to cause runaway behavior," said Tomer Czaczkes, an ant biologist at the University of Regensburg in Germany. "These two simple rules make something very powerful."

The foraging response to food is an example of a positive feedback loop, and familiar to anyone who has had a picnic ruined by a line of ants marching in single file toward their meal. But knowing when not to leave the nest and risk predation and dehydration may be just as important as knowing when to take advantage of a windfall of seeds. At low levels of an input (a small amount of food, for example) positive feedback dominates. At high levels of input, negative feedback dominates, helping to prevent runaway processes.

Such runaway processes can represent a significant danger to the colony. Czaczkes mentions a tale involving the South American army ant, which unlike the harvester ant, relies on pheromones for navigation. In 1936, ant biologist T.C. Schneirla watched a group of army ants fall into an "ant death spiral" as they created a pheromone trail completely around a large tree. The lead ants, Schneirla noted in a 1944 paper, discovered and followed their own pheromone trail. More and more ants joined in, following an endless positive feedback loop around the same tree, continuing for days through pouring rain until the ants began to die from exhaustion.

"Relying only on positive feedback can get you stuck like this," said Czaczkes. He would later show that positive feedback was balanced by negative feedback in the black garden ant, and that negative feedback allowed for rapid adaptation to the environment.

Similar feedback networks are found in the brain, both at the level of individual neurons and of the whole brain. Just as the discovery of a cache of seeds by one or two harvester ants can trigger a massive exodus from the nest, the entry of a few sodium ions into a neuron can trigger a massive influx. This positive feedback raises the voltage of the neuron past a certain threshold, causing it to fire and temporarily stop the influx of sodium ions, while simultaneously letting potassium ions flood out.

The activity of individual neurons induces electromagnetic fields around the brain that can be recorded with electroencephalograms (EEGs). The EEG signal, too, is a form of positive feedback. Scientists at Yale University applied a weak electric field to a piece of ferret brain that was producing slow but regular brain waves, similar to what happens during deep sleep. This field, they found, could strengthen the existing surges of neural activity in the brain tissue, causing ripples

CARRIE ARNOLD

ANT LAND Deborah Gordon has been returning to this New Mexico landscape for years to study its ants.

to become tsunamis. When the scientists applied the opposite electric field to brain tissue that was experiencing regular waves of neural activity, they were able to disrupt this feedback loop.[1]

While these feedback processes in the brain are known to exist, they are hard to observe—much harder than analogous feedback processes in ant colonies. So Gordon and Goldman forged an ant-brain alliance. To get it started, they focused on one particular aspect of ant behavior: the number of interactions it would require for an ant to leave the nest and start foraging.

In August 2013, Gordon returned to the same desert scrubland straddling the border of Arizona and New Mexico that she has visited each summer for 30 years. Armed with a map and a clipboard, she strode over the packed dirt and patches of thick grass to begin her experiments. As she walked past harvester ant colonies, she greeted them like old friends. "Happy birthday, Colony 330. You made it another year," she said as she scribbled a note on a piece of paper, never breaking stride.

Flanked by a group of undergrads and Ph.D. students, Gordon arrived at a nest she had marked 889 with a piece of rusty wire and a stamped metal tag. Everyone set down their equipment, which included everything from large plastic buckets to umbrellas to peanut butter. Gordon removed a roll of blue duct tape decorated with pictures of SpongeBob SquarePants. The students immediately began tucking shirts into pants and jean legs into socks. Then, they carefully wrapped SpongeBob tape around ankles, wrists, and waist—anywhere the ants might be able to deliver a nasty bite. Neuroscience research had never looked quite like this before.

After taping their clothes, the students set up two video cameras. One was aimed at the opening of the nest, a hole in the ground that looks like it could have been drilled by a pencil. Another was aimed at a square

"Individually, an ant is dumb. But the colony? That's where the intelligence is."

about three feet from the nest entrance, measuring about one foot on each side, and with rocks at the corners. Armed with a plastic spoon filched from the cafeteria of the Southwestern Research Center that morning, Gordon began to enlarge the tiny nest entrance. Then cameras started rolling.

For 20 minutes, the group recorded the harvester ants going about life as usual, leaving the nest in search of food and bringing seeds back home. Then, Gordon focused her attention on the square. Like a Cordon Bleu chef pinching a bit of salt, Gordon expertly grabbed the ants in the square between thumb and forefinger, dropping them into a plastic bucket. The cameras kept rolling as the normally bustling ant entrance went eerily still.

"The ants aren't getting feedback from their nestmates," she explained. "No one is coming in, so the ants inside aren't getting the signal to leave."

Gordon and her team found that it took just three seconds for harvester ants to start leaving the nest faster, after their nestmates began returning in droves with food.[2] The opposite reaction was much slower: If foragers didn't return for four to five minutes, ants near the entrance fled deeper underground. The team also measured how long it took the colony to return to normal after being disrupted.

Numbers like these are precious information for Goldman. Like ants, neurons also have first and second responders. When a neuron fires, it releases neurotransmitters that are housed in containers called vesicles. One pool of vesicles, called the "readily releasable pool," lives right at the cell membrane and is the first to be released. The vesicles in this pool, however, are few in number and can quickly be depleted. If firing rates continue at a moderate level, a second pool of vesicles called the "recycling pool" is brought into action, and very intense rates will summon a third pool called the "reserve pool."

A returning forager is like an incoming action potential; a potential forager in the ant colony is like a synaptic vesicle. These potential foragers also appear to be arranged according to their proximity to the tunnel entrance. Those further back are similar to the recycling and reserve pools. Just as a potential forager has to decide whether to leave the nest in search of food, the synapse has to decide whether to release a vesicle.

Goldman believes he can use ant data to understand the foraging behavior of the desert ants and the ways in which it is similar to or different from vesicle recycling. To understand ant foraging behavior, he is using a mathematical construct called a stochastic accumulator. This model sums the inputs that the ants receive inside a certain time window, in a way that takes into account the inherent randomness of the environment. In synapses, the chemical signals that trigger ant foraging behavior are replaced by electrical signals that trigger the release of neurotransmitters, and the leave/stay decision of the ant is replaced by the release/don't release decision of the synapse.

For her part, Gordon is hoping for more precise mathematical models of ant behavior. She hopes it will help her understand how differing responses to interactions at the level of individual ants may lead to differences among colonies. For example, colonies that forage less when conditions are dry are more likely to produce daughter colonies. This adaptation may result from ants requiring more interactions with their nestmates before leaving the nest to forage. "Gathering food can be really risky," Gordon said. "It actually benefits the colony to show restraint, because they're not wasting resources."

In the months since her return from New Mexico, Gordon has spent many of her days watching her newly collected videos. Together with her team of postdocs, graduate students and undergrads, she counts the ants as they swarm around the colony entrance. Each ant arrival receives a sharp click on the stopwatch-like counter the students use, so that the analysis sounds like a machine gun battle in the corner of her Stanford laboratory. With each click, one species moves closer to understanding another—and itself.

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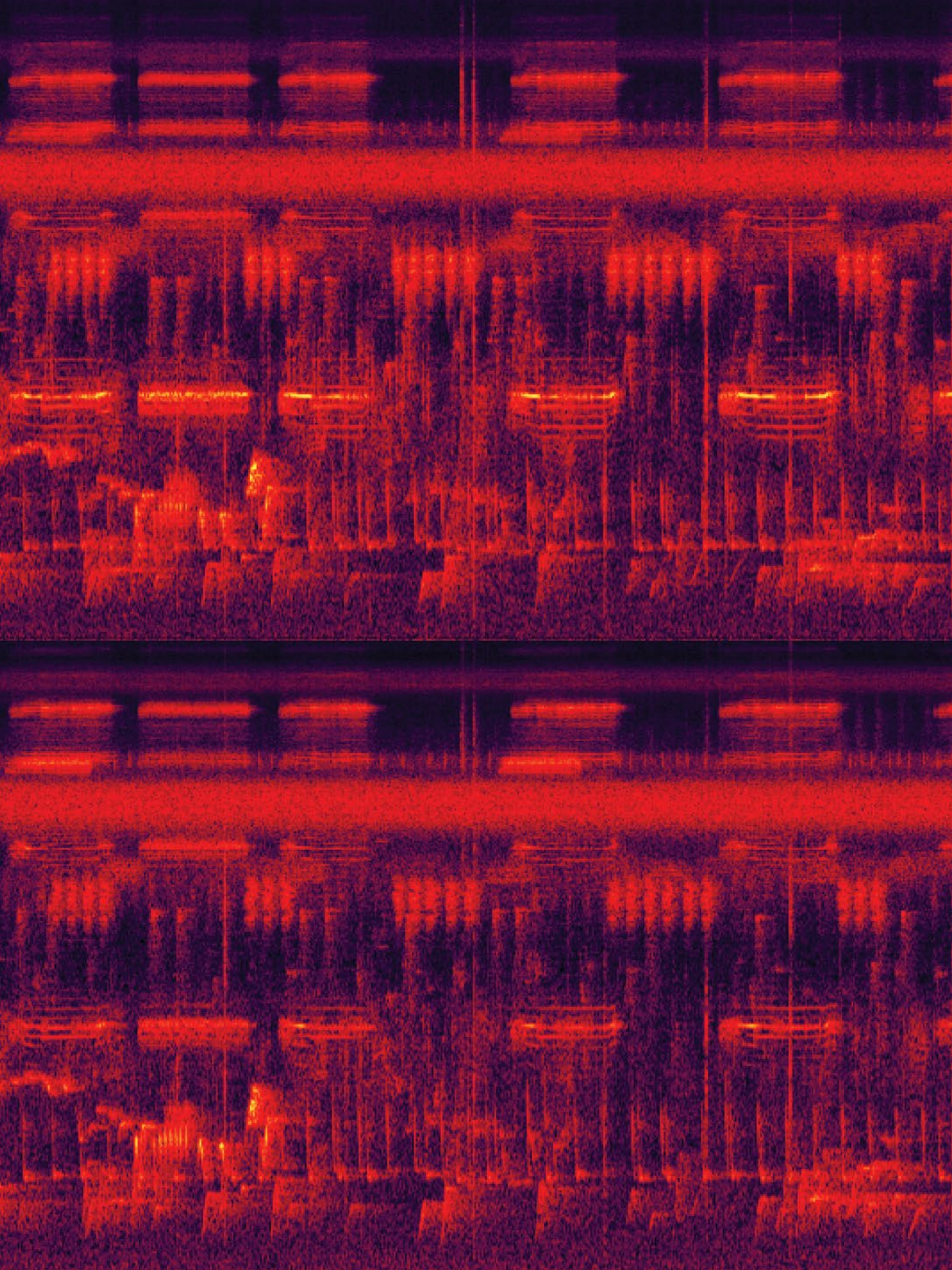


Decoding Nature's Soundtrack

The health of an ecosystem in the Earth's own words

BY BRANDON KEIM

ONE OF THE MOST immediately striking features about Bernie Krause is his glasses. They're big—not soda-bottle thick, but unusually large, and draw attention to his eyes. Which is ironic, as Krause's life has been devoted to what he hears, but also appropriate, since it's the weakness of his eyes that compelled Krause to engage with sound: first with music, and later the music of nature. Nearsighted and astigmatic, Krause has spent most of the last half-century recording biological symphonies to which most of us are deaf.

Even more than Krause sees, he listens. It's an unusual trait. Ours is a society that privileges vision—illumination is insight, leaders are visionaries, do you see what I'm saying—and the habit extends to our interactions with nature. Take a walk in the woods and you'll almost certainly be soothed by birdsong and trilling streams and wind whispering in treetops. But when you get home, you'll likely be asked: What did you see?

That will likely be what you remember, too. The sounds will have been background noise. And in that habit, you won't be alone. In some ways, scientists have tended not to hear nature. Not that they've been deaf; there are plenty of studies on, say, sound production in croaker fish or the neurological basis of finch songs. But to Krause and the scientists he's inspired in the emerging field of soundscape ecology, traditional bioacoustics has too narrow a focus. Their microphones are stethoscopes pressed to Mother Nature's chest. Krause records the feedback between the natural world and us.

"The voice of the natural world informs us about our place in the living world and how we're affecting it," he says. "It tells us everything we need to know about how we're doing in relationship to it."

AT THIS PARTICULAR MOMENT in Earth's history—the morning of what some scientists call the Anthropocene, an age in which human influence on natural processes is ubiquitous and immense—we have many tools to measure our ecological impacts: by eye, generally, focusing on particular species or guilds of interest, counting them in the field, peering by satellite at changes in land use, and translating our observations into the language of habitat type and biodiversity.

To Krause, these are measurements best made by listening to natural soundscapes. In a career of listening and recording, he's amassed a veritable Library of Alexandria of nature's sounds, and he emphasizes that

PHOTOGRAPHY BY BRANDON KEIM

they're not merely recordings of individual creatures. The traditional approach of bioacoustics, focusing on single animals and species, is anathema. It's "decontextualizing and fragmenting," he says, like trying to extract a single violin from Beethoven's Fifth Symphony. "Take an instrument out of the performance, and try to understand the whole performance, and you don't get very much," he says.

Inevitably Krause has captured the players—bearded seals with voices that echo geomagnetic storms, baboons booming in granite amphitheaters, a fox kit playing with a microphone—but they're incidental to recording whole habitats and communities.

In his home studio, perched on an oak-covered hillside in Glen Ellen, Calif., Krause plays me some of his favorites: a Florida swamp, old-growth forest in Zimbabwe, intertidal mangroves in Costa Rica, and a Sierra Nevada mountain meadow. As the sounds pour from speakers mounted above his computer, spectrograms scroll across the screen, depicting the timing and frequency of every individual sound. They look like musical scores.

In each spectrogram, Krause points something out: No matter how sonically dense they become, sounds don't tend to overlap. Each animal occupies a unique frequency bandwidth, fitting into available auditory space like pieces in an exquisitely precise puzzle. It's a simple but striking phenomenon, and Krause was the first to notice it. He named it biophony, the sound of living organisms, and to him it wasn't merely aesthetic. It signified a coevolution of species across deep biological time and in a particular place. As life becomes richer, the symphony's players find a sonic niche to play without interference.

"The biophony is the pure expression of life, of the given organisms in a habitat," he says. "When you're in a healthy habitat, all the species are able to find bandwidth where their voices fit." He puts an ancient Borneo rain forest onto the speakers. At the top of the spectrogram are bats, their echolocation a bare hint of a sound to human ears; below them are cicadas, a plenitude of insects, one chestnut-winged babbler, and nightjars, and the booms of gibbons, each in its own place.

Krause magnifies the view, zooming in so that each animal's call can be discerned as individual orange dots. From this view, the spectrogram looks like constellations seen through a telescope. "You've got a whole universe in there," he says. "Look at the discrimination here. It's so beautiful. It tells you how old this habitat is."

LEVELS OF THE FOREST Krause looks at a spectrogram, identifying the frequency bandwidth of each sound captured by his microphone.

It took a while for Krause's observation, initially made informally in the early 1980s, to reach sympathetic scientific ears. Krause was not, after all, a member of the scientific community. On his studio walls are photos from his early, pre-nature music career—Krause singing tenor with The Weavers' during a 1963 Carnegie Hall performance, the Moog synthesizer he played in early electronic music and for special effects in *Rosemary's Baby* and 1978's *Invasion of the Body Snatchers.*

But the idea of biophony struck a chord with Stuart Gage, an ecologist at Michigan State University

ON SUGARLOAF MOUNTAIN Located in the Mayacamas Mountain range of northern California, Sugarloaf Ridge State Park is nestled between Sonoma and Napa counties, where Krause has recorded for many years.

interested in using sounds to take the pulse of ecosystems and monitor their ecological health. He and Krause recorded Sequoia National Park, using an early gauge of acoustic complexity, measuring patterns of species diversity across different habitats and seasons. It was a proof-of-principle test, and in recent years, with the advent of inexpensive recorders and big hard drives that make it possible to record large areas over long periods of time, the field—now dubbed "soundscape ecology"—has flourished.

Researchers are now recording dozens of landscapes across the world and computationally translating thousands of hours of recordings into numerical indexes of ecological conditions, and ultimately the human impacts on them. These are not ready for practical application. The biophony, formally known as the "niche hypothesis," is still a hypothesis. It's not yet possible to hear whether an ecosystem is healthy. But that may happen soon. "I think we're going to see a rapid shift into applied research," says Bryan Pijanowski, a Purdue University soundscape ecologist, whose projects include sonic assessments of a wildfire-scorched Sonoran desert.

Some of the current indexes—Gage is reviewing six, and there are many more—are relatively straightforward counts of animal calls or the total species in an area. Others, however, resonate more closely with Krause's notion of the biophony. Jérôme Sueur at The National Museum of Natural History in France is trying to quantify species diversity. One of the indices his group developed, the Acoustic Entropy Index, is predicated on the notion that communities of life in undegraded habitats become not just diverse, but structured, like Krause's old-growth Borneo forest biophony.

Ecologist Almo Farina at Italy's University of

THE BIOPHONIC MAN Bernie Krause, father of biophony (“life”+“sound”), outside his home in Glen Ellen, California.

Urbino and Italian composer David Monacchi are applying similar ideas to other forests in Borneo, with Farina’s student Nadia Pieretti leading studies of central Italian forests. When the patterns of birdsong in those forests are analyzed and turned into mathematical measures of complexity, says Pieretti, the symphonies of communities subject to road-building and intrusion indeed seem to be less structured. Birds call louder and repeat themselves, perhaps to be heard above vehicular din; there’s more noise, but not more information.

This particular type of biophonic impact, in which human noise—the anthrophony—drowns out nature’s own sounds, is one to which Krause is especially sensitive. It’s been an active field of traditional bioacoustic study, with researchers finding many cases in which sound pollution seems to interfere with animal communication. That’s not always the case, and often it’s been difficult to disentangle the effects of human presence—the roads themselves, say, not motor noise—from those of our sounds. Soundscape ecology approaches noise pollution in more nuanced ways, focusing not only on noise’s effects on particular species but across habitats and communities.

Although sound indexes of ecological health may be years away, pending rigorous testing, calibration, and codification, Krause says he doesn’t need to wait for the results. He estimates that nearly half of the habitats he’s recorded are now compromised or rendered silent, primarily by human development and insatiable appetites that relegate most non-human interests to irrelevance. Krause requires no scientifically validated tools to hear that feedback. “If you know how to listen to it, then it’s really clear what’s happening,” he says. “As the natural world becomes more silent over time, the question is: Is that what we want?”

KRAUSE IS A FATHER of soundscape ecology, but the methods of its maturity are not his own. He created the niche hypothesis, and has made important contributions to the emerging science, but he's not going to blanket a forest with recorders and let his computer do the listening. There's something profoundly important to Krause about the human act of listening, about being there.

On a cool March morning, Krause drives me to one of his favorite spots, one he's recorded since the early 1990s: Sugarloaf Ridge State Park, 4,500 mostly undisturbed acres in the mountains between the Napa and Sonoma valleys. We pull into the parking lot and head up a trail before dawn. Above a ridge to the south, Antares blazes red; Venus incandesces like a flare.

The park is home to an observatory where local stargazers gather for celestial events. On the path, signposts mark the relative distance of the planets from the visitor center's sun. A little ways beyond Saturn and a tall willow where wild turkeys sometimes roost, beside a stand of coyote brush and bay laurel, Krause stops to set up his equipment. Working by the light of a headlamp, it takes only a minute. He probably could do it with his eyes closed.

Behind the brush a stand of alders and willows marks the edge of Sonoma Creek, burbling from the rains that ended the region's seven-month-long dry spell. It's good songbird habitat, and a few minutes later, after we've walked away from the recorder and up the trail, as the sky grows a shade brighter, they start to sing.

It's the beginning of the dawn chorus: that universal performance, whether in rain forest or tundra or this particular semi-arid riparian pocket, when the community of life greets a new day. Most of Krause's work, and much of soundscape ecology recordings, involves recordings taken at this information-rich time.

Just why the chorus happens, though, remains a mystery. Many explanations have been proffered, from territorial display to the unique sonic qualities of morning air to the possibility that, in such dim light, there's nothing else for birds to do. Farina and Pieretti think the creatures in a biophony aren't just talking to others of their own kind, but listening to each other. Nature recorder Martyn Stewart calls it "a newspaper being read in dozens of different languages."

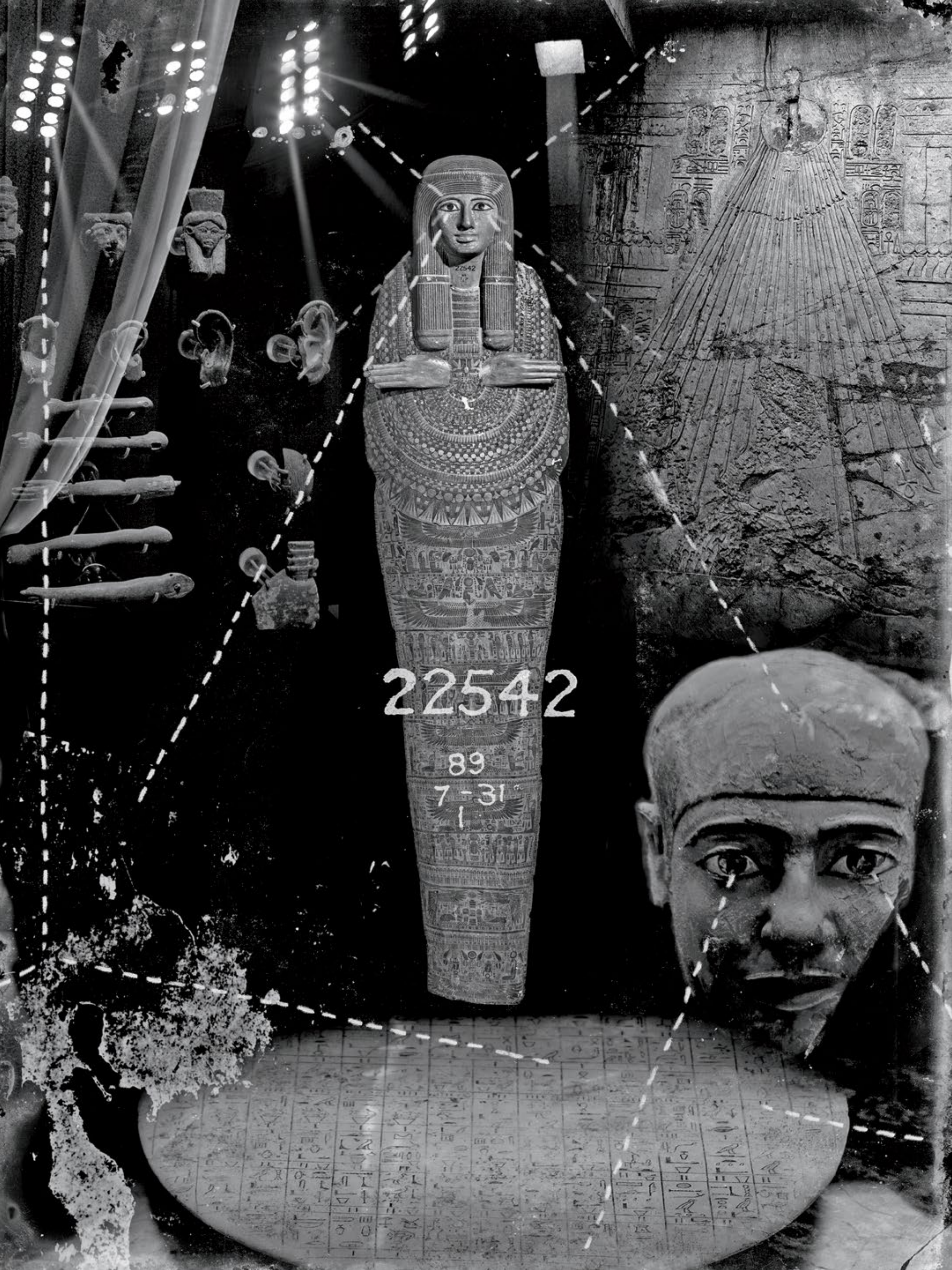
First to read the news is a scrub jay. In a few minutes he's joined by white-crowned and song sparrows, titmice and juncos and towhees and mourning doves. A red-shouldered hawk is heard, and a pileated woodpecker, and a great-horned owl. Just before we return to the recorder, the turkeys make their appearance. They've got a lot of news.

Back in the studio, Krause seems a little disappointed, almost like someone who's heard a band so many times that only exceptional performances stand out. Compared to other choruses he's heard at that spot, ours was relatively quiet—reflecting, he suspects, the lingering consequences of drought, or changes in local climate. The last few years, says Krause, seem to have gotten quieter.

Despite Krause's misgivings, it's still an extraordinary concert, at least to my ears. Above the creek's burble, the birds have arrayed themselves neatly in sonic space. The chorus is still rich and orderly. A few jets can be heard in the distance, but without causing any apparent disturbance. Sugarloaf is far from pristine—it was ranched a century ago—but it's now protected and generally undisturbed. Despite the drought and surrounding urban sprawl, there's still habitat, a chance for life to flourish.

"Although it is not nearly as robust as in past years, either in density or diversity," says Krause, "it is, nonetheless, a sonorous and hopeful expression of seasonal life." As much as Krause laments that many soundscapes he's recorded will never be recovered, in more hopeful moments he talks of those that might still be protected, even regrow. Where we allow it, life will thrive. If only we would listen.

BRANDON KEIM is a freelance journalist who writes about science, technology, and nature. His work has appeared in *Wired*, *Aeon*, *Scientific American Mind*, and other publications.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The Curse of the Unlucky Mummy

When science and fear collide, a supernatural story thrives

BY ROSE EVELETH

SOMETIME IN THE 1860S, five recent Oxford graduates took a trip to Egypt. Together they sailed down the Nile, a tourist attraction even then. To remember their trip, they bought a souvenir in the mummy pits of Deir el-Bahri—the coffin lid of a priestess of Amen-Ra. The high priests of Amen-Ra, named after an Egyptian deity, were military rulers who commanded southern Egypt in the 21st Dynasty (1085 to 945 B.C.), a time of turmoil and strife. Powerful and prone to keep secrets, the priesthood worked to appease the gods that Egypt had clearly angered. With her wide, baleful eyes, open palms, and outstretched fingers, the priestess on the coffin lid seemed to cast a malevolent allure.

On their way back from Egypt, two of the men died. A third went to Cairo and accidentally shot himself in the arm while quail hunting and had to have it amputated. Another member of the group, Arthur Wheeler, managed to make it back to England, only to lose his entire fortune gambling. He moved to America and lost his new fortune to both a flood and a fire. The coffin lid was then placed under the care of Wheeler's sister, who attempted to have it photographed in 1887. The photographer died, as did the porter. The man asked to translate the hieroglyphs on the lid committed suicide. The coffin lid seemed almost certainly cursed. But this was only the beginning.

Today, the 5-foot-tall "mummy board" lives in the British Museum, where it's officially known as "artifact 22542." The mummified priestess that may have lain beneath it has been lost to eternity. But it has another, more commonly used name: "Unlucky Mummy." Since its arrival at the museum in 1889, the Unlucky Mummy has been blamed for everything from the sinking of the Titanic to the escalation of World War I. How this piece of wood became so intimately and persistently connected with death and destruction is a story of the endlessly swirling tales that people tell when they are afraid—of change, of politics, of science. It is the kind of story that never dies, only feeds upon itself,

ILLUSTRATION BY JONATHON ROSEN

Why Mummies Grab Us

The British Museum can take some solace in the fact that it wasn't through any fault of its own that the Unlucky Mummy took on such a life after death. If it weren't this artifact, it might be another one. The human love affair with ghost stories, mummy myths, and general superstition goes back further than the Egyptians, all the way to the beginnings of what makes us human.

"Humans like narratives," says Gordon Pennycook, a psychologist at the University of Waterloo. "We like stories." If a story can explain a series of events—particularly events that are scary and uncontrollable like death, disease, and disaster—we'd rather have them than nothing at all. This isn't special to mummies. We see this kind of storytelling in all kinds of mythology: Gods bring the rain, demons punish us with earthquakes, healers channel the dead, vaccines cause autism.

"The human brain is just terrible at recognizing coincidences," says Will Gervais, a psychologist at the University of Kentucky who studies supernatural beliefs. "We have a lot of cognitive biases that make us infer hidden causes, even if they aren't there."

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updating and morphing and tightening its grip no matter how much light is thrown on it.

BY THE TIME THE UNLUCKY MUMMY arrived at the British Museum, its reputation had seeped through British private society. While the museum curators generally scoffed at the alleged curse, men at soirees, dinner parties, and "ghost clubs," traded stories of its powers. But it wasn't until 1904 that the broader public got a whiff of the curse. That was the year that a young, dashing, and ambitious journalist named Bertram Fletcher Robinson published a front-page article in the *Daily Express*, called "A Priestess of Death," about the allegedly haunted mummy. "It is certain that the Egyptians had powers which we in the 20th century may laugh at, yet can never understand," he wrote.

Three years later, Robinson died suddenly of a fever, and his friends immediately thought of the mummy's curse. "The very last time I saw him he told me a wonderful tale about a mummy which had caused the death of everybody who had to do with it," wrote Archibald Marshall, an English author and journalist.

Sir Arthur Conan Doyle, creator of Sherlock Holmes, recalled that he had cautioned Robinson not to get involved with the mummy. "I warned Mr. Robinson against concerning himself with the mummy at the British Museum," he wrote. "He persisted, and his death occurred... I told him he was tempting fate by pursuing his inquiries, but he was fascinated and would not desist." Doyle even went so far as to point out that should the mummy kill someone, fever would be the way she did it. "The immediate cause of death was typhoid fever," he wrote, "but that is the way in which the 'elementals' guarding the mummy might act."

Robinson was not the only alleged victim. The list of stories about the mummy's influence began to grow longer—people who sketched the mummy having mysterious accidents, a lady falling down the stairs, a captain meeting financial ruin, a psychic claiming the mummy haunted him for

REVENGE After killing an archeologist for desecrating a tomb, the Mummy (Lon Chaney Jr.) abducts the beautiful Isabel (Elyse Knox) in the 1942 film, *The Mummy's Tomb*.

weeks. There was a rumor that the mummy had been on the Titanic and caused the ship's deadly collision. One person claimed the mummy, at the peak of her wrath, had been presented to the Kaiser and caused the outbreak of World War I.

As it happens, the Unlucky Mummy arrived in England during the perfect curse-making storm. It was a time when science was challenging traditional beliefs, experiments into the occult were becoming more common, and tales of ghosts and threatening monsters were entering their golden age. The Victorians were afraid of a lot of things: empires, the rise of women in society, and the role of expertise. And on top of that, there was a war going on.

At the time, Britain was occupying Egypt. It had invaded the Middle Eastern country in 1882, bombarding Alexandria for 10 and a half hours from the sea in an attack that was largely one sided—the British didn't lose a single boat. The fires that followed destroyed much of the city and two days later the British army entered Alexandria and took on Egyptian forces in a handful of skirmishes, the most notable being the battle at Tel-el-Kebir. Because the Egyptian land was flat and open, the British decided to attack at night. After an hour of fighting, the Egyptians fled. The British military stayed in Egypt in a variety of capacities until 1922.

While the occupation of Egypt was a military success, it was met with trepidation back home. Should a European power intervene in the goings on of a Middle Eastern country? The British said they were there to help depose a tyrannical rule, but the British people weren't sure that was their government's job in the first place. While the occupation troubled many, some didn't want to outwardly express their anxieties. So they turned to objects that represented the country in question: Egyptian artifacts.

"You can't talk about how difficult it is to occupy another country because that's unpatriotic," says Roger Luckhurst, a professor of literature at Birbeck College, University of London, who details the Unlucky Mummy's journey through myth and reality in his 2012 book, *The Mummy's Curse*. "This is a narrative that lets you talk about it in another way." The idea that objects from Egypt like the mummy board would exact revenge was a way to express anxiety without actually talking about war.

Scientists weren't just moving rocks, they were moving sacred ways of thinking.

As wartime fears ran through much of England, people also began to worry about just how far scientists would go to uncover truth. When scientists went into tombs to gather relics, they weren't just moving rocks, they were moving sacred ways of thinking. "There are incentives to disturbing the dead, and archaeology is one of them," says Kathlyn M. Cooney, an Egyptologist at the University of California in Los Angeles. The archaeological incentive, however, was also uncovering guilt.

In the 1899 novel, *Pharos the Egyptian*, by Guy Boothby, Pharos asks the son of a famous Egyptologist, "And pray by what right did your father rifle the dead man's tomb?" Perhaps, he continues, "you will show me his justification for carrying away the body from the country in which it had been laid to rest, and conveying it to England to be stared at in the light of a curiosity." He could just as easily have been talking about the priestess of Amen-Ra. "Here you've got a mummy board that's depicting a human female, and that mummy board was meant to be kept in an intact tomb," Cooney says. "And it's not. It's floating around the world, bought and sold, and now it's on display. It's separated from its mummy, it's been wrested from everything it's been a part of. That upsets people. It worries people."

It wasn't just in the realm of stories that the British were venting their fears. This was also the era that gave birth to tabloid journalism. Newspapers fanned the flames of anxiety and reinforced them, building a base for more tales of monsters and mummies. In the late 1890s the *Daily Mail* took flight. It was joined by the *Daily Express*, which published the original Unlucky Mummy story, "A Priestess of Death," the *Morning Star*, the *Daily Sketch*, and others, dedicated to selling papers

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Pennycook argues that there are two kinds of thinking at work here: low-level processing and high-level processing. "If I ask you your name, you don't have to think to come up with a response," he says. That's a low-level process. "If I give you a math problem, you have no access to the answer," he says. "You have to do the math problem." That's a high-level process.

According to Pennycook, these kinds of mythologies and stories are far more like your name than a math problem. They are solidified in the low-level process. But to recognize that something is fake, you have to think about it. And it turns out that people do not like to think about math problems. Or psychological math problems. It's far easier to accept the story than to track back through each step and figure out the missing logical link.

Not only do humans love stories, we also care a whole lot about objects. While other species might collect shiny things or guard their tree, humans imbue our items with a whole other level of meaning. We have good luck charms, burn objects in sacrifice, bury things for good luck, hide teeth under pillows, save locks of hair, and box up old, tattered blankets for sentimental value. If you give someone a coat and tell them it was worn by a serial killer, they won't put it on, as if they could catch murderousness from simply coming in contact with the fibers. The opposite is true, too—people handed a pen that belonged to Albert Einstein treat it far differently than a regular pen.

For humans, objects hold memories of those who used them. Which is part of why objects associated with death, like our mummy board, are so emotionally charged. Artifact 22542 reminds us that this lifeless piece of wood once covered a priestess with mysterious powers. What can we do? That's just the way the mind is made up.

with bold headlines and little regard for facts. Philosopher R.G. Collingswood wrote that tabloids were places where the reader was expected to "think of the news not as the situation in which he was to act, but as a mere spectacle for idle moments." The Unlucky Mummy was too big of a spectacle to remain fodder for just England's tabloids. A 1909 headline in William Randolph Hearst's *San Francisco Examiner* exclaimed, "Ghost of Mummy Haunts the British Museum: MUST GO NOW: For Thirty Years Dead Egyptian Priestess has Spelled Disaster."

The Unlucky Mummy story, Luckhurst suggests, forged a template for an even more spectacular story about excavating ancient spirits. In 1922, the long sought-after tomb of King Tutankhamen was uncovered, and both rigorous and tabloid papers were jostling to get their hands on the goriest and most gilded stories that emerged from the burial ground. Lord Carnarvon, the man who funded the expedition that found King Tut's tomb, had signed a strict and exclusive agreement with the *Times of London* that essentially locked all other papers out of the story. The competition got their revenge by stoking rumors that Carnarvon, who died from blood poisoning (he was bitten by a mosquito) not long after the excavation, was driven to his grave by vengeful Egyptian spirits. The *Daily Express* gave voice to a Christian mystic novelist who claimed, based on a rare book called *The Egyptian History of the Pyramids*, that "the most dire punishment follows any rash intruder into a sealed tomb."

TODAY THE BRITISH MUSEUM has little to say about the Unlucky Mummy. The artifact page for the mummy board has a brief note, hidden in the curator's comments. It recounts a few of the most notable myths, including that the mummy was on board the Titanic, and adds: "Needless to say, there is no truth in any of this; the object had never left the Museum until it went to a temporary exhibition in 1990."

For Luckhurst, the museum's dismissal of the myths is unfortunate. The myths, he says, "tell us a lot about how people react and respond and interact with these ancient artifacts." Once an item is encased in glass, given a number and archived into a database, it is supposed to be stripped of its mythical aura and magic. Pushing magic away, though, only makes people cling to it harder, especially when the object is intimately connected with human remains. "We're always going to feel ambiguous and vaguely transgressive about these sorts of things," Luckhurst says.

Indeed, mummy stories still walk among us. In 2013, a headline in England's *Manchester Evening News* read: "The curse of the spinning statue at Manchester Museum." The story concerned a 10-inch-tall statue of a man, found in an Egyptian mummy tomb, that mysteriously spun in its display case. An Egyptologist quoted in the paper, explained, "In Ancient Egypt they believed that if the mummy is destroyed then the statuette can act as an alternative vessel for the spirit. Maybe that is what is causing the movement." In fact, the base was slightly uneven, and tiny vibrations from road traffic and visitors' footsteps were making the statue rotate.

In a culture of anxiety, conflicted over how science shapes our understanding of the world, the allure of the occult remains. Will Gervais, a psychologist at the University of Kentucky who studies superstitious beliefs, says the British Museum should embrace the Unlucky Mummy's curse. "I'd advise the museum to sell T-shirts about the mummy, then take the proceeds and pour them into other science-education programs that are more likely to succeed." And, in one way, the British Museum has. Last summer it showed the 1959 film *The Mummy* in its courtyard. "You can bury people's superstitions under a mountain of evidence," Gervais says, "and the superstitions will climb right on out." Not unlike an unlucky mummy.

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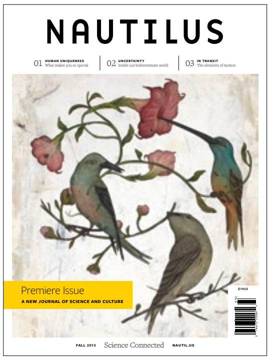

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“The beauty of a life in astronomy is that every moment, it seems, is a phenomenon decribed in a way that’s both precise and lovely in it’s description.”

TOOD PITCOCK
“Falling in Love with the Dark” p. 126

BUZELLI

MATTER | ASTRONOMY

The Madness of the Planets

Our home in the universe continues to rock out of control

BY COREY S. POWELL

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

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

But these incidents are mere pixels in the sweeping picture emerging from the latest theories of how our solar system formed and evolved. Collisions and dislocations are not occasional anomalies; they are a fundamental cosmic condition.

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

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

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

ILLUSTRATIONS BY CHRIS BUZELLI

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Neil Shubin

The paleontologist and author of Your Inner Fish *and* The Universe Within *reflects on the themes in* Nautilus

INTERVIEW BY KEVIN BERGER

ON MERGERS & ACQUISITIONS

When I think about mergers in nature I think of the human body. We have atoms that come from the stars, molecules that come from the workings of the Earth and comets, and body parts that have arisen from other species. I also think of the deep merger of two kinds of microbes coming together to make a new kind of cell over a billion years ago. The fact that cells act together and make a functioning body is profound and amazing. The most important thing evolution has taught me is how my body is connected to other creatures. I look at my hand and I see a fish fin. I see my head as a modified version of a structure that first appeared in wormlike creatures. It gives you humility. It also gives you a deep sense of aesthetic beauty in being connected.

ON LIGHT

The deepest piece of us that we share with algae, flies, and other creatures is a link to the light-dark cycles of the planet. Our planet rotates on a diurnal circle and every one of our biological activities relates to that cycle of light and dark. Each one of us has a molecular clock inside our cells. That clock is based on the rise and fall of the production of DNA and proteins. It's one of the great discovery stories in science. And what's beautiful is that I have 2 trillion cells in my body, 2 trillion clocks, and I share those fundamental clocks, based on light and dark, with the rest of life on the planet, with the planet itself.

ON FEEDBACK

To understand how fish took their first steps on land, you have to think about it as a push and pull. Life in the water is pretty much all predatory. It's a real fish-eat-fish world. Any variation that would allow creatures to step away from that hostile environment would be favored. You get armor or get out of the way. That's one strategy. But there's also a pull. Going on land, 375 million years ago, you would find all kinds of insect-like creatures and plants. Land was a place where there was food with very few competitors and predators. Feedback is not just a one-way street. Organisms react to changes in the environment. But organisms produce changes in the environment. The evolution of plants and invertebrates on land 375 million years ago made it possible for our fishy ancestors to take their first steps. We wouldn't be here without this wonderful nexus of interactions and feedback.

ILLUSTRATION BY ANDY FRIEDMAN