NAUTILUS

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Premiere Issue

A NEW JOURNAL OF SCIENCE AND CULTURE

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Science Connected

WELCOME TO THE INAUGURAL *Nautilus* quarterly.

Nautilus is a different kind of science magazine. We believe science deserves our attention, not only because it can save us from our problems, but also because it is forever changing our perspective on the world.

These changes are connected to every aspect of our lives. To discover and describe them, *Nautilus* weaves together science, philosophy, and culture into a constellation of ideas describing a shape that is both familiar, and surprising.

Our inaugural quarterly issue opens with two essays that take us into the frontier. Biologist and author Aaron Hirsh considers the changing ecology and economy of the United States through two of its symbols: the songbird and the big-box store. Then Caspar Henderson walks us through the world of Manticors and archaea, showing us how science has changed the very idea of frontiers.

These essays compel us to consider our place in the universe, transportation to far-away places, and the uncertainty of what we may find there. We devote one section of the quarterly to each of these topics, refracting them into primatology and particle physics, philosophy and fiction, and into illustrations by some of the world's best artists. Finally, Jared Diamond escorts us out of the conversation with The Last Word.

On our pages, science spills over its usual borders to construct broad, encompassing conversations. We are so glad to have you join them.

—Michael Segal

01

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BACK COVER Gérard DuBois
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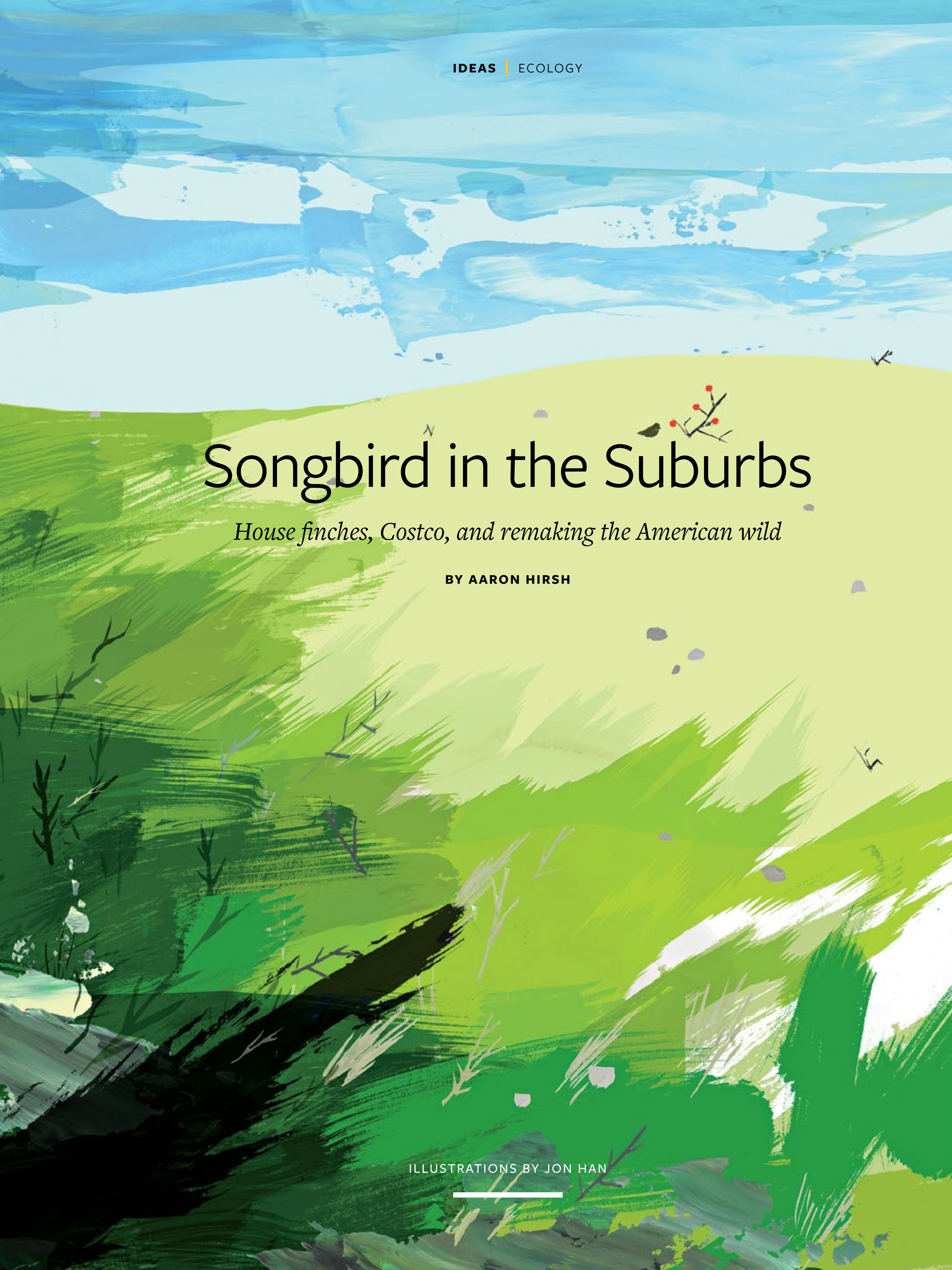


Songbird in the Suburbs

House finches, Costco, and remaking the American wild

BY AARON HIRSH

ILLUSTRATIONS BY JON HAN

1.

THE PARKING SPACES AT Costco are especially wide, laid-out to accommodate vehicles like the immense Ford Excursion that Veronica now turns cautiously toward an open berth. She has picked a spot that is just to the left of another Ford Excursion; in fact, it appears to be precisely identical to our rental, so while we edge gradually into place, I get to watch the reflection of our own tinted windows sliding across an equivalent row of tinted windows. Sinking momentarily into the befuddlement of infinitely regressing reflections, I find myself hoping, only half-coherently, that this precise pairing of vehicles is in truth a result of my wife's oddly powerful yen to organize. Because the alternative—that there are so many matching Excursions out here that this event is not so unlikely, after all—seems vaguely repellant.

Sidling through the narrow aisle between twin SUVs, I emerge to peer down the receding parallel rows of vehicle rear-ends, which flash blindingly in the sun. In the distance, where the lot is still vacant, the savannah of asphalt is bounded by a chain-link fence, and then the ground gives way to a downslope. The freeway is down there—I can hear it from here—and across the valley of the freeway, on the distant opposing shore, yellow machines move like insects, sculpting fresh hills out of ferrous red earth.

"Is that Hallmark?" I ask. Veronica has just told me about this on our drive over. The company well known for finding the right phrase—I love you ... You're the one and only—is now working at a more comprehensive scale, constructing planned communities. At one edge of the terra-cotta landscape, a row of freshly completed houses gleam white and pale yellow, weirdly clean. There are two different models, which alternate.

When I catch up to Veronica, who is already heading in the other direction, toward Costco, she's reading as she walks, studying the list of a hundred or so items we are about to purchase for our field-course. This is the day we call gearing-day—24 hours in San Diego to gather everything that 15 people will need for three weeks at a remote research station on the Sea of Cortez. And if we are true to the pattern of gearing-days past, then Veronica is sure to be a force of efficiency and order, while I, for my part, will stay mostly out of the way. It is a truth quietly acknowledged between us that logistics have never been my strong suit.

"Did you check the first-aid box?" Veronica asks, without looking up from her list.

"I did," I say, lying, because I'm pretty sure I remember what's left from last year.

As she rattles a conjoined pair of oversized shopping carts from one of many long, telescoped ranks, she shouts to me over the clatter: "Two more!" Each of us will push a collapsed pair until we need to double our payloads, at which point we'll expand into a train of four carts and two connective humans.

Inside the warehouse, we are instantly and exuberantly greeted by a row of televisions stacked three screens high. They are all showing the same animated movie, and their luminous images move in perfect synchrony, like a grinning line of can-can dancers. As we walk along the row, I avert my eyes and stare at our feet until we've made it into the low-lying archipelago of special offers that precede the actual aisles. Veronica pulls over beside something we need—large boxes of snack bars—and begins inspecting our options: 60 Powerbars; 48 Luna bars; 120 Chewy Granola bars.

"Veronica," I say, placing my hand on the embankment of bars, "do you realize what this means?"

"No," she says, absently, "what does it mean?" She has turned her attention back to her list.

"It means, Veronica, that the scale of commerce has shifted. What was wholesale is now household."

She doesn't react.

"Is that not disturbing?"

"It is," she says, looking up from her list. "But we need four-hundred and twenty snack bars."

"That's disgusting."

"Fifteen people, two bars a day, fourteen days. That's four-hundred and twenty bars."

As she places three boxes of Balance bars in my cart, I take one out and put it back on the embankment. "Those are Twix in disguise," I say.

"People like Twix," she replies, putting the box back in.

The actual aisles are U-shaped canyons carved through paletted goods, which have been stacked by machines to reach the 30-foot ceilings. As we move steadily along, our eyes pass over the canyon walls, scanning for the familiar labels of items we might need. Certain products are sold in such quantity as to seem like a visual joke—a gag on the expected proportions—and just for fun I pull one such prop off the shelf. It's a trash-can sized tub containing 300—so the label exclaims—maraschino-red licorice twists.

"Did you need this?" I ask, holding it up with two hands.

"Yes, actually." She takes it from me and places it in my cart.

"Come on," I say, taking it out.

"Movie night," she replies, pressing my wrist back into my cart.

In the middle of our next passageway sits a waist-high cube composed of orange blocks, each of which is, in turn, composed of 72 individually wrapped packages of cheddar-cracker-and-peanut-butter sandwiches. It's a dizzying, electric-orange fractal, and it gives me an idea: As casually as I can, I pick up an orange block and place it in Veronica's cart, saying only, "good snacks." Then, as she stares at the new item in her cart, I wait patiently, preparing to declare—just as soon as she accepts my suggestion—that I've just proven her deranged consumerism, and she'd better go put back the red licorice.

"Are you insane?" she asks, and instantly it's clear: my tactic has backfired. She takes the orange block from her cart and presses it back on me. "The wrappers will end up everywhere!" Losing patience, she says I need a mission of my own. She'll gather the rest of the food, and I should visit the pharmacy, because I'm the one who knows what's missing from our first-aid box.

So maybe Costco is just as just as beautiful as any other setting in which we might immerse ourselves.

He flits up to a table, where he perches on the edge of a plastic bin and fixes me with a tiny eye.

The pharmacy… my only hope of reaching it without getting lost or, worse, waylaid by the sirensong of HDTV, is to walk transects—the systematic to-and-fro one would trace in an ecological survey. And so, starting with one edge of the warehouse, I march, my gaze fastened straight ahead. To my left, the glass cases of frozen meats pass as a beige-pink blur, and on my right, the openings to aisles are flashes in the corner of my eye—bright malls I manage to refuse. But as I walk by the bakery, with its distinctive scent of glazed donuts, a sudden grey flicker pierces the sidewall of my private tunnel.

It is a house finch: a small brownish-grey bird with a red head, which means he is male. On the smooth cement floor, he hops, pecks once, pauses to tilt his head and observe the ground, and pecks again. The movements are quick and exact, at once mechanical and vibrantly alive. He flits up to a table, where he perches on the edge of a plastic bin and fixes me with a tiny eye—a pinhead of glossy obsidian.

People are passing close to him, talking on their phones, reaching into the bin for flats of muffins, but he doesn't seem to mind. He stays right where he is, and keeps his eye trained on me. Evidently, it is my own behavior that is suspicious, not everyone else's. He hops a quick, irritated 180, and fixes me with his other eye: *Why the interest?* he seems to ask. *Why the sudden interest?*

2.

ODDS ARE YOU'VE SEEN the little brown bird with the red head, because the house finch, *Carpodacus mexicanus*, follows us nearly everywhere: the bird's particular needs—plants to feed on, places to nest—happen to coincide precisely with the sort of habitat that human beings tend to generate. We convert almost every landscape—redwood forest or salt flat; peat swamp or sandy desert—into a patchwork of the weeds and grasses that provide house finches with their favorite seeds. And when it comes to nesting, the little birds seem to adore stubby ornamental trees, the overhangs of parking structures, and the ivy that grows on building walls.

Until the late 1950s, house finches were hemmed into the southwestern third of the United States, mainly by the vast swath of grasslands that covered the center of the country. While these regions offered plenty of seed, they were severely short on nesting sites. A parsimonious guess at ecological history might suggest that the finches hopscotched gradually eastward, alighting on islands of human settlement until they reached the promised land of Midwestern suburbs. But that is not, in fact, how it happened. Instead, when the invasion finally transpired, it came from the rear: a small population of *Carpodacus mexicanus* appeared in Long Island, N.Y., and from there they began a steady march westward. When they reached the Great Plains, about a decade later, they couldn't cross from the east any more easily than they ever could from the west.

But why Long Island? How did a small but momentous flock find itself next door to New York City? The seeds of biological invasions, like the sparks that start wildfires, are often obscured by the very process they initiate: By the time an invader has advanced far enough to gain notice, it has altered the ecology of a fairly large region, and there's no reconstructing where, exactly, the rings of expansion had their epicenter. But birds are uniquely beloved animals, monitored by a diffuse but nationwide federation of obsessively vigilant observers. Like no other organism, birds get noticed.

In this particular case, a red-headed finch was noticed in April, 1941, in Nassau County, N.Y., and the sighting was duly reported in the weekly ornithology column of the *Nassau Daily Review-Star*. The enthusiasts filing the report were well aware that their sighting represented an exception to the known range of the species, but they confidently identified the bird as *Carpodacus mexicanus*. The column's editor, Dr. John J. Elliott, followed up on the intriguing report, and over the next five years, he discovered several small colonies of house finches nesting in Long Island tree nurseries. He published his findings in the May 1947 issue of the *Linnaean News-Letter*. As to the origin of the birds, he was dumbfounded, though he did note that the Long Island birds appeared to be especially dusky, much like the subspecies of *Carpodacus mexicanus* found in the vicinity of Denver, Colo.

Dr. Edward Fleisher, of Brooklyn, happened to be a subscriber to the *Linnaean News-Letter*, and upon reading Elliott's article, he immediately wrote him a letter. In January of 1940, he wrote, he had entered a Brooklyn pet store, where his attention was drawn to a cage labeled Hollywood Finches. To his dismay, the 20 birds in the cage were in fact specimens of *Carpodacus mexicanus*. As Elliott would later describe the fateful resolution made then and there, "Dr. Fleischer had previously seen Bohemian Waxwings for sale in this same store, and decided to put an end to this traffic in protected American passerines."

Fleischer wrote to the National Audubon Society, requesting immediate action, but since the officer responsible for such matters was on vacation, the case was referred to the State Game Protector. After a brief investigation, this official informed Fleischer that the birds had come from a supplier in California, and therefore their sale was not illegal, as *Carpodacus mexicanus* was "neither protected in California nor native to New York State."

Unsatisfied, Fleischer consulted the Bureau of Biological Survey, which informed him that house finches were indeed protected, as the U.S. and Mexico had recently listed them in a treaty concerning migratory birds. The Survey also dispatched Orin D. Steele, Game Management Agent, to pay Fleischer a personal visit and discuss the matter more fully. As Fleischer later described the conclusion of this episode, "A few days later, April 1, 1940, Mr. Steele sent me a letter in which he said, 'based entirely on information furnished by you, we have been able to stop the trapping and transportation from California, and have stopped sales throughout the United States.'"

About this time, the Audubon Society, tardily roused by Fleischer's call to action, sent their own team to New York area pet stores. The birdcages, they discovered, were empty of *Carpodacus mexicanus*. And when an undercover agent expressed an interest in acquiring house finches, he was told there had been some legal trouble, though for the right price, he might still get some—only they'd have to be sold as purple finches, which weren't listed in a certain treaty with Mexico.

It seems quite likely, then, that the worthy efforts of Dr. Edward Fleisher, of Brooklyn, not only put a deep dent in the transcontinental shipment of protected American passerines, but also prompted a number of worried pet-store owners to release their flocks of *Carpodacus mexicanus* in the vicinity of Long Island, N.Y.—an ecological experiment that would have unexpectedly far-reaching and long-lasting reverberations.

As for that little inconsistency in the story—if the birds had come from California, why were they dusky, like the subspecies in Denver?—it was resolved a few years later, when a curator at the American Museum of Natural History washed one of his specimens and discovered that it was actually quite pale. Life in New York had sooted the house finches.

3.

EVENTUALLY, VERONICA FOUND ME by the muffin bin, watching a small bird forage for crumbs.

"Oh, that's right," her voice said, behind me, "you were supposed to go to the bakery, to look for birds."

At first I tried to explain: *Why the interest?* the bird had seemed to ask, but of course it was my own question, not his—

"Pharmacy?" Veronica said, and for the next hour, I forgot all about the house finch. But later, staring blankly at propagating waves of brakelights—5 p.m. on the I-5—or examining, in my boredom, the tub of red licorice, which we had ended up wedging under the windshield, since it had proved a maddening remainder of otherwise perfect packing, I thought again of the bird and the question it had provoked: Why treat Costco as a swirl of unwanted distractions, whereas a little grey bird instantly receives rapt attention? Or to phrase it, frankly, as more of an indictment: Why can't I enter Costco with the same sort of curiosity I would bring to a forest full of birds? Why can't I, for instance, pick a product off the shelf and try to understand its origin and design, or the challenge of its manufacture, or the meaning of its widespread appeal?

Veronica was on her phone, resolving some complication with tomorrow's border-crossing, so I settled into the numb rhythms of driving and began to puzzle over Costco on my own. Was there, I wondered, a real difference? Some critical distinction that made a warehouse of stuff less rewarding to investigate than a forest of birds? What occurred to me first was that the distinction might lie in ecology, for if Costco is viewed as a kind of foodweb, it exhibits drastic simplification, with all those thousands of products going straight to a single top consumer. In contrast, the forest's ecological network is reticulate and integrated, with each organism affecting many others. So maybe that's what makes the forest feel whole and coherent, whereas Costco gives you that fragmented, centrifugal feeling—too much stuff for you alone.

And yet, if one thinks just a bit less literally, ecological links do begin to appear, tracing their way throughout the warehouse. Certainly there is something like ecological competition (Powerbar versus Luna), as well as symbiosis (DVDs and red licorice). If one were keen about discerning cultural or symbolic relationships between otherwise disparate items—Barbie dolls and treadmills, for instance—then surely the warehouse's ecological network would light up like a cobweb in the sun. And finally, to suggest that Costco lacks real ecology is to ignore a point of history: Early ecological thinkers, including Charles Darwin himself, found their most instructive metaphors in Adam Smith's theories of the free market. If Darwin saw ecosystems as economies, it ought to be possible to invert the metaphor.

Ecology, then, was not going to offer the meaningful difference I was after. But every other distinction I tried—evolved versus designed, natural versus manufactured—failed just as soundly to vindicate my disposition toward the warehouse. At that point, I began to feel a bit like a detective whose investigation is steadily gathering clues that point unmistakably to himself: what made Costco less interesting than a forest was not Costco, or the forest, but me.

But what was my problem? Why couldn't I get excited about Costco?

Ignorance, probably. If I knew a bit more—some engineering, maybe, or economics—then surely I could approach Costco with real focus and interest. I remembered, for instance, what Primo Levi, the Italian chemist and writer, could find inside an ordinary can of housepaint: a mini-drama of molecular affinities; a distillation of professional success or failure; a gift to posterity or an ugly reminder of a chemist's incompetence. Just imagine, then, what he might have done with our bucket of synthetic licorice twists.

For five miles of traffic, I felt quite satisfied with my mea culpa: Costco could be truly engaging, if only I would follow the example of writers like Levi, who could read the manufactured world in such fascinating ways. But before I could make good my new resolution, it soured.

I remember exactly where it happened, because the street signs had something to do with it. We had just exited the highway and were now entering a vast residential development, where some friends had generously offered their home as base camp for gearing day. I was beginning to feel uneasy, wishing Veronica would get off the phone and remind me where to turn. Granted, I had driven to our friends' house many times before, but my sense of direction is exceptionally bad, which makes this sort of neighborhood—where the houses are all identical, the blocks self-similar—my own personal purgatory. That very morning, in fact, returning from a short errand, I had unwittingly parked in the driveway of a neighbor, and blithely walked into his house.

After that incident, I had memorized our five-digit street address, but now, in my involvement with the Costco problem, I'd missed my turn, or I thought so, anyway. Veronica was immersed in her conversation, so I was craning forward over the wheel, searching helplessly for any geographic cue. Irrationally, I sped up, then swung the truck around the next corner, looking up at the green street signs.

Rock Ridge, said one.

Tamarack, said the other.

And at that moment, I disavowed my recent resolution.

Each of us knows, from firsthand experience, that Costco is a small part of an increasingly widespread environment. A plexus of shopping malls, parking lots, and residential sprawl now extends for hundreds of miles around every American city. In many places, it actually is the city. Its consistency is both extensive and exact: the box stores and the goods on their shelves; the restaurants and the food on their plates; even the residential neighborhoods—it is all replicated, with astonishing fidelity, from one coast of the U.S. to the other. When I pulled into the wrong driveway, I could have been in Albuquerque or Schenectady.

The metaphor of cancerous tissue is loaded, but it is also precise in certain ways: In cancer, cells of a single variety replicate rapidly; they form a strangely homogenous tissue, because differentiation—the development of the distinctive properties that characterize mature, functional cells—is a relatively slow process, and cancer cells divide before they manage to differentiate. In fact, the less they differentiate, the more rapidly they tend to replicate, and soon they begin to invade and outcompete the various specific types of well-differentiated tissue.

In ecosystems and economies—just as in the body—differentiation takes time: Whether it is the biological evolution that makes the sage scrub of southern California different from that of western Australia, or the cultural development that makes San Diego taco shops different from Maine chowder shacks, the accumulation of local differences happens at a stately pace. But when that stereotyped plexus of malls and sprawl moves in, all the singular places give way to one single place.

At the corner of Rock Ridge and Tamarack, I saw a signpost of the problem. Developers often name their new neighborhoods and streets after what was there before the development. Near my hometown of Boulder, Colo., for instance, there is a mile of replicated townhouses called Rock Creek, and I can testify, from childhood experience, that once upon a time there was indeed a lovely creek in exactly that location. I suspect that, similarly, on a certain hillside north of San Diego, there was once an actual and particular rock ridge.

Tamarack, on the other hand, does not memorialize a tree that once stood on that same hillside. Of this we can be sure, because the tamarack is a cold-weather tree, which grows around the Great Lakes and northward into Canada. It is possible, however, that the street sign in San Diego does in fact hearken back to a particular tree somewhere—in Minnesota, say—because developers have, on occasion, constructed virtually identical subdivisions in multiple locations. Perhaps, then, somewhere in the native range of the tamarack, there is a corner, marked by a pair of street signs, identical to the one in San Diego, only there, it is the word Tamarack that marks the site of a towering tree now gone, while Rock Ridge refers to a place thousands of miles away. Whether or not such a duplicate really exists, the juxtaposition of those disparate landmarks struck me as a concise testament to the erosion of geography, the end of distinctions between one place and another in the new American landscape.

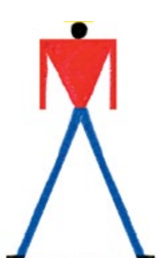
So maybe Costco is just as fascinating, or wondrous, or even, in its own way, just as beautiful as any other setting in which we might immerse ourselves. At least, we could find a perspective that would make it so. But what I decided, as I turned the corner at Tamarack and Rock Ridge and found myself lost in a familiar neighborhood, was that I would not try to find that perspective. In fact, I would resist it, because we are now in the process of trading our entire library of unique volumes for so many copies of the selfsame text. And the exchange seems not just foolish, but tragic.

4.

TWELVE YEARS AFTER HIS column in the *Daily Review-Star* announced house finches in Nassau County, Elliott published this diagnosis: "The future prospects of the species in this region seem favorable; it would appear that this adaptable and colorful bird is a securely established resident of the Eastern United States." To a modern ecologist, such delight at the establishment of an exotic species seems awfully innocent, because we have since come to understand that biological invaders—even colorful ones; even those that seem, at first, basically harmless—often lead to unforeseen and grave ecological consequences.

A handful of examples will illustrate how Elliott's warm hospitality has given way to our current xenophobia. Although this small sample may shortly come to feel like a litany of modern blights and scourges, my intention is not to flagellate us until we achieve Job-like understanding of the bad things nature has to offer. My hope, rather, is that this sample will provide some evidence for more general questions about what biological invasions are, how their unstoppable march might work, and even, perhaps, what they've got to do with that other sort of advancing front, the one I contemplated in a suburb of San Diego.

The female brown-headed cowbird is a bit smaller than a robin, rather drab, and quiet. Whenever I see her hopping around a lawn with a flock of other birds, the image called to mind is that of a shadowy spy, her



brown overcoat wrapped tight, her gaze askance and ever-watchful. What she's looking for is a bird gathering twigs for a nest. And when she catches sight of such activity, she'll trail the expectant parent to the new home and begin surveillance. Then, when the mark steps out, she'll swoop in and deposit an egg of her own. If there happen to be eggs there already, she'll make a meal of one, ensuring that when the parents return, the number of eggs in the nest won't betray the intrusion.

This final effort at disguise seems a bit preposterous—like a bad fake moustache—because the cowbird's egg is likely to be several times larger and a markedly different color than the rest of the clutch. Cowbirds can't possibly lay eggs that mimic those of their victims, because their victims are so varied, ranging from miniscule gnatcatchers to hefty meadowlarks. And yet, strangely enough, the ruse usually works: the parents carry on incubating the misfit as if nothing at all were wrong, and then, when it hatches, they feed it even more than its siblings, because it is precociously large and forever hungry.

A few bird species are canny enough to foil the con. Robins, for instance, will chuck out the cowbird egg nine times out of 10. And there's an interesting pattern here: It's not just a random one in 10 couples who happen to be gullible; it's couples from particular places—the places that have not yet been invaded by cowbirds. The perspicacity to spot an anomalous egg, therefore, appears to be a mental trait that has evolved in response to the danger of cowbirds. And this helps explain why cowbirds are such effective invaders: whenever they land somewhere new, the locals are defenseless against them. Consequently, quite a few little birds that nest in the U.S. are presently foster-parenting their way into oblivion.

There is something particularly grotesque about the way cowbirds invade—the deceit of it; the perversity of tiny yellow warblers struggling to feed their gargantuan brown chick—but other, less graphic stories of invasion will also prove instructive. Across the desert Southwest, the Asian salt cedar, a scraggly tree with glaucous needles, was originally planted to provide a bit of shade. But salt cedars, it turns out, have an irrepressible tendency to take over: they not only suck water with unrivaled verve, but also deposit salt in the soil, poisoning every other plant in the vicinity. The invasive trees have now conquered every waterway in the desert Southwest, and what were once diverse forests of cottonwood and willow are now dense thickets of salt cedar.

Another invader, a little weed now spreading across the American west, deploys a scorched-earth strategy of its own. Eurasian cheatgrass looks innocuous—a thin stalk bends elegantly under the weight of a loose cluster of slender, tufted seeds—but come summertime, the pretty little plume becomes highly combustible, inviting wildfire. And when the blaze rolls through, it destroys most plant life, but the cheatgrass seeds are fire-resistant: the following spring, they sprout from soil enriched with the ashes of their erstwhile competitors. In the century since cheatgrass arrived in North America, it has blanketed 100 million acres.

Just a couple more examples before we reckon with the problem in more general terms. In 1955, a colonial Ugandan administrator surreptitiously slipped a bucket of Nile perch into the waters of Lake Victoria, the largest tropical lake in the world. Scientists at the East African Fisheries Research Organization had expressly forbidden such a move, fearing that the predatory perch could have unforeseen effects on Lake Victoria's extraordinary biodiversity. At first, it appeared the scientists had been wrong: The exotic predator established a local population, but nothing catastrophic came to pass. In the late '70s, however, the perch began to proliferate, and over the next ten years, they ate their way through 200 species of fish found nowhere else in the world.

Finally, our litany should not omit the invaders that are less exotic to us but no less successful in expanding their range: Across the world's oceans, island after island has yielded to rats, mice, rabbits, house cats, goats, pigs, and other feral domestic animals. Rats and cats eat the island-nesting birds; rabbits and mice eat indigenous plants that would otherwise feed native herbivores; and goats and swine denude whole islands. This process began in the 14th century, when Europeans first reached the Azores, the Madeiras, and the Canaries, and it has continued ever since. All in all, the proliferation of European pests and domestics on previously isolated oceanic isles has annihilated dozens of species of reptiles and mammals, and at least 100 species of birds.

5.

NOW, WITH OUR MIXED bag of invaders in hand, we can ask the more general question such variety seems to beg: If all these species are invasive, what really is an invasive species? What unites these powerful few and equips them to drive native inhabitants over the cliff of extinction? To answer this question would be to solve the problem of invasive species—not just intellectually, but practically, as well, because if we knew in advance which species might turn malignant, we could nip their incipient invasions in the bud.

In certain respects, however, this general question—what makes a species invasive?—defies a general answer. In different groups of organisms, different attributes are associated with a penchant for invasion. Among insects, for example, invasive species tend to be small, while among vertebrates, they tend to be big. Among pine trees, invasives tend to have small seeds, while in another group of plants, the invaders have big seeds. Such trends, confined to certain groups of organisms, are not without meaning, and in some cases they make a lot of sense: invasive birds often lay multiple clutches in a single season; invasive trees are likely to reproduce by sending out runners that sprout lots of new individuals. But even within such delimited groups, some invasives don't fit the expected description, and many species that do fit the description never turn invasive. The trends, therefore, don't tell us with sufficient specificity whom we need to monitor.

The fundamental difficulty is that invasions depend on the details of natural history. Cowbirds are invasive in part because other birds happen to be dimwitted about the color of their own eggs. Salt-cedars are invasive in part because no herbivores in the desert Southwest will eat them. And there are a thousand other peculiarities of natural history which, were they a bit different, would drastically alter the outcome of cowbird or salt-cedar invasion. In short, invasions are essentially accidents of fit between an organism and its new ecosystem. Consequently, the only way we can know for sure whether an organism will thrive in a new habitat is to see the experiment run its course—and by then it's too late.

And yet, before we despair of moving beyond our bag of anecdotes, we should remember that there is another process—in fact, a well-understood one—in which outcomes depend on the details of natural history, and thus lie beyond the reach of our predictive abilities. We cannot foretell which novel mutation will help, rather than hurt, the individual who happens to possess it, because every mutation's effects will depend not only on the attributes of its possessor, but also on the nature of other organisms in the neighborhood. (Imagine, for instance, a mutation that makes a songbird feel murderous toward anomalous eggs; in the presence of cowbirds, the mutation is certainly beneficial, but without cowbirds, it's useless at best, and might even cause some accidental ejections.) Perhaps it is not surprising, then, that invasions and evolution by natural selection are intelligible in much the same fashion: They are comprehensible in retrospect, but very difficult to predict. On a case-by-case basis, they make a detailed sort of sense, but they are hard to speak of in terms of generalizations.

Charles Darwin, who cracked the mystery of evolution, was very good at finding general rules amid the riot of idiosyncrasies, so we might ask how he thought about biological invasions. In characteristic fashion, he approached the question historically, with a view to origins. That is, he didn't even try to find the attributes common to all invasives, but instead rearranged the question a bit. He asked not what makes a species invasive, but instead what makes an invasive species. In other words, what place or process produces these organisms that overrun all others?

The most effective competitors, Darwin figured, must be crafted in the most inventive and exacting workshops of evolution. But where are those? Natural selection, he reasoned, has two crucial limitations. First, it can work only on existing variation. Or to use a more modern phrase, selection can favor mutations, but it cannot generate them. And therefore, invasives must come from very large populations: the more individuals there are to mutate, the more new mutations will arise, and the more raw material natural selection will have to work with.

The second crucial limitation of natural selection is that it can only adapt a population to existing circumstances; it cannot work with an eye to the future. And so, Darwin figured, in the course of their own evolution, invasives must have faced many other organisms: the more challenges a certain species has confronted, the more solutions natural selection will have discovered.

Finally, Darwin thought, large populations contending with great biodiversity can only occur where there is a vast continuous tract of habitat to support all the interacting organisms. So while small, isolated islands have produced many exotic new species, the really tough critters—essentially, the ones made to win—must have been crafted and tested in the setting of large continents. "In accordance with this view," Darwin concluded, "we can, perhaps, understand some facts… for instance, the fact of the productions of the smaller continent of Australia now yielding before those of the larger Europaeo-Asiatic area. Thus also, it is that continental productions have everywhere become so largely naturalised on islands."

We are now in the second wave of global invasions: Widespread human and cultural expansions are now leading the way for a variety of species that follow in their wake.

6.

IT'S HARD NOT TO hear in Darwin's conclusion an ominous reference to European colonialism. But do the different sorts of invasion—the human versus the non-human, the cultural versus the biological—really have anything to do with one another?

We can, I think, find certain parallels. The plexus of malls and residential sprawl, for instance, expands by a kind of positive feedback: the more it dominates a particular place, the less distinctive that place becomes; and the less distinctive the place becomes, the more easily large corporations—the multi-national chains and home builders—can market their single, stereotyped way of life. On reflection, this does sound a lot like cheatgrass and salt-cedar, which gradually alter the environment to make it suitable for nothing but more of themselves.

Also, in biological and cultural arenas alike, the process that generates local differences is dilatory relative to the pace of invasion, and this discrepancy helps to explain why the local variety so often loses: the same stately process that creates diversity is also the primary—and fatally slow—means by which local residents can devise adaptations to the invader. Kirtland's warblers will almost surely go extinct before they evolve the robin's defensive attitude toward the cowbird's eggs. Although cultural evolution is a lot faster than the biological kind, it is but a crawl in comparison with racing invaders.

And finally, there seems to be an economic analog of Darwin's theory about the creation of invaders: the fiercest economic competitors, the invaders-to-be, seem to emerge from the largest economy, the hotbed of competition, and to spread out across the globe, displacing the productions of smaller economic systems.

So yes, there are parallels, and they may even be illuminating. But we should not forget something else we learned from Darwin just a moment ago, when we tried in vain to define what exactly makes organisms invasive: In the face of endless variety, it may be more productive to tell a story of what happened than to probe the essential nature of what is. Instead of trying to pry beneath the distinct forms of invasion, we could ask about their interplay through history.

Here's a hypothesis: Over the last half-millennium or so, the different sorts of invader have changed places on the colonial frontier. In the first wave of global invasions, various species other than humans led the way across the islands and continents of the world. These species were effectively an advance guard that drove back the natives and set up camp in the newly claimed territories. Meanwhile, human invaders marched mainly in the rearguard, securing and settling the conquered lands. By contrast, we are now in the second wave of global invasions: Widespread human and cultural expansions are now leading the way for a variety of species that follow in their wake.

Evidence concerning the first wave comes mainly from environmental historians. When Europeans first sailed for the mid-Atlantic isles, and then for the

West Indies, North and South America, and finally, the South Pacific and Australia, the sailors carried with them what historian Alfred Crosby called a *portmanteau biota*—essentially, a partial ecology of Eurasian organisms, including plants, animals, and microbes. To reach the new lands, these species required human help, but once the ships hit the beachhead, the biological invaders marched out on their own, advancing well ahead of the humans who had brought them. Therefore, if we were to imagine the Europeans battling their way into the interior, where they could then establish outposts of European life—with crops, domestic animals, and even annoying pests—we would be quite mistaken.

The leaders of the biological invasion varied from one place to another: In the West Indies, pigs proliferated, while on the Pampa, it was horses and cattle; in New England, white clover and even peach trees invaded like weeds, while in Peru, it was turnips and mint. Generally speaking, however, the biological invasions followed a pattern. When Europeans landed, they unloaded a goodly part of Old McDonald's farm: goats, sheep, pigs, cattle, horses, and fowl. Sometimes, animals were released intentionally, but more often, a few simply got away. Similarly, crops might be sown, but this wasn't necessary to initiate botanical invasions, because the livestock's feces and muddy feet carried plenty of seeds. If the sailors made contact with Native Americans, pathogens—most notably, smallpox—were transmitted.

The Europeans then departed, or perhaps tarried by the coast. But the other organisms were less patient. With their first Native American hosts, pathogens traveled back to settlements, where they wiped out half the humans, sometimes more. Livestock populations increased exponentially, and Eurasian botanicals overgrew their native competitors. So when the Europeans finally returned, or elected to extend their frontier, they walked into a landscape that had already been subdued and familiarized. Their pests and pestilence had laid waste to their enemies; their crops and livestock had founded their farms.

Certain Native American tribes recognized as much, for they viewed biological invaders as grim harbingers of the humans following behind. St. Jean de Crevecoeur wrote that when the Indians saw honeybees, which they knew to be a European import, "news of this event, passing from mouth to mouth, spreads sadness and consternation in all minds." And news, of course, was not the only thing passing from mouth to mouth. Smallpox was spreading like a rumor.

Sometimes, the non-human invasion moved so far ahead of the human one that the link between them was lost on European observers. Bartolomé de Las Casas, a friar who arrived in the West Indies just 10 years after Columbus, asserted that a variety of European plants were already in the islands when the Spanish arrived. He was wrong, of course. Those plants had come on Spanish ships. But their spread across the landscape had been so swift that Las Casas, arriving a decade later, could only presume they'd been there all along. A similar confusion attached the name Kentucky bluegrass to a species that in fact came from England.

For me, what is poignant about such confusion is that it pushes back, by hundreds of years, the date of onset of our culture's acute amnesia about landscape. We imagine the wildest place we know—a place from childhood, perhaps; or from an expedition we took; or even from a nature show on TV—and we take that place to be Wilderness, Nature, a landscape undiminished. But again and again, we are mistaken. This is how Thoreau put it:

> I take infinite pains to know all the phenomena of the spring, for instance, thinking that I have here the entire poem, and then, to my chagrin, I hear that it is but an imperfect copy that I possess and have read, that my ancestors had torn out many of the first leaves and grandest passages...

And now it appears that even Thoreau's ancestors—and their ancestors before them—never read the whole poem, because the American landscape was Europeanized even before Europeans laid eyes on it. In the first wave of invasions, biological invaders—microbes, plants, and animals—transformed ecosystems all over the world, and European humans, coming along behind, moved into turnkey continents.

7.

BUT THE ORDER HAS shifted: In the second wave of global invasions, the human rearguard has moved to the front, and a motley troop of species follows behind, inserting themselves into newly transformed landscapes. Evidence for this half of the hypothesis comes mainly from studies of invasive species, so here we can turn to the varied sample we gathered up earlier.

The brown-headed cowbird, sneaky bane of naïve warblers, did not in fact launch its expansion across North America until European settlers began to carve forests into a patchwork of fields. The cowbird

By 1997, the disease had spread through the entire eastern range of the house finch, and had killed 225 million birds.

prospers in this landscape, and it followed the advancing front of settlement into every corner of the continent now losing its native avifauna. Salt-cedar, too, is thriving on ground that humans have primed for its arrival. The damming of virtually every major waterway in the western U.S. has had important ecological effects: underground watertables have dropped; soil salinity has risen; and seasonal floods no longer occur. All of this, together, has greatly facilitated the expansion of salt-cedars.

But what about Nile perch? What could humans possibly do to facilitate an invasion transpiring entirely underwater? Between 1955, when the perch was secretly released, and the late '70s, when the species began to explode, cutting of forests and fertilization of crops around Lake Victoria greatly accelerated a process that had been underway since the '20s: the lake was filling up with biotic muck. The diverse flock of native fish, having evolved in a clear lake, struggled under the new conditions. Deprived of visual cues for species-discrimination, species started interbreeding rather haphazardly, eroding certain characteristics that had formerly distinguished them. And the veils of algae may also have tipped the balance in favor of Nile perch, which is well-adapted to dusky conditions. The evidence suggests that, even underwater, humans can usher along biological invasion.

Still, we should not make our sweeping story too tidy. There is, of course, no stark line in history, before which the invading ranks held exclusively to one arrangement, and since which their order has been wholly reversed. Certain species have played both roles—frontline as well as rearguard—and thus blend one stage of invasion into the next. Take rats, for instance. They certainly advanced ahead of the Europeans, and even helped subdue New World peoples by eating through food stores and spreading bubonic plague. And yet, rats also bring up the rear, breeding with special abandon in Europeanized landscapes.

Another important complication in the tale of two stages is that certain species have lately been ushered not only by humans and their newfound habits of land-use, but also by other non-human invaders. Cheatgrass, the pyromaniac weed, is an example. Humans help cheatgrass, because they often start the fires that reduce native competitors to fertilizer. But cattle are implicated, too, since overgrazed rangeland is often colonized by cheatgrass. And if we are no longer thinking of cattle as extensions of European settlers, but rather as biological invaders in their own right—they did, after all, march ahead of their humans—then cheatgrass has been led into its new territory not only by human activity, but also by another invasive species.

Invasion upon invasion brings us, in a sense, full circle. As house finches advanced across the splendidly suburban landscapes of the Eastern United States, from Long Island tree nurseries to farms in the Midwest, they encountered something they hadn't seen much in their native deserts: warehouses packed with poultry. This must be where a very unlucky finch first contracted a very lucky mutant of *Mycoplasma gallisepticum*, an eye infection that had long pestered chickens, but had never made the leap to wild songbirds. The disease hit the house finches hard: whereas chickens often recovered, finches usually died. And the infection spread through the finch population even faster than the finches had spread across the U.S. The first case of *Mycoplasma* in a house finch was diagnosed in Maryland, in January of 1994. By 1997, the disease had spread through the entire eastern range of the house finch, and had killed 225 million birds.

The Great Plains, you'll recall, had always seemed an impassable barrier for house finches. But *Mycoplasma gallisepticum* soon revealed that suburban expansion had spanned the gap. In April of 2002, the disease appeared in Missoula, Mo. To quote the paper that announced this finding: "As native house finches are highly susceptible to this novel pathogen, western populations may now be at risk of high mortality, similar to that experienced by non-native eastern populations." It is also likely that the infection will now jump from house finches to other native songbirds, including many species that are already endangered.

8.

EARLIER, WE FOLLOWED DARWIN in setting aside questions of essence, what makes for invasiveness, in favor of an account of history. But Darwin knew, I think, from his own work on the origin of life and diversity, that when history is traced deep enough in time it may, in the end, reach beneath questions of essence. Come back, then, to this question: When European plants, animals, and microbes led their human companions across the globe, why were those species so wildly successful?

For the microbes, the answer is straightforward. A virulent pathogen can persist in a population only by finding new susceptible hosts as frequently as its old hosts die or recover. As a rule, this can take place only in populations that are sufficiently large. (Think of it this way: a population of a million produces babies, which are new susceptible hosts, a thousand times faster than a population of a thousand.) Australia and the oceanic islands simply weren't populous enough to sponsor the evolution and maintenance of their own nasty microbes. And while there were indeed populations of the requisite size in the Americas, they were descended from much smaller groups that had crossed the Bering Strait within the last 20,000 years. All over the world, then, Eurasian emigrants had enjoyed millennia-long respites from disease, but this same blessing left them immunologically naïve, and therefore utterly vulnerable when European microbes finally arrived.

But what about the plants and animals? Why did European species dominate native ones from the Azores to the Americas? On the oceanic isles, Darwin's idea about area applies: in comparison with the Azores, the West Indies, or even New Zealand, Eurasia is vast, and this territorial advantage translated into the evolution of better-honed competitors. But what about the other continents? Eurasia does comprise the broadest span of terrestrial habitat on earth, but still, the sweeping success of Eurasian invaders seems entirely out of proportion with the territorial advantage that Eurasia has over the other continents. There must, it seems, be more to the story.

The archaeological record in North America shows that *Homo sapiens* arrived and spread across much of the continent between 10 and 15 thousand years ago. It also shows that, around the same time, more than 30 genera of large mammals went extinct: woolly mammoths and saber-tooth tigers; scimitar lions and short-faced bears; giant ground sloths and New World camels—all of them, gone from the fossil record just about when garbage piles from hunter-gatherers start showing up.

The methods used to date 10,000-year-old archaeological sites have a margin of error of about 1,000 years.

This wiggle-room probably explains why humans seem to appear in Patagonia a bit before they do in North America, even though they had to travel farther from the Bering Strait land bridge to get there. And in this very same window of apparent simultaneity, 50 genera of large mammals disappear from South America's fossil record.

Humans arrived in Australia earlier than the Americas—about 50,000 years ago—and you're probably now anticipating what comes next: At about the same time—the margin of error that far back is more like 10,000 years—21 genera of large Australian mammals laid down their last fossils.

At first, the suggestion seems preposterous: Bands of Paleolithic humans drove lions, tigers, mammoths, camels, and bears into extinction? Yet there seems no real alternative. For a while, researchers considered climate change. And indeed it seems likely that the end of the last ice age, which came about 11,000 years ago, conspired in some extinctions. But only conspired, for there were previous shifts of similar magnitude, and they did not have the same cataclysmic effects. What's more, the climatic changes in South America were mild by comparison, but that continent lost even more mammals. And there is no indication of exceptional climate transition in the regions and times of most of the Australian extinctions.

To overcome our incredulity—cavemen wiped out lions?—we can at least remind ourselves of a few helpful details. First, besides their stone spears and axes, human beings wielded fire. They could have moved large numbers of animals by starting wildfires, which would have had the additional impact of depriving herbivores of forage. Second, the humans did not have to hunt the predators into oblivion; destruction of their only prey, the large herbivores, would have done the job. And third, animals that have evolved in isolation from humans may be especially vulnerable to them. This last point is often raised to explain why the mammals of Africa and Eurasia largely escaped mass extinction: They had lived around hominids continuously, allowing them to evolve the fear and instinctual defenses they needed to contend with a uniquely intelligent predator.

Skip forward again now, to European livestock arriving on the shores of new continents. The landscapes they entered were idyllically free of predators and competitors: no scimitar lions or short-faced bears to hunt the European species; and no camels or ground sloths to vie for the tastiest herbage. No wonder, then, that the pigs, goats, cattle, and so forth expanded exponentially. Meanwhile, the European weeds that travelled with the livestock had the advantage of being well-adapted to the animals they accompanied. "Kentucky" bluegrass, for instance, was adapted to the grazing of English sheep and cattle. By contrast, the native competitors of bluegrass had evolved in the absence of large grazers for at least 10,000 years, and were therefore less prepared for their impacts.

These facts have important implications for our account of invasion. Looking at the last half-millennium, the tale of two waves holds true: first, biological invaders led European humans across the globe; later, as roles shifted, human and cultural expansions led biological species. But if we look much deeper into the past, we see that the global wave we called the first was in truth made possible by one that had already transpired 10,000 years before. In a sense, the story becomes simpler: It was humans out front all along.

I confess that when I began this essay—and even when I sketched the waves of invasion—I envisioned pre-Columbian America as a final redoubt of pristine nature. I imagined the Adirondack glade plump with deer and turkey, ennobled by the presence of grizzlies and wolves, and I thought, now that—that was really nature. But in this fantasy of wilderness, I was submerged in our age-old amnesia concerning the natural world, our cycle of reduction followed by forgetting. For those places were anything but pristine. Their first leaves and grandest passages had been torn out long ago, because it was not sometime in the last few hundred years that humans became the prime movers in biological invasion. It was thousands of years ago, when we exterminated the fauna of three continents, and thus paved the way, millennia in advance, for the massive expansion of Europe.

9.

TWO HOURS DOWN THE peninsula, where the highway edges steep hillsides of chamise and agave, San Diego and Tijuana seem already far away. To our right, over the Pacific, a thick layer of clouds is just now tearing into tatters, striating the ocean below with bright silver and dark blue. Veronica veers that way now, off the highway and toward the ocean, leading our caravan of three SUVs bumping along a potholed road atop a jutting headland, at the tip of which perches an abandoned touristic complex. The place looks like a decaying Moorish palace, complete with ogive windows, onion-shaped domes, and minarettes. And while Alhambra may seem strangely out of place here on the cliffs of Baja California, fantasies of the exotic East have swirled around this peninsula for 500 years. In fact, the very word "California" was born in a 15th-century Spanish novel, as a fantastic eastern isle:

> Know that to the right hand of the Indies was an island called California, very near to the region of the Terrestrial Paradise, which was populated by black women, without there being any men among them, and almost like the Amazons was their style of living.

When Hernán Cortés first sailed for Baja California, having just blazed through Mexico under the escort of a variety of European species, he believed he was sailing for an island, a place disconnected from the world he had conquered. He thought he might find oysters bearing pearls of a sort never seen by Europeans, and perhaps even women, black women, who lived there without men. He was, in other words, pursuing his own preposterous fantasy of the untamed and untainted wild.

Twenty miles further down the highway, in the port town of Ensenada, we pass a shopping mall that was not here last summer. There is a box store called Smart & Final, another called Bed Bath & Beyond, and, a bit further on, a Costco. To provide some shade for a pavilion out front, a resourceful landscaper has planted a row of Asian salt-cedar.

Is it quixotic, in the end, to resist this process that has been underway for millenia, this advance of human invaders and their ecological collaborators? Is it ludicrous to mourn the loss of the local, the distinctive, the diverse, when the march of victors seems all but inevitable? Is such a posture of bereavement perhaps even fraudulent? After all, I myself partake of the fruits of victory. And, what is more, fantasies of a remote, undiscovered, and exotic land—visions of the New World not entirely unlike those I have caught myself entertaining—played no small part in driving the march of Hernán Cortés himself. Shouldn't such hints of hypocrisy give one pause?

Bartolomé de Las Casas, that Spanish friar who arrived in the Indies and reported wild proliferation of European species, went on to become a passionate defender of New World peoples, decrying the conquistadors' extravagant violence, their destruction of civilizations, and their scorching of the earth. It is safe to say Las Casas viewed the New World with far more interest and openness than did his nemesis, Cortés. And yet, Las Casas, too, harbored fantasies of a pristine and unspoiled land: he conceived of New World natives as Innocents from Hesiod's Golden Age, or as close kin to naked Adam and Eve. He was also guilty of certain hypocrisies: he had owned an estate and native slaves in Hispaniola. And ultimately, of course, his campaign was waged in vain: it is to the Sea of Cortez that we are now driving. But in spite of all this—the illusions, the hypocrisy, even the inevitable futility—we head for that sea hoping never to resemble its namesake.

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The Death and Life of the Frontier

A voyage to the limits of the knowable

BY CASPAR HENDERSON

WHERE DOES THE WORLD begin and where does it end? In many creation stories the Earth has well-defined edges. In early Mesopotamian mythology it is a flat disk floating in the ocean and surrounded by a circular sky. The Hopi people of northeastern Arizona envision it as a series of layered worlds, of which humans have emerged into the fourth tier, escaping from the turmoil below through a hollow reed in the Grand Canyon. The ancient Greeks were probably the first to light on the idea of the Earth as science understands it today: as a sphere, and therefore without an end point on its surface.

Through time, science and exploration have changed where frontiers lie and how those frontiers are imagined. Such inquiries have shown them to be tenuous and unstable. Frontiers share the qualities of both a boundary and a threshold: they at once define, delineate, and exclude, but also act as permeable borders through which one may pass into a strange country and be transformed by the experience, or through which the unknown passes into the realm of the familiar.

ILLUSTRATION BY JASON HOLLEY

The Greeks obtained much of their evidence for the theory of a spherical earth from observing the heavens. The Earth, noted Aristotle, casts a circular shadow on the moon during a lunar eclipse, and constellations on the southern horizon rise in the sky as you travel south. But at least one line of reasoning followed from a hard slog on the ground, even if its logical foundations were shakier. Elephants were a prized weapon of war in Alexander the Great's conquest of the Persian Empire. In Egypt, his successors went to enormous pains to import them from parts of Africa, far to the south and west. If there were elephants to the east and elephants to the south and west, and the north was icebound, the Greeks reasoned, didn't that show that the Earth was elephants all the way round?

Seeing the Earth as round rather than as flat, or in some other form, affected the Greeks' perception of frontiers. At that expansive phase of their history, distant lands might be unknown but they were not necessarily beyond reach. There were no restrictions on how far men might travel, only the limitations that they imposed on their own endeavors—a notion that has persisted in the West for most of the last 500 years. Today, with the Earth mapped, imaged and charted down to the last square foot, the frontier is supposedly in outer space: Mars, the moons of Jupiter, and beyond. But humans' power to transform themselves and their environment suggests that the most important contemporary frontiers lie in the realm of inner space, in the possibilities for conceptual and moral transformation. It is at these boundaries that our future will be decided.

EUROPEANS REDREW THE FRONTIERS of their world after the collapse of Greek and Roman civilization. This is not a figure of speech. They produced beautiful world maps, or *mappae mundi*, to represent a mythic and religious order circumscribed by God rather than by proto-scientific enquiry. The new vision lasted more than 1,000 years and can be seen today in a fine example from about 1300 A.D., kept at Hereford cathedral in England. The world, round but flat, is centered on the holy city of Jerusalem. Europe and the Mediterranean are distorted but just about recognizable to the modern eye. (East is at the top of the map.) In most of the rest of the map, especially the peripheries beyond land and sea where few Europeans had ventured, wonders dwell—strange beasts, hybrids, and men.

Intricate lettering on the map reveals the Lynx, a wolf-like creature that sees through walls and produces a valuable carbuncle in its secret parts. The Manticor, in India, has a lion's body, a scorpion's tail, a triple row of teeth in a man's face, and the voice of a Siren. Semi-humans such as the Phanesii, bat-like people with enormous drooping ears, live in Asia, as do the Spopodes, who have horses' feet. The king of the Agriophani Ethiopes has one eye in his forehead, and his people feed on the flesh of panthers and lions. The Gangines of India live exclusively on the scent of forest apples and die instantly if they perceive any other smell. The Arimaspians fight with griffins for diamonds. Fully human but utterly foreign, and terrifying, are the Scythians: they love war, drink the blood of their enemies from the gushing wounds they inflict, and make cups from the skulls of the vanquished. The Hyperboreans, by contrast, are the happiest race of men. They live without quarreling and without sickness for as long as they like. Only when they are tired of living do they throw themselves from a prominent rock into the sea.

Like the books of beasts, called bestiaries, that were created in the same period, *mappae mundi* offered instruction and wonder to their viewers. They showed possibilities and alternatives beyond distant frontiers, but also warned of the terrors awaiting those who were overly curious. Wonder was permissible so long as one did not stray too far from revealed and unchanging doctrine. Curiosity had been condemned by St Augustine as *concupiscentia oculorum*—lust of the eyes.

In the 15th century, however, a revolution in thinking and behavior began to take root. In 1417 the scholar Poggio Bracciolini discovered a manuscript of *De Rerum Natura* by the Roman poet Lucretius, which propagated the explosive idea that everything is made of atoms (the one scientific idea, Richard Feynman later said, he would pick to survive the collapse of civilization). The revival of ancient knowledge, combined with new reports from adventurous travelers, contributed to a growing sense of man's importance and potential.

The *Erdapfel*, or Earth apple, embodies this change. It is a terrestrial globe made in Nuremberg in 1492. In a particularly dramatic break with the medieval European past, and showing knowledge that the ancients never possessed, the *Erdapfel* features the entire African coast and the route around the Cape to the other side of the world, where the Portuguese monarchy, for whom the globe was made, hoped to find fabulous wealth. Gone are the fanciful creatures and races of men. The emphasis is on the practical—on showing navigable routes to the far East that would bypass the Islamic world.

Unless they fail to notice altogether—something that happens surprisingly often—most people who look at the *Erdapfel* today are struck by one thing: there is no North or South America. Sail west from Lisbon and your landfall is in Japan. But this and other inaccuracies, such as the distorted shape of the African continent, pale beside the confidence that the *Erdapfel* proclaims in the human capacity to reach any part of the world, no matter how remote, and to find prizes there for the taking.

There is a risk of over-romanticizing the age of discovery and the scientific revolution that followed. The empires of early modern Europe could be as cruel as any in history, and many leading figures in the emerging field of natural philosophy had little time for the sense of wonder that is palpable in medieval *mappae mundi*. Francis Bacon, who is widely regarded as the father of the scientific method, was dismissive of wonder, calling it "broken knowledge." His aim was the betterment of the condition of humanity, or—not quite the same thing—European adventurers. Results, not frills.

But the cumulative experience of the scientific age suggests that greater knowledge does not abolish wonder. Discoveries are often more amazing than the mysteries they resolve. They uncover depths that are more beautiful and far stranger than anything we had previously imagined, and motivate ever greater endeavors. They have expanded our sense of the possible, with breakthroughs that redraw not only the location of the frontier but also its significance.

THE GEOLOGISTS WHO DISINTERRED "deep time" at the turn of the 19th century illustrate the power of scientific discovery to precipitate profound conceptual shifts. Their analysis of rocks and fossils shone a light backwards into the dark, and revealed prehistory's almost unimaginably vast contours with precision.

Mappae mundi *offered instruction and wonder to their viewers. They showed possibilities and alternatives beyond distant frontiers.*

The inner lives of our fellow creatures offer a frontier of wonder and beauty to explore as wide and deep as the sea, and they change humanity's sense of its own borders.

For those accustomed to thinking of the world as only a few thousand years old, the discovery of "deep time" was shocking, like a swoop into stereoscopic vision for someone who has previously only seen in two dimensions and suddenly finds himself on a high promontory above a chasm. "The mind [grew] giddy by looking so far into the abyss of time," wrote John Playfair, a friend of the geological pioneer James Hutton, in 1788. The past, it became clear, was another country, or rather several. There had been periods lasting millions of years filled with monstrous creatures such as mososaurs (huge and ferocious marine reptiles) and pterosaurs (enormous flying lizards). The anatomist George Cuvier, who named both creatures, wrote in 1812 that he and his successors would "burst the limits of time" by making prehistory legible, just as astronomers had "burst the limits of space" by making the solar system knowable to human beings who were confined to one small planet.

Charles Darwin's theory of natural selection, first described in detail in his 1859 book *On the Origin of Species*, followed elegantly from the discovery of deep time. The English naturalist was not the first to argue that species evolved and changed, but every previous account had failed to provide a sufficiently detailed and robust explanation of how this happened, and orthodoxy remained on the side of the immutability of forms. Prehistoric monsters were interpreted as special creations of a different age. Darwin's insight was that small gradations over what were inconceivably long periods of time, at least to humans, could lead cumulatively to profound transformations that turned monsters into familiar animals.

Darwin's vision was of life as both astonishingly fecund and productive, and as a field of relentless war and destruction. But it was not, in the end, bleak. The *Origin* concludes, famously, with a declaration that there is grandeur in the view of life in which "from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved."

Darwin's theory indicated that, contrary to Christian teaching and 300 years of scientific orthodoxy, humanity was animal in origin and wholly continuous with (though not the same as) the rest of nature. It broke down boundary conditions accepted by most philosophers and scientists since Descartes. Not all of Darwin's contemporaries were receptive to this message, however. On seeing an orangutan named Jenny at the London Zoo in 1842, Queen Victoria declared it "frightful and painfully and disagreeably human." Cousin to half the crowned heads of Europe though she may have been, here was one frontier the young Queen was not willing to breach on grounds of consanguinity.

A FEW YEARS BEFORE Jenny received Victoria, Darwin had observed the more hirsute of the two in her cage, writing:

> Let man visit *Ouranoutang* in domestication, hear its expressive whine, see its intelligence when spoken to; as if it understands every word said; see its affection to those it knew; see its passion & rage, sulkiness, & very actions of despair; ... and then let him boast of his proud pre-eminence.

But the gulf between accepting humanity's biological proximity to other creatures, and appreciating their unique social, moral, and cognitive worlds, was not an easy one for Darwin's successors to bridge. When the zoologist Donald Griffin wrote in 1976 that biologists should investigate "the possibility that mental experiences occur in animals and have important impacts on their behaviors," it was still a radical suggestion. In the decades since, numerous studies have proven him right.

Many of the characteristics thought to be important for higher consciousness, such as brain size and a sense of self, turn out not to be unique to humans.

IMAGINING THE WORLD The Hereford *mappa mundi*.

THE MANTICOR As described in the Hereford *mappa mundi*, the Manticor has a lion's body, a scorpion's tail, a triple row of teeth in a man's face, and the voice of a Siren.

Last year, leading neuroscientists signed what they called "The Cambridge Declaration on Consciousness," stating that "humans are not unique in possessing the neurological substrates that generate consciousness. Non-human animals, including all [sic] mammals and birds, and many other creatures, including octopuses, also possess [them]." Working memory and episodic memory are widespread among animals, as are social inclinations born of environmental pressures that favor their evolution. The distinction between cognition and emotion is also increasingly seen as a false one. Crows and other members of the corvid family have self-awareness and a theory of mind. Octopuses can solve some problems as well as 3-year-old children, not to mention perform feats of dexterity far beyond the scope of humans. Chimpanzees grieve for non-related individuals, and records of their reactions to stimuli such as a majestic waterfall and the birth of a baby chimp suggest that they may be capable of a sense of wonder.

The inner lives of our fellow creatures offer a frontier of wonder and beauty to explore as wide and deep as the sea, and they change humanity's sense of its own borders. The animal kingdom is a symphony of mental activity and other intelligent processes of which we apprehend only a small part. Take bird song: what sounds to our ears like simple single notes resolve at slow speed and lower pitch into dense, subtle tone-poems.

DENTAL HYGIENE WAS NOT well advanced in 17th-century Holland. One trembles to think of the sight and smell that greeted Antonie van Leeuwenhoek when, in 1683, the cloth merchant and gentleman microscopist gazed into the mouths of two old men who had never cleaned their teeth in their lives. But his curiosity yielded astonishing results. Looking at samples taken from the men's mouths under his microscope, he found "an unbelievably great company of living animalcules, a-swimming more nimbly than any I had ever seen up to this time.... [A]ll the water. . . seemed to be alive."

Van Leeuwenhoek was, of course, describing bacteria. It was the first glimpse of a domain whose nature and importance scientists are, even now, only beginning to appreciate. For the first 300 years after their discovery, bacteria and other microorganisms were studied with a view to understanding their role as agents of disease and decay. Only in recent decades has a fuller, more nuanced picture emerged—one that challenges our sense of the frontiers between beings, and within the category of life itself.

The microbiologist Lynn Margulis was rejected by about 15 leading journals before her pathbreaking paper on symbiosis was published in 1967. She argued that the complex cells of protists, plants, and animals resulted from earlier and simpler organisms merging and cooperating. The ancestors of chloroplasts and mitochondria, the organelles in plants and animal cells that provide them energy, were once free-living bacteria that larger organisms then swallowed. But instead of becoming lunch, the bacteria took up residence, like Jonah in the belly of the whale. Unlike Jonah, however, they paid for their keep by performing a new role as 'batteries.'

Today the evidence for Margulis's theory of endosymbiosis, as it has become known, is overwhelming. The physician and essayist Lewis Thomas captured the essential point in an essay published in the 1970s, proposing "some biomythology." A bestiary for modern times, he argued, should be a micro-bestiary, since microbes teach us an essential lesson: "There is a tendency for living things to join up, establish linkages, live inside each other, return to earlier arrangements, get along whenever possible."

The implications of this insight are deeply personal. In the last decade, science has attempted to reckon with the power of the bacteria that live on us and, mostly, in us, in a miniature ecosystem known as the microbiome. It has been shown to play a role in digestion and immune response, and there is mounting evidence that the composition of the microbiome affects cognition and the risk of contracting illnesses like heart disease. The abundance of its constituents is astonishing: there may be around 500 trillion bacteria with us at any one time, outnumbering our own cells by 10 to 1. During a lifetime we excrete five elephants' weight of them.

Micro-organisms are, quite literally, part of our make-up. The human body is littered with scars from the viral attacks on cellular life that have been going on since at or near its beginning. Some 8 percent of our DNA is made up of remains of endogenous retroviruses that invaded us in the past. The ascendancy of the microbial domain and its coevolution with the human body raises the question of where the human ends and the microbe begins. A viral infection is thought likely to have given rise to the placenta in the ancestor of all mammals. Without it, we might still be laying eggs.

THE ABYSSAL PLAIN BENEATH much of the world's ocean is, at first sight, a dark, silty no-place. But it harbors 2.9×10^{29} single-celled organisms—10 million trillion for every human on the planet. Even the deepest trenches, 11,000 meters below the surface, teem with microbial life. At volcanic "black smokers" on the sea bed, in almost total darkness and scorching temperatures, chemosynthetic bacteria and archaea use hydrogen from the vents to support assemblages no fabulist could have dreamed of: gutless worms taller than men, crabs with hairy claws, and bleached octopuses that bear a striking resemblance to Marge Simpson.

Microbes have been found in stupendous abundance in the most unlikely of places. Tourists may be familiar with some of the spectacles that they create on land, such as the Grand Prismatic Spring in Yellowstone National Park, a round lake whose rainbow rim has been painted by heat-loving bacteria. Yet fewer know of the strange phenomena in the Antarctic interior, far inland from a frontier that is almost impenetrable to most multi-cellular life forms. At the Blood Falls in east Antarctica, sulfur- and iron-eating microbes buried in the oxygen-parched ice give the surface water a bright sanguine hue. Beneath the icy crust of Lake Untersee, to the north and west, cyanobacteria find enough light to photosynthesize and build

Life on these stars would have a very slow metabolism and rate of consciousness, taking 1,000 years to complete a single thought.

pinnacles and cones that may resemble some of the earliest forms of life on Earth. Moving to Antarctica's South Shetland Islands, below the tip of South America, bacteria living 15 meters beneath the permafrost have been found to be capable of surviving gamma-ray radiation exposures 5,000 times greater than any other known organism.

Such discoveries have recast our sense of where the frontiers congenial to life might lie—including those beyond Earth. The idea that we might find living things in space long predates the discovery of a microorganism such as *Halorubrum lacusprofundi*, whose adaptations to the cold are, in the words of one researcher, likely to allow it "to survive not only in Antarctica, but elsewhere in the universe." In the preface to the work that inspired van Leeuwenhoek, the *Micrographia* of 1665, Robert Hooke wrote "there may be yet invented several other helps for the eye, as much exceeding those already found, as those do the bare eye, such as by which we may perhaps be able to discover living Creatures in the Moon, or other Planets."

Technology may finally be catching up with Hooke's prediction. Recent observations indicate that there may be as many as 17 billion stars in the Milky Way galaxy which are orbited by Earth-sized planets at life-friendly temperatures. Within 10 years, the James Webb Space Telescope may be able to tell us if the atmospheres of those nearby exhibit the chemical signatures of a biosphere.

If extraterrestrial life does exist, how "weird" might it be? The adjective can be used in a semi-precise way to mean any life form with which, unlike everything we know of on Earth, we do not share a common ancestor. On the principle that life can evolve or endure where there is a flow of energy to be harvested, one of the most statistically likely places is in the vicinity of white dwarf stars—common enough objects in the universe—where collisions with dark matter will continue to provide a steady trickle of energy until the universe is 10^{25} years old, or about 10,000 trillion times long as it took life to appear on Earth. Life on these stars, if it were to exist, would have a very slow metabolism and rate of consciousness, taking 1,000 years to complete a single thought.

For the moment, we have a sample size of precisely one from which to draw conclusions. Seeking to anticipate just how different life might look, however, requires us to look again at what we think we know—and, often, realize just how little we understand so far. There is no such place as home, and we live there.

HERE AND NOW ON Earth, life itself may be facing a frontier unlike any other it has known before. The manipulation of organisms to forge "creatures born from an idea, not an ancestor," as an editorial in *Nature* put it just before the 200th anniversary of Darwin's birth, challenges the foundations of the distinction between organic and inorganic forms. Genomics and genetic engineering have made it possible to swap traits and capabilities between species, or insert them into newly created species, to spur adaptation at vastly quicker speeds that has ever been possible.

In 2010 a team headed by Hamilton Smith and Craig Venter announced, to much fanfare, that they had created life from scratch. The claim was not entirely as it seemed: What they had done was to make a copy of the genome of a pre-existing microbe, and put it inside the cell walls of another one. Their experiments are the most visible of those pointing the ways in which it might be possible to reprogram the code of life. An inventive riff on DNA and RNA molecules, known as "xenonucleic acid" or "XNA," can, it is claimed, carry genetic information and do all the things its organic counterparts can, and more. The physicist Freeman Dyson has dreamed of a future in which anyone and everyone is able to manipulate the building blocks of life, and a new generation of entrepreneurs and artists who will be "writing genomes as fluently as Blake and Byron wrote verses," making the planet "beautiful as well as fertile, hospitable to hummingbirds as well as to humans."

Whatever one thinks of the plausibility and desirability of Dyson's vision, the artists and inventors who are exploring this biological boundary herald a growing awareness of the fact that life's borders are shifting beneath us. Artistic collaborators Oron Catts and Ionat Zurr have made Guatemalan worry dolls out of "semi-living" human tissue. Dutch designer Joris Laarman has built a lamp illuminated by hamster cells modified with firefly DNA. Christian Bök, the Canadian poet, aims to engineer a life-form so that its genetic code becomes "not only a durable archive for storing a poem, but also an operant machine for writing" one, generating a protein-based "literary" product he calls the Xenotext.

Humans need not be exempt from this tinkering, although proposals to adapt our minds and bodies have proved controversial. Julian Savulescu, professor of practical ethics at Oxford University, advocates intervening chemically and neurologically to mold personalities into forms that are more conducive to civilization's survival. "Unless you believe that evolution provided just the perfect number of psychopaths in our community and just the right level of selfishness within different individuals," he writes, "you should believe that we should change that natural distribution for the better." Savulescu's detractors counter that the triggers for antisocial behavior lie in social and political conditions, and it is there that the interventions need to be made.

How far could this go? A recent report from the U.S. National Science Foundation suggests that by 2020, not only will we be fitter, happier, and more productive, but that people from all backgrounds and of all ranges of ability will "acquire valuable new knowledge and skills more reliably and quickly." By 2030, "fast, broadband interfaces between the human brain and machines will transform work in factories, control cars, and enable new sports, art forms, and modes of interaction between people." Most of us will probably welcome many of the foreseeable changes. Who would object to 100 or even 120 years of healthy, "augmented" life?

A HUMAN/POST-HUMAN FRONTIER MAY now be coming into view. Those who support the idea of "the singularity," the emergence of man-machine hybrids with vastly greater intelligence than our own, tend to believe that humanity will imminently and irreversibly cross that threshold. Nietzsche, for one, would be happy: "What is glorious in Man is that he is only a bridge." What is notable about the post-human frontier is that the very thing that keeps us on this side of the divide—our limited cognitive capacities—makes it impossible to know what lies beyond it once it is crossed. Perhaps the view would be different from the other side; perhaps it would not seem like a side at all, but rather the commencement of a history for which humanity is prehistory.

THE SCYTHIANS The Hereford *mappa mundi* describes the Scythians as a very violent, war-loving people who would drink the blood of their enemies and make drinking cups out of skulls.

THE LYNX According to the Hereford *mappa mundi* the lynx is a wolf-like creature that moves through walls and secretes a valuable black stone with magical properties.

For now, however, we have no choice but to live within the bounds of what our minds allow, limited by our ability to grasp the mathematics in which the universe appears to be written. In many respects, our frontiers as conscious individuals and as communities are and will remain extremely circumscribed. For all the miracle that is the brain, with each of its 85 billion neurons connected to an average 7,000 others and collectively performing several hundred trillion operations per second, our attention is necessarily finite. Vladimir Nabokov put it well:

> Reality is a very subjective affair. I can only define it as a kind of gradual accumulation of information: and as specialization... Take a lily[,]... more real to a naturalist than it is to an ordinary person. But it is still more real to a botanist. And yet another stage of reality is reached with the botanist who is a specialist in lilies. You can get nearer and nearer, so to speak, to reality but you never get near enough because reality is an infinite succession of steps, levels of perception, false bottoms, and hence unquenchable, unattainable. You can know more and more about one thing but you can never know everything about one thing...So we live surrounded by more or less ghostly objects.

Even our most precise conceptions of reality are only fleeting glimpses of what Richard Feynman called "the inconceivable nature of nature." But this can be a counsel of joy, not despair. Over time we can nurture a consciousness that is open to perception of the most beautiful and surprising patterns around us.

Preserving a capacity to appreciate wondrous phenomena, however, demands facing up to urgent ecological challenges, for which individual enhancement will not suffice. An enhanced jerk, after all, is still a jerk. At a time of proliferating discoveries and innovations, humanity's most important frontier is not scientific or geographic, but moral and political.

The concept of the Anthropocene, as many geologists now call the epoch in which we live, distills the dilemma. It proceeds from evidence that humans now exert a massive and decisive influence on the planet and its ecosystems, with consequences that will reach far into the future. People sometimes object to the term on the grounds that it suggests humans are in control. But influence is not the same as control. Humans are no more in control of the planet than a

Loss of biodiversity is a systemic phenomenon; focusing conservation efforts on residual pristine landscapes, protected areas behind artificial frontiers, treats the symptoms and not the causes.

heavy smoker is in control of his lungs.

The Anthropocene is likely to be a time of rapid and unpredictable environmental change. Rapid, because the conditions that underpin all life are changing faster than they ever have at any point over tens or even hundreds of millions of years. Unpredictable, because we struggle to foresee the likely consequences of these changes, and because we cannot be sure how people will react to them in the future. We don't know where some tipping points may be or, indeed, whether they will really unfold as models predict. Such future calamities are Rumsfeldian "unknown unknowns."

One way to get a handle on how things might go, however, is to look at times in the past when the Earth system has been subjected to considerable pressure. Paul Wignall, professor of palaeoenvironments at the University of Leeds, says that humans are adding greenhouse gases at a rate and for a duration that are similar to the massive burst of volcanic activity that kicked off the end of the Permian period some 252 million years ago. On that occasion, about nine-tenths of life on Earth was destroyed. The event has been called "The Great Dying" and it was the greatest catastrophe in the history of life. Ecosystems took more than 10 million years to recover afterwards, with a very different mix of plants and animals.

Today's world is very different, and disaster on such a scale is not inevitable. But there are other factors besides greenhouse gases to think about. The degradation and erosion of fertile soil, on which civilizations throughout history have depended, is a huge problem in many parts of the world. Toxics, plastics, and other man-made chemicals are likely to have damaging, long-term effects on human and animal health. In the global ocean—seven-tenths of the planet's surface and 90 percent of its habitable space—acidification, pollution, temperature rise, overfishing, and other stresses may, singly and in combination, prove highly destabilizing. Most scientists think a global mass extinction of species is already underway. Loss of biodiversity is a systemic phenomenon; focusing conservation efforts on residual pristine landscapes, protected areas behind artificial frontiers, treats the symptoms and not the causes.

Yet technological advances may open new ways to intervene and even to revive what has disappeared. The technical hurdles to recreating recently extinct animals, and even those that died out longer ago, such as the mammoth, have largely been solved. But de-extinction efforts raise more questions than they answer. However powerful our astonishment, delight, or horror at what may be technically feasible, we should not lose sight of the context in which such experiments, if they ever happen, will take place. Species only thrive in an appropriate environment, and individuals from highly social species need a pre-existing social group. "It's the ecology, stupid," might be an appropriate mantra for our times. Ignorance is unavoidable, but willful

"Reality is an infinite succession of steps, levels of perception, false bottoms, and hence unquenchable, unattainable." —Nabokov

ignorance and reluctance to perform careful experiments is not. As the physicist John Archibald Wheeler said, "our whole problem is to make the mistakes as fast as possible."

ONCE UPON A TIME the Earth really was elephants all the way around. Straight-tusked elephants, closely related to the Indian elephant, roamed all over Europe and much of northern Asia until about 50,000 years ago. Ancient mastodons and gomphotheres—members of the same order of creatures as living elephants—were widespread in the Americas until the arrival of man. The extirpation of elephants from China occurred at the dawn of the historical period. Today, African and Asian elephants are increasingly endangered in the wild. Perhaps, one day, an abundance of elephants in the most surprising places will be part of our world again. Elephants do not always make easy neighbors, and can crush crops and people with their bulk. But their intelligence, compassion, and playfulness are a reminder that there are other worlds beyond humanity's din.

Perhaps all that we are and all that we treasure exists at a frontier. Humans are creatures of uncertainty, created—at least to date—largely by natural selection acting upon random mutations. Yet here and now on Earth, we should not dismiss our potential to innovate more intelligently and benignly in the future than has been the case in the past. We may yet find a sense of dwelling and celebration, through art and story, and what they have to teach. In Italo Calvino's novel *Invisible Cities*, Marco Polo concludes his tales to the Great Khan:

> The inferno of the living is not something that will be; if there is one, it is what is already here, the inferno where we live every day, that we form by being together. To escape suffering in it...seek and learn to recognize who, in the midst of inferno, are not inferno, then make them endure, give them space.

Medieval Europeans believed the universe to be much smaller and of vastly shorter duration than we now know it to be. But some of them still dreamed magnificently, devoting their lives to the construction of great cathedrals that, for the most part, they would never live to see completed. We can recreate something of their world in ours. A replica of a 12th century *mappa mundi* was recently made in England using gold leaf, black ink derived from oak galls, and paint made from ground-up lapis lazuli, malachite, and dragon's blood, the red extract of a plant root. The gold was formed within stars; the rest by great, creating nature here on Earth. Today, with our vastly greater knowledge and capabilities, what else might we yet conceive?

CASPAR HENDERSON is the author of *The Book of Barely Imagined Beings: A 21st Century Bestiary* (2013, Chicago University Press).

01

“At the hands of astronomy and cosmology, we seem to have been reduced to near nothingness, specks within slivers of time and space, inside specks that are themselves entire universes.”

CALEB SCHARF,
Goodbye Copernicus, Hello Universe

Human Uniqueness

WHAT MAKES YOU SO SPECIAL

Human Tendencies

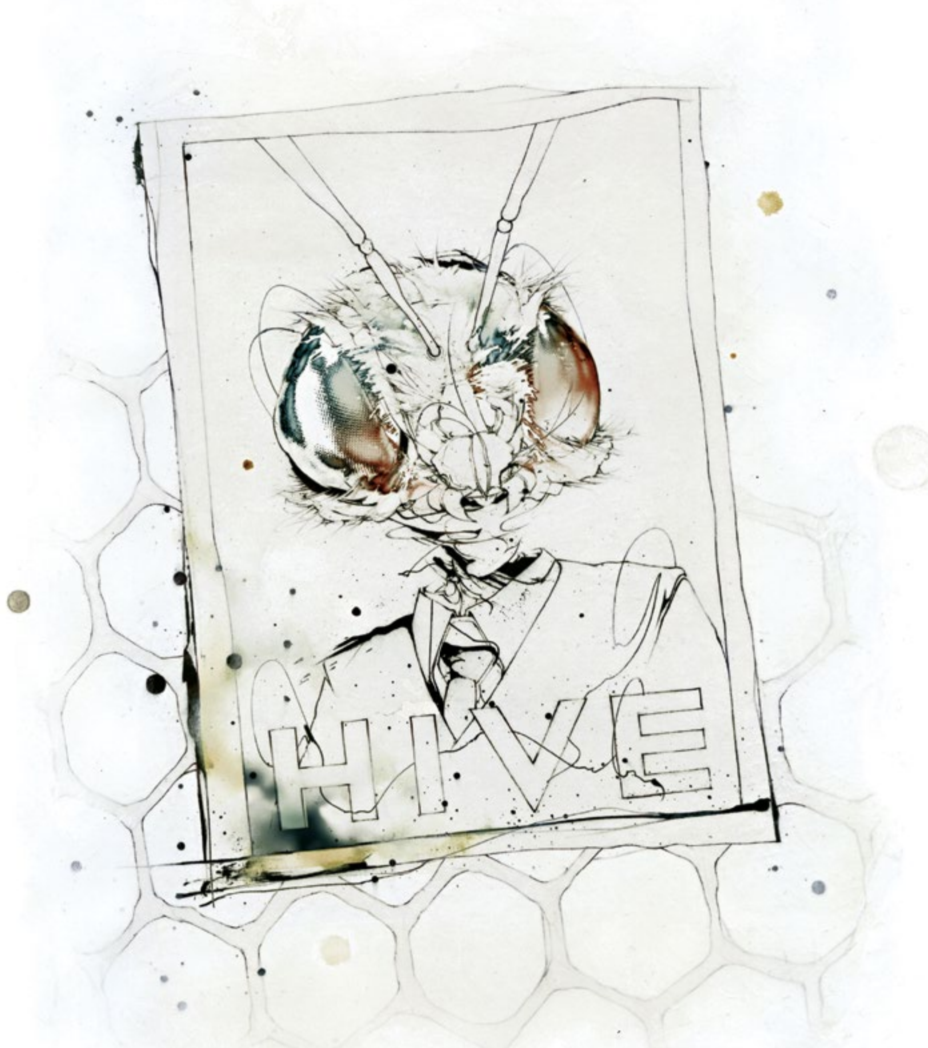
Some of our most cherished traits are shared by other animals—and even plants

BY AMOS ZEEBERG, JONATHON KEATS & BRANDON KEIM

ILLUSTRATIONS BY ANDREW ZBIHLYJ

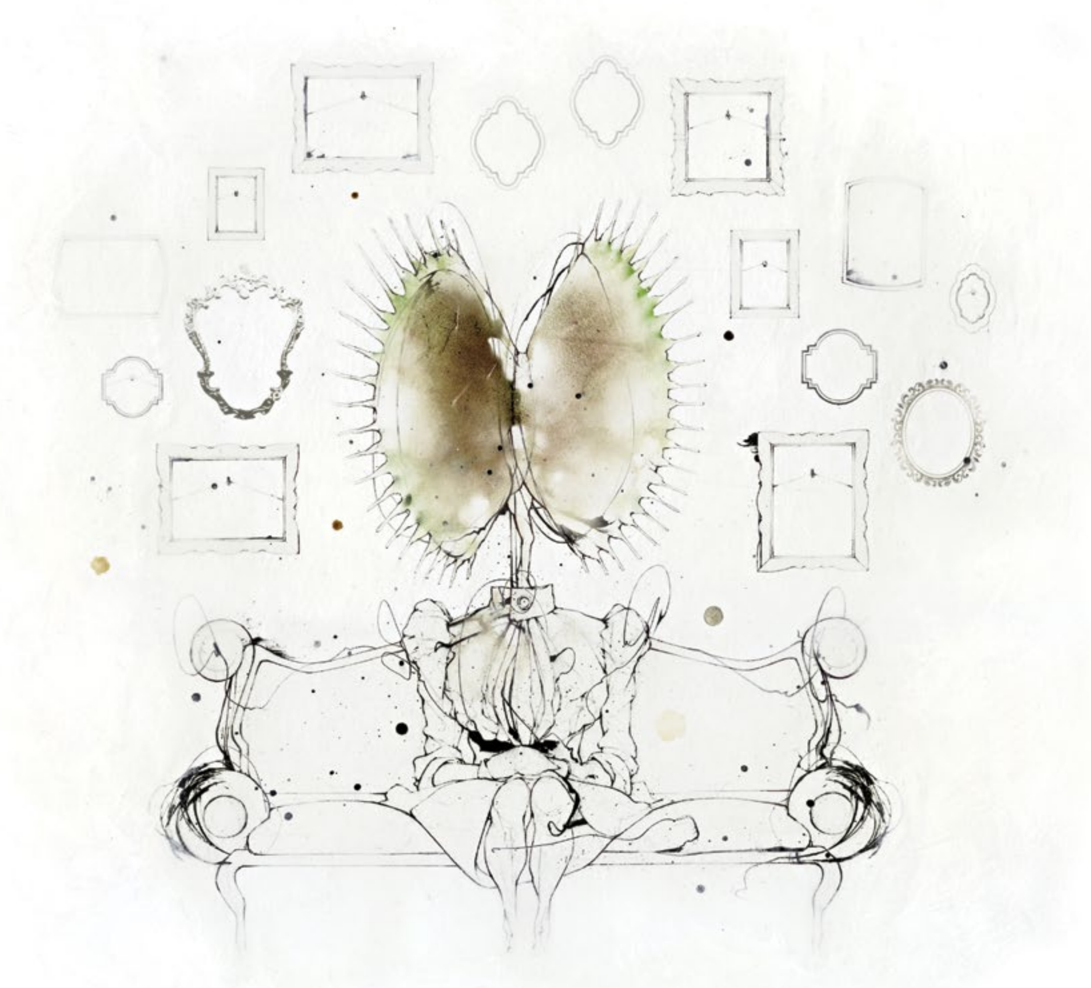
Hello, It's Me

Like family members announcing themselves on the phone, sperm whales, those giants of the ocean, with the largest brain of any animal, call out their names. Technically they click their names in various rhythm patterns, fractions of seconds apart, called codas. (If the whales made their clicks on land, they would sound as loud as rifle shots.) The whales roam the seas in matriarchal families: daughters, mothers, grandmothers. Young female whales live with their mothers for years (males leave within two to four years) and the family groups swim hundreds of miles to hunt squid, often in the range of predators like orcas and humans—so communication is paramount. Some sperm whale families share codas whose patterns signify group affiliation. Clearly the whales, like teenagers, know the importance of their clicks.



Democracy Is a Hive

When a honeybee colony grows too big for its nest, thousands of bees suddenly split off and look for a new tree to call home. The group bivouacs at a branch and sends out hundreds of bees to scout for new locations. When a scout finds a potential nesting spot, she comes back and performs what scientists call the waggle dance, revealing the location of the tree. The closer to ideal the site is—large, high off the ground, with a small entrance hole facing south—the more she repeats the movements—up to 100 times. Other bees pick up on the news and fly out to investigate. Once about 75-100 bees "vote" for one tree by assembling there, they achieve a quorum, and the swarm's "decision" is made. But no one—no human, that is—knows how bees tally their votes. Bee scouts scramble through the swarm, pressing their bodies against other bees. The resting bees begin shivering to warm up and prepare for flight. The vibration sounds like a race car revving. The destination set, the newly born colony is ready to roll.



Thanks for the Memory

The Venus flytrap, like most people in the Internet age, has about a 30-second attention span. But that's a blessing for the carnivorous plant, which relies on memory to survive. The lobes of the plant are laced with three or four "trigger" hairs. When an insect enters the plant and rubs the trigger hairs, the lobes snap shut and the plant consumes its prey. Each stimulation generates an electrical charge, but it generally takes two charges to spark the electrochemical signal that triggers the closure, so the plant must "remember" the first charge as it waits for the second. It has only enough energy to remember for about 30 seconds, so its survival depends on short-term memory and the ability to forget. Similarly, in a human brain, a neuron builds up an electrical charge when stimulated by other nerves, approaching a threshold above which it will fire an electrical signal—the basis of everything from recognizing a plant, like a Venus flytrap, to contemplating the meaning of life.

It Takes a Herd

Around the world many elephants from broken homes appear to suffer from post-traumatic stress disorder. In South Africa, adolescent male elephants have raped and killed hundreds of endangered rhinoceroses. In some places, 90 percent of male elephant deaths are caused by other males. Those are not the only victims. Around 500 humans a year are killed by elephants, according to National Geographic. Zoologists say the killer elephants are ones that have been exposed to violence, or grew up outside of normal elephant social groups, due to poaching, culling, or relocation of their relatives by humans. But wildlife experts at the Pilanesberg National Park in South Africa have found a way to get young bulls under control. They airlift in older males from other areas. Just hours after an aggressive young male gets into a scuffle with an older, more dominant bull, it begins to come out of musth, a sexually active, aggressive state. They settle down. It seems that to live healthy lives, elephants need healthy communities.

The Cosmopolitan Ape

Empathy, morality, community, culture—apes can have it all!

BY STEVE PAULSON

T**HE NEXT TIME YOU** mutter under your breath about the big gorilla in the next office, you might want to reconsider. The insult may reflect badly on you. Renowned primatologist Frans de Waal has spent decades studying chimpanzees and bonobos and found that nearly everything we hold in high esteem as "human nature" can be found in great apes.

De Waal runs Living Links Center at the Yerkes National Primate Research Center in Atlanta. He's written a series of influential books, including *Chimpanzee Politics* and *Our Inner Ape,* which add up to a sustained argument against human exceptionalism. His new book, *The Bonobo and the Atheist,* takes aim at critics and dissenters—anthropologists, behaviorists, Christian fundamentalists—and at the "strident atheism" of Richard Dawkins and Christopher Hitchens. De Waal, a non-believer himself, sees religion as an offshoot of our biological drive to do good.

I recently caught up with de Waal to talk about why humans are not nearly as unique as they think they are. He is an amiable conversationalist with a sly sense of humor. He's a fast talker, bursting with ideas, displaying the self-assurance of a prominent scientist who's fought his share of intellectual battles.

ILLUSTRATION BY JOHN HENDRIX


WISDOM

Most people assume that humans are fundamentally different from the rest of the animal world. What do you think?

Many people believe that. But to biologists we are animals. It's hard to believe we are fundamentally different because there is no part of the human brain that is not present in a monkey's brain. Our brains are bigger and we certainly have a more powerful computer than any other animal, but the computer is not fundamentally different.

So there's no fundamental divide between humans and chimpanzees?

No. If you were to ask what the big difference is, I would say it's probably language. But like all capacities, once you break them down into pieces, you are going to find some of these parts in other species.

Why are so many people wedded to the idea that humans are special?

We're raised with those ideas. It's an old Christian idea that humans have souls and animals don't. I sometimes think it's because our religions arose in a desert environment in which there were no primates, so you have people who lived with camels, goats, snakes, and scorpions. Of course, you then conclude that we are totally different from the rest of the animal kingdom because we don't have primates with whom to compare ourselves. When the first great apes arrived in Western Europe—to the zoos in London and Paris—people were absolutely flabbergasted. Queen Victoria even expressed her disgust at seeing these animals. Why would an ape be disgusting unless you feel a threat from it? You would never call a giraffe disgusting, but she was disgusted by chimpanzees and orangutans because people had no concept that there could be animals so similar to us in every possible way. We come from a religion that's not used to that kind of comparison.

Yet a lot of the scientists who make the case for human exceptionalism are not religious. They still believe that humans are fundamentally different.

Of course, they are not biologists. The social sciences and the humanities are still very influenced by religion. They have this whole mindset that humans are absolutely special. But the average biologist believes that everything is continuous. We know that plants have DNA and humans have DNA, so we see that all of us are totally connected.

Do animals have culture?

There is quite a bit of evidence for cultural transformation in primates and many other animals, where

Humans overestimate the complexity of empathy.

they learn things from each other. For example, different groups of wild chimpanzees will have very different behaviors, different stone technology, tool technology, social customs, communication signals. We speak of cultural variation in the apes.

You say chimps display a sense of morality. How so?

They have a sense of fairness and are cooperative animals like we are. Let's say I go hunting with you regularly and you always take the best pieces of meat and I only get little scraps. That's not a good partnership for me. We find that chimpanzees and bonobos are sensitive to fairness. They can be empathic. They respond to the distress of others by reassuring them and by sharing food with them. We do experiments on this. Do they prefer outcomes that benefit only themselves, or do they prefer outcomes that benefit both chimpanzees?

How do you test that?

In a typical experiment, you put two chimpanzees who know each other side by side into two rooms, with mesh between them so they can see, hear, and smile at each other. Then you let one of them choose between two tokens. They get a bucket of tokens with different colors, let's say blue and red tokens. If they pick a blue token and give it to us, they get rewarded. If they pick a red token, they get a reward but the partner also gets a reward at the same time. So it doesn't make any difference for them because they get rewarded every time they give us a token. The only difference is, "Does my partner also get something?" What we find is that, over time, they start to prefer what we call the pro-social token, the token that rewards the two of them.

Tell us about Peony, an old female chimp in your colony at Yerkes.

Peony had arthritis and was very old, so she could barely move. She would try to climb into a climbing frame where a bunch of chimps were sitting and grooming each other. She wanted to join them, but she could barely get in there. The younger females would walk up to her, put their hands on her behind, and start pushing until she was up there with the rest. We've also seen cases where she started walking towards a water faucet, but, since it's a very large enclosure and she walked with so much difficulty, a younger female would run ahead of her, take water in her own mouth, walk back to Peony, and then spit the water into her mouth so she wouldn't need to walk all the way to the faucet. The acts of kindness made us interested in testing for altruistic behavior more systematically because the literature has claimed only humans care about others, that if primates are altruistic, it's only to get favors in return.

FRANS DE WAAL with chimpanzees at Lincoln Park Zoo in Chicago.

PHOTOGRAPH BY KUNI TAKAHASHI/CHICAGO TRIBUNE/MCT VIA GETTY IMAGES

And what did the tests reveal?

Chimpanzees have a lot of altruistic behavior towards unrelated individuals. This was tested in the field because people claimed that chimps were only altruistic toward relatives. You can measure the DNA of an individual, so you know who's related to whom. Scientists found that most of the helping partnerships within groups of chimpanzees in the field are actually non-relatives.

So humans aren't the only ones who can recognize the pain or difficulty of another?

Humans overestimate the complexity of empathy. If you tell the average psychologist there's empathy in animals, they will say that's not possible. They think empathy means you consciously put yourself in the shoes of somebody else. We now know from human research that there's a lot of empathy in automatic responses. If I'm frowning and looking sad, you're going to frown and look sad because you will be affected by my facial emotions. If I'm laughing and smiling, you are going to laugh and smile.

That bodily connection, usually called emotional contagion, is easily demonstrable in lots of animals. We do research on yawning contagion in chimpanzees. If I'm yawning, you are going to yawn at some point. We know from human studies that it's correlated to empathy. People who are very empathetic are also very sensitive to the yawns of others, and they're more likely to yawn in response to the yawns of someone they're close to. So we tested chimpanzees. We showed them videotapes of yawning chimpanzees and they started yawning. They actually do it more if they see it in an individual they know, just like humans. These bodily connections are basically how empathy starts.

More than any other animal I know, chimps seem to have some understanding of their community as a whole.

Is this the same as "mirror neurons," or brain cells said to stimulate emotions we observe in others?

The mirror neuron is now often mentioned as a source of empathy, though there is quite a bit of controversy about the hyping of mirror neurons. But yes, mirror neurons are probably involved in this kind of emotional contagion. The body of the other is going to be represented in your brain. And we should never forget that mirror neurons were discovered not in humans, but in macaques. The evidence is that the neural substrate of empathy is very much present in all the primates. A chimpanzee who watches another chimpanzee screaming after losing a fight is going to be distressed himself. That may explain why chimpanzees console, and why we console others who are distressed.

Chimpanzees have complicated social lives. There's a lot of jockeying for social status among both males and females. Do alpha males always rule the roost?

People always think the strongest male is dominant, and when he's not so strong anymore, another male will take over. But I've known groups where the smallest male is the alpha male. He needs buddies who support him, so he needs to groom his supporters and share his food with them and sometimes share females with them. He cannot be completely exclusive in his mating rights.

He needs to build political alliances.

Yeah, he needs to bribe them. In captivity, females very often have quite a say. Since all the families live together, there's an enormous power bloc which no male can get around. So if the alpha female doesn't like a certain male, he's in deep trouble because she's going to support one of his rivals to take over the alpha position. It really becomes a political game.

You say that when an alpha male assaults a submissive female, other females will band together to protect the female under attack.

In captivity, forced copulation by males is basically impossible because the females as a bloc are opposed to that. Female chimpanzees don't always support each other in other circumstances, but when a male tries to force himself onto a female, then all of a sudden they act in solidarity and he will regret what he tried to do. Now in the wild it's more difficult because male chimpanzees don't have all these females around, so the power difference between males and females is actually bigger than in captivity.

You also write that after two males have been fighting, a female will sometimes force them to make up, and even take weapons out of their hands.

Darwin believed morality was part of the evolutionary story.

They confiscate weapons. Only females can do that. A male could not be a mediator because as soon as he walks into a scene like that, he's going to be perceived as the buddy of one of the two. More than any other animal I know, chimps seem to have some understanding of their community as a whole. They seem to worry about the level of harmony in the group. Of course, they have a self-interest in doing that. Everyone benefits if the group is harmonious, so females will monitor the fights between males. If two males don't reconcile after a fight, a high-ranking female will go over and start grooming one. After a few minutes, she will march to the other unruly male, bringing the first along with her. If he doesn't want to follow, she will take his arm and make him follow. Then she will bring the two males together, at which point these males are supposed to groom each other. And they often do.

There are also certain high-ranking males who take what we call "the control role." As soon as there's a little fight—even the littlest fight between two juveniles—they will go over and break up the fight. And they are very impartial. They do not necessarily support their friends or their mother. It's very important that they do this because small fights often escalate to big fights. I hear that's also not unusual in human daycare centers. So it's very important that they nip these things in the bud.

How do you explain that? We've been told for decades that selfishness drives natural selection. Only the strong survive.

That's a simplification. The struggle for life is very often won not by struggling and fighting, but by having a better immune system, or better ears or eyes. Survival is not necessarily based on defeating somebody else. Yes, competition is part of the picture, but there are very strong counter-mechanisms that keep the society together. We live in groups because they are beneficial for us, so we need to keep our group together. That is also true for many animals.

Chimpanzees can be violent and dominance-oriented, and they can also be cooperative and friendly. So what species does that remind you of? People sometimes say you can't call chimpanzees empathic if they kill each other. Well, the same argument applies to humans. Humans also have that whole spectrum. I feel that humans are more altruistic than any other species, but we are probably also the nastiest when it comes to our enemies.

Won't chimps go to war against a rival group in another territory?

Yes, but chimpanzees don't have genocide as far as we know. So we humans can be very proud that genocide

is one of our distinguishing features. I also compare us with bonobos. Bonobos are equally close to us as chimpanzees and, in my opinion, are equally relevant. They've shown more empathy than what we've seen in chimpanzees.

You call them the "politically correct" primate.

They are the hippies of the primate world because they have sex instead of war. When two groups of bonobos meet in the forest there will be some hostility, but very soon they may overcome that. They will have sex with their neighbors and then they start grooming each other and the kids will play with kids in the other group. In all the years that we've studied bonobos in captivity and in the field, not a single case of lethal aggression has been documented.

You say sex is routine among bonobos.

It is very casual. It's a little greeting of ten seconds and then it's over. They rub their genitals together and they may touch each other's genitals. Sometimes it gets a bit more involved. But most of the time it's like, I slap you on the back.

Bonobos are also matriarchal. In what way are the females dominant?

The females are not individually dominant over males. They are smaller and less muscular, and they don't have the big teeth that males have. But as a collective, female bonobos can travel together and be together. Collectively, they dominate the males.

Primates are very strongly affected by the death of others. They will not eat for days after one of their group members has died.

Our evolutionary ancestors broke off from the common ancestor of chimpanzees and bonobos at about the same time. Is our common ancestor more bonobo-like or chimpanzee-like?

That's the big question that we may never answer. The chimpanzee fits the thinking that humans are killer apes and only with time did we become peaceful. Another school of thinking doesn't believe that we've always waged war because the evidence for warfare goes back only about 12,000 years, which coincides with the agricultural revolution. This group thinks bonobos are highly relevant.

So are humans inherently good or evil?

I'm of the school that we are inherently good and under certain circumstances do horrible things. The resistance to evolution that comes from fundamentalist Christians is partly a resistance to the idea that you could be moral without God.

Francis Collins, the prominent geneticist and director of the NIH, has said you can't explain morality through evolution.

He must have read the wrong books. There has been a spate of books, starting with *The Selfish Gene,* that told us evolution cannot explain morality, that we're born selfish and we don't know where our morality comes from. These books are not Darwinian. If Collins read Darwin's *The Descent of Man,* he would have seen that Darwin believed morality was part of the evolutionary story. We now know that moral judgments are intuitive. They are not necessarily a product of the reasoning that Kant talked about. We also know that very young children, sometimes before one year of age, are already picking the good guy over the bad guy in puppet shows. So the whole story has changed and neuroscientists now know that a lot of moral decision-making is rooted in evolutionary processes that we share with other primates.

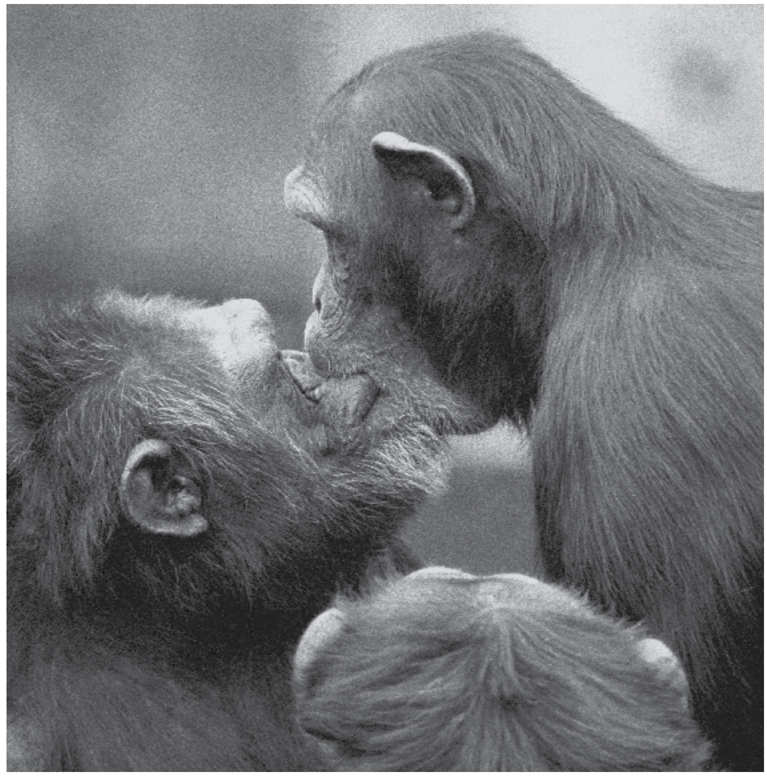
Where does religion come in?

Religion is very interesting to me. My book is called *The Bonobo and the Atheist* partly because I'm objecting to the New Atheist who trashes religion as irrelevant and bad and morally wrong.

Yet you identify yourself as an atheist.

Yeah, but I really don't care if God exists or not. If people can lead good lives by believing in God, that's perfectly fine with me as long as they are not overly dogmatic. But some atheists have also become dogmatic.

Why are you bothered by atheists who don't like



religion and want to smash it?

Because religion is so inherently human that I don't know what happens if you kick it out of society. Sigmund Freud wrote a whole book against religion and in the end he says that he is still not sure what would happen if we would remove it from society. It might not be good. We've seen the Communist experiment where they tried to get rid of religion. Stalin killed a lot of religious leaders and that experiment did not go well. Religion is so much part of human society. All human societies we know of have some sort of belief in the supernatural, so the question for me as a biologist is not so much whether religion is good or bad, but where does it come from? Why do we have this tendency? Is it some very special survival skill that humans developed? I believe morality came before religion, so religion cannot claim to be the source of human morality. But religion may contribute to maintaining morality in society.

Especially in large societies?

That's the thinking of some people who study religion. Human groups used to be 100 or maybe 200 people, a bit like primate groups. In these small groups you can keep an eye on everybody if they're not cooperative or if they cheat or lie. But that doesn't work so well if you go to a big society of a thousand people or several million. At that point we needed another system to monitor morality. And what better way than imagining some being who's omniscient, who can see you from every corner and even at night? So that may be why religions evolved and helped sustain these large societies.

But religion also has a dark side.

Humans do terrible things to each other, sometimes in the name of God, sometimes without any religious reference. There is no proof that without religion we

Chimpanzees can be violent and dominance-oriented, and they can also be cooperative and friendly. So what species does that remind you of?

would be treating our enemies any better. We're just not a particularly nice species when it comes to the out-group. But I have no patience with cruel religious practices, such as witch burning and genital mutilation. In this regard, I agree with the atheists that banning all of those superstitious behaviors would be a great relief.

Your take on religion is fascinating because you're not religious yourself. You don't believe in God but you seem to have what I would call a kind of "spiritual atheism."

That's an interesting term.

Well, you write about the experience of transcendence.

I believe the reason you find so many scientists who are agnostics and atheists is because we replace religion with something else. We do not see science as a religion, but we have a connection to the larger universe through our science. So that's part of the transcendence that we feel.

But transcendence is more than just an understanding of the larger world. There's a deeper, powerful emotional feeling that comes with it.

Yeah, it's an emotional feeling of connection. Of course, every scientist, myself included, is very unhappy if you say this is mysterious and must be caused by some supernatural force. Still, we feel connected to a larger whole. I was recently at a meeting where an astronomer started crying. He choked up when he showed pictures of stars billions of light years away. He couldn't speak, and then he composed himself and explained that ever since childhood, he's been deeply affected by seeing these images. For the primatologist, most of us were completely fascinated the first time we looked into the eyes of an ape. We felt an immediate connection between apes and humans. We feel this connection at a very visceral level.

Do other primates have some form of religion?

I don't think primates have religions, but they may have certain superstitions. For example, if a thunderstorm comes through with an enormous amount of noise and rain, male chimpanzees will put their hands up and start walking around bipedally, in a dancing sort of fashion. It's called a rain dance and it has been observed with chimpanzees approaching a waterfall. We really don't know why they do it. Are they impressed by what happens? Do they think they can stop it? Of course, that would be superstition. Are they somehow in awe of nature? They also react to death. We see that primates are very strongly affected by the death of others. They will not eat for days after one of their group members has died.

They grieve?

You could call it grieving. Let's say a mother loses her child. It's not only that she doesn't eat; she screams or sits huddled in the corner. I think they know death is permanent, but we don't know if they have that knowledge about themselves, like humans know they will die one day. That's interesting because the afterlife plays very heavily in religion.

Can you tell the story, from your new book, about the chimp named Lody at the Milwaukee County Zoo? It seems to be a remarkable story about memory and regret.

One day, Lody attacked the veterinarian who fed him. He bit off one of her fingers. Apes have such strong jaws, so they can do this in a fraction of a second. She came back from the hospital and the next day held up her bandaged hand to this male through the zoo window. As soon as he saw her, he ran to the corner and huddled in a sort of fetal position.

This veterinarian left the zoo, but then 15 years later, she came back to visit and Lody was still there. He immediately came up to her. She was standing at a railing, with her left hand out of sight. He kept trying to look at that hand but he couldn't see it. Then she held it up and her hand was missing a finger. He looked at her hands and face, and she had this clear impression that after 15 years Lody still knew what he had done.

STEVE PAULSON is the executive producer of Wisconsin Public Radio's nationally-syndicated show "To the Best of Our Knowledge." He's the author of *Atoms and Eden: Conversations on Religion and Science* (Oxford University Press).

The Candle Burned

Welcome to the future, where people read no more

BY MIKE GELPRIN
TRANSLATED BY LINA ZELDOVICH
ILLUSTRATIONS BY TOMER HANUKA

ANDREY PETROVICH HAD GIVEN up all hope when the videophone rang.

"Hello, I saw your ad. You give private literature lessons?"

Andrey Petrovich peered at the man on the screen. He was about thirty, with an open smile and serious eyes, dressed in a suit and tie. Andrey Petrovich's heart skipped a beat. Posting the ad on the Net had become but a hapless habit. In the past ten years he had received six responses. Three callers had dialed the wrong number, two others were old-fashioned insurance salesmen who still made phone calls, and the last one had confused literature with legislature.

"Y-yes, I d-do," Andrey Petrovich stutered anxiously. "In my apartment. You are interested in literature?"

"I am," the man nodded from the screen, and introduced himself. "My name is Maksim. How much do you charge?"

Andrey Petrovich almost blurted, "it's free," but caught himself. "Rates are per hour. And negotiable." He took a deep breath. "When would you like to start?"

"Well, I... you see," Maksim started.

"First lesson is free," Andrey Petrovich said quickly. "If you don't like it, there's no obligation."

"Let's start tomorrow then," Maksim said definitively. "Are you free at ten in the morning? I drop the kids off at school by nine, and then I'm good until two."

"I'm free," Andrey Petrovich said happily. "Here's my address. Got a pen?"

"I'll remember it," Maksim assured him. "Go ahead."

ANDREY PETROVICH COULDN'T SLEEP that night. Pacing from wall to wall in his tiny room, nearly a closet, he tried to tame his shaking hands and jumbled thoughts. For the past twelve years, he had been living on a meager subsistence, ever since the day he was fired. He had given up all hope of teaching.

"Your specialty is too narrow," the principal of The Arts and Humanities Academy for the Gifted and Talented had told him during their last conversation. "You are an excellent pedagogue, but your subject has outlived itself. Children don't study it anymore. Why don't you retrain, take on something modern like virtual ethics or robotic torts legal code? Or as a last resort, the history of cinematography. It's on its way out too, but it would carry you to retirement. The Academy would reimburse you for some of the cost. What do you say?"

Andrey Petrovich declined the offer, which he regretted later. There were no jobs in literature and philology, and former teachers were moving into other disciplines, grasping at any conceivable straws. For the first two years, he diligently went through liberal arts colleges and conservatories, but departments of humanities were disappearing and libraries were closing. When all proved fruitless, he tried to retrain, despite his aversion to the dry modern disciplines. When his wife left, he gave up.

As his savings dwindled, Andrey Petrovich spiraled into poverty. First, he sold his aircar, old yet still in good shape. Then he let go of the antique tea set, his mother's memento. Furniture and clothes followed. And once he was left with nothing in his sad bachelor pad, it was the books' turn. The real books—the old-fashioned, leather-bound tomes with original illustrations, still smelling of ink, paper, and glue. Collectors paid top price for the rare old volumes, so Leo Tolstoy brought food to his table for almost a month. Fyodor Dostoevsky lasted for two weeks. Ivan Bunin sufficed for about ten days. Every time Andrey Petrovich thought about his lost treasures, he felt like throwing up.

Finally, he was left with a few dozen of his absolutely favorite books, which he couldn't sell even if faced with starving to death. Hemingway, Balzac, Zola, Pasternak, and a few other authors huddled together on his four remaining shelves, and every day Andrey Petrovich lovingly dusted them.

"If the lessons work, I may be able to buy back Tolstoy," he mumbled to himself, shuffling from wall to wall, anxiously waiting for the morning. "Or maybe Murakami. Or should I do Amado first?"

Suddenly, a realization struck him. It didn't matter whether he could reclaim his books. What mattered was that he could pass on his knowledge of the long forgotten art: the beauty of the language, the flow of the story, the insights of its authors. He could impart, transfer, and transform.

MAKSIM RANG HIS BELL at 10 a.m. sharp.

"Please, have a seat." Andrey Petrovich ushered him in. "What would you like to start with?"

Maksim awkwardly lowered himself into a chair.

"What do *you* think I should start with?" he asked—and blushed. "I have to confess, I'm a total ignoramus. No one ever taught me anything. Do you understand what I mean?"

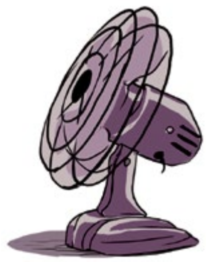
"Oh, but of course I understand!" Andrey Petrovich burst out sympathetically. "No one taught anyone for generations. Literature has been an academic stepchild for more than a hundred years. It's even been abandoned by schools with a humanitarian focus. It's no longer offered anywhere."

"Anywhere?" Maksim echoed.

"I'm pretty sure of it," Andrey Petrovich replied with a sigh. "See, the crisis began at the end of the twentieth century. People had no time to read. First children had no time to read, then their kids really had no time to read, and so on, every generation worse than the one before. Interactive entertainment pushed out reading. Technology pushed out philology. Literature, history, and geography couldn't compete with cybernetics, quantum mechanics, and plasma physics. But literature was worst of all. It just fell by the wayside. Do you understand?"

Maksim nodded. "Yes, I do. Please continue!"

"In the twenty-first century electronic platforms took hold and publishers stopped printing paper books. Because people no longer read, the



Maksim listened intently. He had an almost uncanny ability to focus, and he never seemed tired or overwhelmed.

number of writers dwindled and eventually they went extinct. Writers stopped writing! The literary reserve built over twenty centuries of writing is still more than sufficient to teach literature, but no one cares anymore. We're losing our history."

Andrey Petrovich paused for a few seconds and wiped off his suddenly sweaty forehead.

"It's so hard to talk about," he finally uttered. "I understand that it was an inevitable process. Literature died because it didn't fit into evolutionary progress. But it used to carry the wisdom of mankind to the next generation. It used to nourish souls and build spirits. It helped form the minds of children. Today, our children are raised emotionally and intellectually empty. They grow up soulless like machines. It's horrible and it's frightening!"

"That's what I felt too." Maksim nodded. "That's why I came to you."

"Do you have children?" asked Andrey Petrovich.

"Well..." Maksim stuttered. "Yes, two, a year apart. Pavlik and Anechka. I need the foundation. I'll find and read the manuscripts on the Net. I just need to know *what* to read. And how to *think* about what I read. Will you teach me?"

"Yes," Andrey Petrovich said, inspired. "I will and I shall."

He stood up straight and spread his shoulders, suddenly growing taller and stronger as he filled his lungs with air. "Boris Pasternak, poetry," he announced, fetching the dormant words from his memory.

"As blizzards whirled around the earth
And snow churned
A candle burned upon the table,
A candle burned..."

WHEN THE LESSON WAS over, Andrey Petrovich asked, with a slight tremor in his voice, "Will you come tomorrow?"

"I sure will," Maksim answered with determination. "The only thing is—you know, about the payment. I work as a secretary for a wealthy couple. I manage bookkeeping, I do shopping, I run errands. My salary is kind of low, but I can bring food, clothes, merchandise, and even some electronics—as payment. Would that work for you?"

Andrey Petrovich blushed. He felt so inspired after his first lesson, he would do it for free.

"Of course it works," he said. "Thank you. I'll see you tomorrow."

"LITERATURE IS NOT ONLY about the story, but also about how that story is spoken." Andrey Petrovich was pacing around the room as he explained to Maksim the art of storytelling. "Language is a wonderful and wondrous tool, and our talented ancestors had mastered it brilliantly. Just listen to the words, just listen!"

Maksim listened intently. He always looked as if he was trying to absorb and commit to memory every line Andrey Petrovich uttered. He had an almost uncanny ability to focus, and he never seemed tired or overwhelmed.

"Pushkin, 'Eugene Onegin,'" Andrey Petrovich would announce the next poem, and then recite. When he was done, he would move onto another author. "Lermontov, 'Demon.' Vysotsky, 'Capricious Horses.' Have I tired you, Maksim?"

Maksim was never tired. He never lost his concentration either.

As weeks and months went by, Andrey Petrovich rejuvenated. He grew youthful and energetic. His life made sense again, it now had purpose and reason. After poetry they moved on to prose and fiction, which were more complex and time-consuming, but by then Maksim had developed into a terrific student with a keen intuition. Originally nearly tone-deaf to the beauty of the language, he warmed up to the rhyme and rhythm, the cadence and the harmony of words. He made leaps of progress every day as Andrey Petrovich ventured into Balzac, Hugo, Hemingway, and Nabokov. Together, they went from classics to science fiction and from mysteries to fantasies, traveling through centuries, countries, and empires—from Shakespeare to Remarque, from Maupassant to Fitzgerald, and from Mark Twain to Rabelais.

IT WAS JUST ANOTHER Wednesday morning when Maksim didn't come. Andrey Petrovich waited anxiously. By the end of the day he was a nervous wreck. He tried to convince himself that his student had suddenly fallen ill, but his sixth sense told him otherwise. Punctual like a Swiss clock, Maksim wouldn't miss a session without fair warning. In a year and a half he hadn't been late once. He would've called. As a matter of fact, he would've called the night before!

When Maksim didn't show up the next morning, Andrey Petrovich knew something bad had happened. He found Maksim's number in his videophone history, poked the callback button, and gasped when he heard the cold metallic response.

"This number has been disconnected."

THE NEXT FEW DAYS were a blur. Even his favorite books didn't save Andrey Petrovich from the swiftly resurrected feeling of uselessness, which now gnawed at him with newfound strength. He considered calling hospitals and morgues, but didn't know how to describe the person he sought. Looking for a fellow named Maksim, thirtyish, sorry, no last name?

When he finally felt so stifled he could no longer breathe inside his chipping walls, Andrey Petrovich staggered outside.

"Hey there, Petrovich," Nefedov, his neighbor from the floor below, greeted him on the stoop. "Good to see you again. Whatcha hiding for? It

Literature died because it didn't fit into evolutionary progress. But it used to carry the wisdom of mankind to the next generation. It used to nourish souls and build spirits.

wasn't your fault."

Andrey Petrovich stared at him in bewilderment. 'What wasn't my fault?"

"Well, that guy of yours, you know." Nefedov made a cutting move across his throat. "The one who's been coming to see you all this time. I was wondering cuz it's not like you to hang out with those types, but I just kept my mouth shut."

"What types?" Andrey Petrovich asked, still stupefied. "Who are you talking about?"

"Who do you think? Them, the smartass thugs," Nefedov snorted with distaste. "I can tell 'em a mile away. Spent thirty years training that sort."

Andrey Petrovich grew cold.

"Can you tell me what you're talking about?" he pleaded desperately. "I don't get it!"

"You really don't know anything?" It was Nefedov's turn to be stunned. "Check out Net News, it's all over the place!"

Andrey Petrovich stumbled back into the elevator and almost fell into his apartment. He booted his computer up, connected to Net News—and moaned in almost physical pain.

"Caught stealing foodstuff, merchandise, and electronic equipment," the words blurred in front of his eyes. So did Maksim's picture, but he forced himself to keep reading. "Household Robot-Secretary, enhanced self-learning model, serial number MKS-4355. In his statement, MKS-4355 said he unilaterally resolved that children were growing up soulless and took it upon himself to educate them on literary subjects outside of the established school curriculum, while keeping it secret from his owners. The manufacturer identified a bug in the knowledge control module and issued a recall for the MKS series while liquidating the defective #4355 from the force. The incident caused public outrage and raised questions about the loyalty and honesty of our machines."

On disobedient legs, Andrey Petrovich staggered into the kitchen and reached for a bottle of cognac Maksim had brought a few weeks ago as yet another payment. He frantically searched for a glass, didn't find it, and latched onto the bottle in a long gulp. But the alcohol was too strong for his old throat and he doubled over in a wheezing cough. His knees gave way and he sank onto the floor.

"MKS-4355," he moaned, fighting a sharp pain that suddenly squeezed his heart. "A machine, oh my God, another faceless machine!"

He felt betrayed, cheated, humiliated. He had given this piece of electronic equipment everything he had—his knowledge, his heart, his soul. All this time he thought he was teaching a human being who'd bring the sacred spirit of storytelling back into the world. Instead, he had wasted his time on a preprogrammed whirl of wires. Literature was doomed, and he was doomed with it.

With a sudden determination, Andrey Petrovich pulled himself up and slammed his window shut. Then he stumbled over to the stove to turn on the gas. It would take an hour, max, and then it would be over.

His hand was on the knob when the doorbell rang. Andrey Petrovich moaned, but let go of the stove and staggered to the hallway. At the door stood two kids: a boy of ten and a girl, about a year younger.

"You give literature lessons?" the girl blurted out, her bright eyes dazzling from under her long bangs.

Andrey Petrovich was rendered speechless. "W-who are you?" he finally managed.

"I am Pavlik," the boy answered. "And this is Anechka, my sister. Maks sent us."

Andrey Petrovich gasped. "Who?"

"Maks," the boy repeated with determination. "He told us to tell you, before they... before he... before his..."

Anechka stepped forward. "As blizzards whirled around the earth and snow churned..." she began.

"A candle burned upon the table, a candle burned," Pavlik continued.

Trying to push his pounding heart from his throat back into his chest, Andrey Petrovich swallowed hard. "I can't believe it," he whispered. "I can't believe it."

"Andrey Petrovich, will you teach us?" asked Pavlik. "Maks said you would."

Grasping at the coat rack to keep his balance, Andrey Petrovich stepped back into his hallway.

"Come in, children, please," he whispered. "Come in, children, my dearest."

A New York writer originally from St. Petersburg, MIKE GELPRIN has published more than a hundred science fiction and detective stories in Russian periodicals. His book, *The Reluctant Nomads*, was published this year. "The Candle Burned" is his first story published in English. He can be reached at mgelprin@yahoo.com.

Metaphors Are Us

War, murder, music, art. We would have none without metaphor

BY ROBERT SAPOLSKY

THE OTHER DAY I fixed something—a rarity for me. The flotation device in the toilet water tank was rubbing against the side, getting stuck halfway up so that the tank didn't fill completely. I own a hammer and know how to operate it. But I couldn't fit it into the tank to whack the device back into place. Ditto for owning and using a wrench. It wouldn't fit either. But fortunately I also own a plunger and I used its handle to push the floating thing back the other way, using the side of the tank as a fulcrum. It worked, although the device got bent so that the top of the tank didn't quite fit. That overwhelmed me, so I called it a good day's work.

I was proud of myself. "There," I thought smugly. "It's not just chimps who can use tools."

Humans used to be unique in lots of ways. We were the only species who made tools, murdered each other, passed on culture. And each of those supposed defining features has now been demonstrated in other species. We're not so special after all. But there are still ways that humans appear to stand alone. One of those is hugely important: the human capacity to think symbolically. Metaphors, similes, parables, figures of speech—they exert enormous power over us. We kill for symbols, die for them. Yet symbols generate one of the most magnificent human inventions: art.

In recent years scientists from leading universities, including UCLA, University College London, and Yale, have made remarkable insights into the neurobiology of symbols. A major finding from their work is that the brain is not very good at distinguishing between the metaphorical and literal. In fact, as scientists have shown us, symbols and metaphors, and the morality they engender, are the product of clunky processes in our brains.

Symbols serve as a simplifying stand-in for something complex. (A rectangle of cloth with stars and stripes represents all of American history and values.) And this is very useful. To see why, start by considering basic language—communication without a lot

ILLUSTRATIONS BY JOHN HENDRIX

of symbolic content. Suppose you are being menaced by something terrifying and so scream your head off. Someone listening can't tell if the blood-curdling "Aiiiii!" means an approaching comet, right-wing death squad, or Komodo dragon. It just means that things are majorly not right, a generic scream where the message is the meaning. This present-tense emotionality is what communication by animals is mostly about.

Symbolic language brought huge evolutionary advantages. This can be seen even in the baby steps of symbolism of other species. When vervet monkeys, for instance, spot a predator, they don't just generically scream. They use distinct vocalizations, different "proto-words," where one means, "Aiiiiii!, predator on the ground, run up the tree," and the other means, "Aiiiiii!, predator in the air, run down the tree." It's mighty useful to have evolved the cognitive capacity to make that distinction. Who would want to guess wrong and dash up to the top of a tree when the problem is a raptor swooping down?

Language pries apart a message from its meaning, and as our hominid ancestors kept getting better at this separation, great individual and social advantages accrued. We became capable of representing emotions in the past and possible emotions in the future, as well as things that have nothing to do with emotion. We evolved a uniquely dramatic means of separating message from meaning and intent: lying. And we invented asthetic symbolism; after all, those 30,000-year-old paintings of horses in Chauvet cave are not really horses.

Our early use of symbols helped forge powerful bonds and rules of cooperation, as human societies grew increasingly complex and competitive. A recent study by Ara Norenzayan of the University of British Columbia and Azim Shariff of the University of Oregon revealed that, across 186 societies, the larger the typical social group, the more likely it was the culture created a god who monitored and judged human morality—perhaps the ultimate symbol of rule enforcement.

HOW DID OUR BRAINS evolve to mediate this complexity? In an awkward way. As has been said, evolution is not an inventor, it's a tinkerer, making do with the pieces at hand. While a squid can't swim as fast as many fish, it swims pretty fast for something that evolved from mollusks. Similarly, while the human brain turns out to handle symbols and metaphors in an inelegant way, it still does a pretty good job for something that evolved from brains that only processed the literal. The best way to shine a light on this unwieldy process is through metaphors for two feelings critical to survival: pain and disgust.

Consider the following: You stub your toe. Pain receptors there send messages to the spine and on up to the brain, where various regions kick into action. Some of these areas tell you about location, intensity, and quality. Is it your left toe or right ear that hurts? Was your toe stubbed or crushed by a tractor-trailer? This is the meat-and-potatoes of pain processing, found in every mammal.

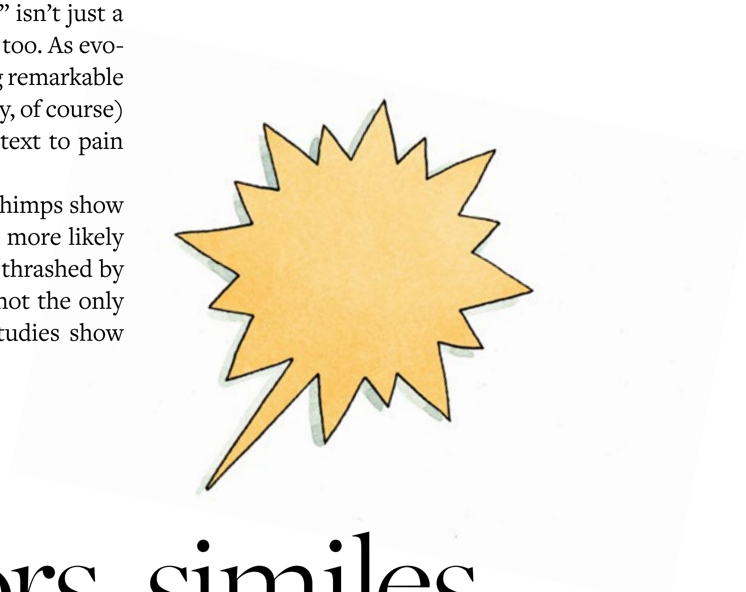
But there are fancier, more recently evolved parts of the brain in the frontal cortex that assess the meaning of the pain. Maybe it's bad news: Your stubbed toe signals the start of some unlikely disease. Or maybe it's good news: You're going to get your firewalker diploma because the hot coals made your toes throb. Much of this assessing occurs in a frontal cortical region called the anterior cingulate. This structure is heavily involved in "error detection," noting discrepancies between what is anticipated and what occurs. And pain from out of nowhere surely represents a discrepancy between the pain-free setting that you anticipate versus the painful reality.

Now let's go a little deeper, based on work by Naomi Eisenberger at UCLA. While lying in a brain scanner, you play a game of virtual catch, where you and two people in another room toss a cyberball around on a computer screen. (In reality, there aren't two other people, only a computer program.) In the control condition, you're informed mid-play that there's a computer glitch and you're temporarily off-line. You watch the virtual ball get tossed between those two people. Now in the experimental setting, you're playing with the other two and suddenly they start ignoring you and only toss the ball between them. *Hey, how come they don't want to play with me anymore?* Junior high all over again. And the brain scanner shows that the neurons in your anterior cingulate activate.

In other words, rejection hurts. "Well, yeah," you might say. "But that's not like stubbing your toe." It is to your anterior cingulate. Both abstract social and literal pain impact the same cingulate neurons.

We take things a step further with work by Tania Singer and Chris Frith at University College London. While in a brain scanner, you're administered a mild shock, delivered through electrodes on your fingers. All the usual brain regions activate, including the anterior cingulate. Now you watch your beloved get shocked in the same way. The brain regions that ask, "Is it my finger or toe that hurts?" remain silent. It's not their problem. But your anterior cingulate activates, and as far as it's concerned, "feeling someone's pain" isn't just a figure of speech. You seem to feel the pain too. As evolution continued to tinker, it did something remarkable with humans. It duct-taped (metaphorically, of course) the anterior cingulate's role in giving context to pain into a profound capacity for empathy.

We're not the only empathic species. Chimps show empathy when, for example, they become more likely to groom someone who has been unfairly thrashed by an aggressive jerk of a chimp. And we're not the only species with an anterior cingulate. But studies show the human anterior cingulate is more complex than in other species, with more connections to abstract, associational parts of the cortex, regions that can call your attention to the pains of the world, rather than the pain in your big toe.



Metaphors, similes, parables, figures of speech—they exert enormous power over us. We kill for symbols, die for them.

And we feel someone else's pain like no other species. We extend it over distance to help a refugee child on another continent. We extend it over time, feeling the terror of what are now mere human remains at Pompeii. We feel it embodied in words, as we contemplate George's sadness that Lennie is never going to get his rabbits. (That part of *Of Mice and Men* never failed to leave me a sopping, tearful mess when I'd reread it obsessively as a kid.) We even feel empathic pain prompted by symbols encompassed in pixels. "Oh no, the poor Na'vi!" we cry, when Home Tree is destroyed in *Avatar*. Because the anterior cingulate has trouble remembering "it's only a figure of speech," it functions as if your heart is literally being torn out.

LET'S CONSIDER ANOTHER DOMAIN where our brains' shaky management of symbols adds tremendous power to a unique human quality: morality.

You're in a brain scanner and because of the scientist's weirdly persuasive request, you bite into some rotten food. Something rancid and fetid and skanky. This activates another part of the frontal cortex, the insula, which, among other functions, processes gustatory and olfactory disgust. It sends neuronal signals to face muscles that reflexively spit out that bite, and to your stomach muscles that make you puke. All mammals have an insula that processes gustatory disgust. After all, no animal wants to consume poison.

We evolved a uniquely dramatic means of separating message from meaning and intent: lying.

But we are the only animal where that process serves something more abstract. Think about eating something disgusting. Think about a mouthful of centipedes, chewing and swallowing them as they struggle, wiping off the little legs that you've drooled onto your lips. Whammo goes the insula, leaping into action, sending out its usual messages of disgust. Now think about something awful you once did, something deeply shameful. The insula activates. It has been co-opted into processing that human invention: moral disgust.

Is it a surprise that the human insula is involved in processing moral disgust along with gustatory disgust? Not when human behaviors can make us feel sick to our stomachs, can leave bad tastes in our mouths, can stink. When I heard about the massacre at Newtown, "feeling sick to my stomach" wasn't just some symbolic figure-of-speech way of saying that I felt distressed. I felt nauseous. The insula not only prompts the stomach to purge itself of toxic food; it prompts our stomach to purge the reality of that nightmarish event. The distance between the symbolic message and the meaning shrinks.

As shown by Chen-Bo Zhong of the University of Toronto and Katie Liljenquist of Brigham Young University, if you're forced to ruminate on a moral transgression of yours, you're more likely to clean your hands afterward. And the scientists showed something even more provocative. They ask you to ruminate on your moral failings; afterward, you're put in a position where you can respond to someone's request for help. Wallow in your moral turpitude and you're more likely to help. Unless you had a chance to wash post-wallowing. Then that urge to compensate for your transgression is gone; you've washed away your sins and gotten that damn spot out. Pontius Pilate and Lady Macbeth could lecture at scientific conferences about this one.

Remarkably, the way our brains use symbols to discern disgust and morality also contributes to political ideology. Work by scientists such as Kevin Smith of the University of Nebraska reveals that on the average, conservatives have a lower threshold for visceral disgust

"Feeling someone's pain" isn't just a figure of speech. You seem to feel the pain too.

than do liberals. Look at pictures of excrement or open sores undulating with maggots, and if your insula goes atypically berserk, chances are that you're a conservative—but only about social issues, say, gay marriage, if you're heterosexual. And if your insula just takes those maggots in stride, chances are you're a liberal. In a study by Yoel Inbar of Tilburg University, David Pizarro of Cornell and Paul Bloom of Yale, participants, placed in a room with a wastebasket marinated in a stink spray (*note to self*: *never do research in that lab*) "showed less warmth toward gay men relative to heterosexual men." In a control room, without the stink, participants evaluated gay and heterosexual men equally. In a nutty, smart, real world example, Tea Party candidate Carl Paladino mailed out campaign flyers impregnated with the smell of garbage during his GOP primary campaign for New York governor in 2010. His campaign trumpeted, "Something really stinks in Albany." Paladino won his primary. (He stunk, however, in the general election, losing by a large margin to Andrew Cuomo.)

Our wobbly, symbol-dependent brains are molded by personal ideology and culture, shaping our perceptions, emotions, and convictions. We use symbols to demonize our enemies and wage war. The Hutu of Rwanda portrayed the enemy Tutsi as cockroaches. In Nazi propaganda posters, Jews were rats who carried dangerous microbes. Many cultures inculcate their members into acquiring symbols that repel, doing so by strengthening specific neural pathways from the cortex to the insula, pathways that you'd never find in another species. Depending on who you are, those pathways could be activated by the sight of a swastika or of two men kissing. Or perhaps by the thoughts of an abortion, or of a 10-year-old Yemeni girl forced to marry an old man. Our stomachs lurch, and we feel the visceral certainty of what is wrong. And we belong.

The same brain apparatus is behind symbols that move us to our most empathic, inclusive, and embracing. It is often art that does this most powerfully. We see the artistry of a skillful photojournalist—a photo of a child whose home was devastated by a natural disaster—and we reach for our wallets. If it is 1937, we don't look at Picasso's "Guernica" and see a menagerie of anatomically deformed mammals. Instead we see the devastation and feel the pain of a defenseless Basque village immolated during the Spanish Civil War. We feel moved to act against the Fascists and Nazis who conducted the aerial attack. Today we can feel moved to care about the fate of animals when we look at the simple artistic symbol, like a panda logo, of an environmental group.

Our metaphor-making brains are unique in the animal kingdom. But clearly we are dealing with a double-edged sword. We can dull the edge that demonizes, and sharpen the one that urges us to good acts.

Robert Sapolsky is a professor of biology and neurology at Stanford University. He is the author of a number of books, including *Why Zebras Don't Get Ulcers, Monkeyluv,* and *A Primate's Memoir.*


YOU

Goodbye Copernicus, Hello Universe

The universe is a big place. But so what?

BY CALEB SCHARF

WHEN COPERNICUS TOLD US more than 400 years ago that the Earth was not at the center of the universe, he could hardly have imagined that it would lead this far. At the hands of astronomy and cosmology, we seem to have been reduced to near nothingness, specks within slivers of time and space, inside specks that are themselves entire universes. But how should we interpret this fact? Does this ultimate extension of the Copernican narrative seal our infinitely mediocre fate? The question is more complex than it initially seems.

It's easy to feel unimportant

It starts in our own galactic backyard,* around the star Alpha Centauri B. Last year, we discovered that our neighbor harbors at least one world[1]. It's not the kind of place we'd call home, mind you. Its year is only three days long. Its surface temperature may be more than a thousand degrees Celsius—enough to melt silicate rock. You would be immersed in scorching mineral vapor on arrival, flash cooking your lungs—that is, before you exploded in an evaporative puff.

But it is Earth-sized, and it is only four light years away. There could be other, more temperate planets in this system. These worlds would, in turn, be merely the nearest motes among our cosmic neighbors. Our Milky Way galaxy has more than 200 billion stars, and is one of a few hundred billion galaxies[2] in the observable universe. And we have learned in the last few years that a flotsam and jetsam of worlds forms around this

* How can we possibly estimate the number of galaxies in the universe? It's not for the faint-hearted because it involves a tremendous amount of inference and extrapolation from some of our most extreme and difficult astronomical observations. A good example is the Hubble Ultra Deep Field, an image of a teeny patch of the cosmos—barely one tenth the width of the full Moon—with a total exposure time of almost a million seconds (that's about 11 days) that reveals close to 10,000 galaxies reaching across 13 billion years of cosmic time. Extrapolate this one patch to the whole sky and you have a ballpark guess at the contents of the universe from which light has had time to reach us.

ILLUSTRATION BY JOHN HENDRIX

dizzying starscape with a shocking degree of efficiency. (See Planet detection on page 75.)

In 1995, we detected the first planets outside of our solar system (exoplanets) around sun-like stars. Since then, the count of known exoplanets has rocketed to a few hundred, with 2,700 robust candidates and as many as 18,000 stars in need of further study. Some star systems are positively bursting with worlds, packed into orbits that hover at the hairy edge of gravitational chaos. In fact there may easily be many more planets than there are stars in the universe—which means hundreds of sextillions of planets, small and big, hot and cold, and, probably, some vaguely like our own Earth. Indeed, recent analyses[3] suggest that at least 15 percent of all stars may have Earth-sized planets orbiting within the zone where liquid water might exist on their surfaces.

Life on these planets is appearing increasingly likely, too. We've learned in recent years that the cosmos is filled with the very same building blocks that life on Earth uses. Look outwards and you'll find that more

Outer space, it turns out, is a vast slow cooker.

SCHARF SPEAKS To see the video, visit nautil.us/issue/1 than 70 percent of the molecules drifting in interstellar space contain carbon atoms, which, with their spare valence electrons, are fantastically good at bonding with other elements.

Outer space, it turns out, is a vast slow cooker. The *densest* interstellar gas may contain 10,000 hydrogen atoms in a cubic centimeter, and three or four carbon atoms. This is only a thousand trillionth of the density of the air we breathe. An atom in deep space may travel 100,000 kilometers before bumping into a partner. But space has its own secret sauce. A long underappreciated bevy of three protons and two electrons called protonated molecular hydrogen[4], or H_3^+, catalyzes a great network of reactions as elements collide, or stick to the surface of star-produced microscopic silicate and carbon dust grains. (See Interstellar reactions on page 78.) Over many millions of years, compounds as complex as polycyclic aromatic hydrocarbons are manufactured, with dozens of carbon atoms in arrays of benzene rings. Other structures are precursors to amino acids, the stuff you and I are made of. Here on Earth, we can read the chemical record of this activity in fallen meteorites containing dozens of amino acid species. If they are falling on us, they are probably falling on other planets, conceivably forging the start of countless alien biochemistries in a kind of starter mix for life. And my own speculation is that there are many, many different ways to end up with complex organisms, that the steps that happened to allow us to be here on Earth do not need to be copied verbatim elsewhere.

Faced with these observations it seems that one would need to invoke some extraordinarily contrived circumstances to argue that the fact and nature of life on Earth is at all special.

Then there is the final frontier—no, not the one from Star Trek, but something far greater than that. Many cosmologists are now convinced that our universe is merely one of a vast array of universe 'things,' each with its own set of physical laws, mostly separated by space and time. Some of these ideas spring naturally from the physics driving the exponential, inflationary expansion of the very early universe and the seemingly inherent instability of 'nothing' itself. While only speculation today, these ideas may soon be testable. Subtle signatures of our cosmos 'bumping' into others could exist in the pervasive cosmic radiation

Planet detection

There are many options for detecting planets around normal stars, but none of them are easy—planets are small and dim, swamped by the light of nearby stellar parents. Direct imaging of either reflected or emitted (infrared) light is probably the hardest approach, and to date has only succeeded for a few systems and giant planets. However, indirect techniques have made incredible progress. More than 500 planets in more than 380 systems have been discovered by Doppler-shift measurements of stars as they 'wobble' about the center-of-mass of the system at mere walking speeds, shifted by the gravitational pull of planets. More than 290 confirmed planets in more than 230 systems have been detected by the transit method—possible when a planet moves between us and its parent star by chance system alignment and blocks or eclipses a tiny (1 percent or less) amount of the star's light. Spotting the characteristic dip of transits as small as 0.003 percent has allowed NASA's Kepler telescope to find more than 2,700 good planetary candidates, and more than 10,000 potential candidates moving around over 140,000 stars. The smallest exoplanets so far? About the size of our moon. Another method exploits the gravitational lensing of light as planetary systems drift between us and more distant, background stars. With the right alignment the stellar backlight is magnified and changes in brightness over hours to days in patterns that can reveal the intervening planets. It happens rarely, but by monitoring millions of stars astronomers have found 18 planets in 16 systems, and have produced some of the best estimates of the abundances of planets at large—putting the counts ahead of the number of stars in our galaxy.

background, or in the motion of matter across vast scales, both amenable to detection by the next generation of astronomical experiments.

Even in the seemingly unlikely case that there is absolutely no other life in the dizzying expanse of our own universe, it is far less likely for there to be none among an indefinite stretch of universes, each with their own physics, their own untold planets, and their own cosmic chemistries.

We are here. Therefore they are there?

Phew. We are in a big, big place. It can be exhausting to think about. And we are a long way from being the center and purpose of creation as imagined by the average scholar just 600 years ago. But what does this vastness really mean for us? How should we react? If we *are* the only life in these many universes, we are, in some ways, *more* special—more significant. And there's the rub. Our reaction depends on whether or not other life is actually out there.

Our quantitative reasoning about the occurrence of life beyond Earth owes a debt to a previously obscure 18th century British mathematician and non-conformist theologian called Thomas Bayes[5]. Bayesian statistics are all about confidence. To illustrate this, imagine, if you will, a rather inexperienced but mathematical gardener[6].* She has a plot of land and a large bag full of these mysterious things called 'seeds.' On a whim the gardener buries one of these seeds in the soil, waters it, and waits.

At this stage she has no idea what will happen next. A couple of days pass and, lo and behold, a shoot appears! But what does this mean? Will seeds always produce shoots? This is a promising possibility and so the gardener formulates a measure of her confidence that this will happen again. Her hypothesis is that there is equal probability of a seed sprouting or not sprouting—the odds are 1-to-1, or 50 percent, for either outcome. This assumption, called a "uniform *prior*," is clearly not true—but it is the most logical hypothesis. The gardener knows only that her experiment has two possible outcomes: a sprout, and no sprout. Since there is too little data to bias her one way or the other, she gives equal odds to each outcome.

She goes ahead and plants another seed in the ground, waits a couple of days, and another shoot appears. She has now seen two seeds sprout, and so modifies her confidence to give 2-to-1 odds for planted seeds to sprout (66.6 percent, or two out of three possible outcomes). A third success and this increases to 3-to-1 (75 percent) and so on. With every new sprouting the gardener becomes more and more confident, but never absolutely sure, that planted seeds will grow. Even by the time she's seen the hundredth shoot appear, she is only about 99 percent confident that this will happen again.

The question of life's abundance in the universe is ripe for this kind of Bayesian analysis. And in 2011 two Princeton scientists, David Spiegel and Edwin Turner[7], did just that. Their approach was much more sophisticated than the gardener's, but it shared a key characteristic: they were working with very little data. In fact, the totality of their data can be summarized (a bit glibly) by saying that microbial life 'sprouted' quickly here on Earth (an event termed abiogenesis), and some 3.8 billion years later, complex-celled, intelligent life emerged to make this very observation. What do these two facts tell us about the likelihood of life elsewhere in the cosmos?

The answer is, not much. At its core, Bayesian analysis weighs how much our conclusions stem from our prior assumptions and how much comes from our actual data. In this case it reveals that our conclusions about life in the universe are acutely dependent on what we assume—what our *prior* theory is for the probability of life arising on planets, and to a lesser degree on the specific outcome on Earth. A simple, optimistic model assuming that the frequency of abiogenesis is

* This allegorical example is a variation of an explanation given by Richard Price in his notes accompanying the posthumous publication of Bayes' essay on probability in 1763. Price described a precocious newborn trying to make sense of the Sun rising and setting—while keeping count with colored marbles in a bag. Bayes himself made use of a thought experiment with red and white balls being rolled across a table—computing the probability of how they will come to rest relative to each other. This may all seem simple now, but in the 1700s this was really a new way of looking at the world, a place full of uncertainties and probabilities.

a constant, or perhaps decreases with planetary age, predicts an abundance of cosmic life when calibrated to abiogenesis here on Earth. But the model admits abiogenesis rates as low as once per 10 billion or even 100 billion years, implying we could also be the first life in the cosmos. Change the model slightly, and all bets are off. There is simply too little data to swing our confidence in either direction.

Furthermore, Spiegel and Turner show that this analysis hinges on the simple fact that, because we are here to ask the question, we must be on a planet that supports the eventual emergence of intelligent life. Unfortunately, as a result, our own existence tells us very little indeed about the probability of life off of Earth: it is, in some sense, an echo of the question itself.

What their investigation *does* vividly demonstrate is how enormously our understanding changes if we find just *one* other example of life in the universe. The probable rate of abiogenesis on a given planet would rise by a factor of 10 or more, to more than once every billion years. The universe is only 13.8 billion years old, so this makes a difference! Suddenly, our galaxy is full of life.

Are we a standard example of carbonaceous life in a universe teeming with it? Simply put, we don't know. But there is something else I can tell you: science has shown us how life, any life, is in some ways far from mediocre.

One would need to invoke some extraordinarily contrived circumstances to argue that the fact and nature of life on Earth is at all special.

At one with the universe

There is something very old, deep, and, yes, significant that might challenge the notion of our mediocrity.

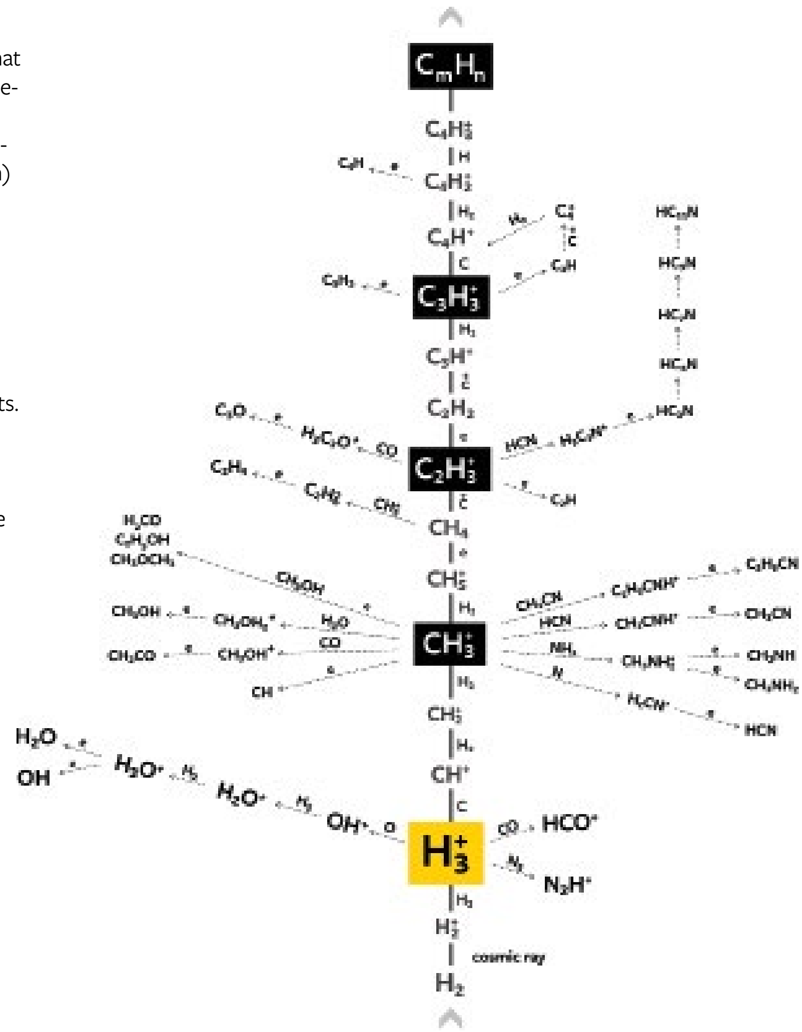
It starts because you're made of the cumulative stuff of the cosmos. A little more than 3.8 billion years ago some part of you came crashing to Earth. It might have been a handful of your carbon, oxygen, or nitrogen atoms, or some of the many hydrogen nuclei that now exist in your molecules. Primordial things are these, the remains of a hot Big Bang that took place 10 billion years earlier. Pieces of the one-in-a-billion tailings of a universe filled with annihilating matter and antimatter.

Your heavier elements passed through the digestive system of other stars. Cooked up by nuclear fusion in 10 million degree stellar cores. Hidden from sight under seething cloaks of plasma that could be millions of miles deep, these tiny clusters of matter were eventually dispersed to interstellar space in supernovae explosions that could momentarily outshine an entire galaxy. Cooling in the chill of space, they inhabited nebular clouds, eventually once again succumbing to gravity's relentless embrace to fall inwards to the tumult of a youthful swirl of matter surrounding a growing baby star. Going through this process just once is enough to make a smattering of heavier elements if the star is sufficiently massive, but it takes multiple stellar generations to enrich the universe enough to build worlds like ours, and us. We are well down the family tree.

Back at the birth of our planet the elements arrived first in great embryonic collisions and later in a tapering,

Interstellar reactions

A 'new classic' reaction diagram of what H_3^+ leads to, from Ben McCall (Ph.D. thesis, U. Chicago, 2001, available online). Interstellar clouds of molecular hydrogen, H_2 (at the bottom of the diagram) are acted on by cosmic rays, leading to H_3^+. The vertical column indicates the subsequent chemistry possible simply with the addition of hydrogen and carbon atoms, both of which are abundant in space. Branches of this column indicate possible chemistries that start with more complex reactants. Compounds like alcohols or cyanides can be produced by this network, and were likely an integral part of the chemical environment from which the pre-biological Earth formed.



diminishing rain of metal, rock, and ice[8].* In the billions of years that followed, these atoms took many different paths. Some were carried into oceans and atmospheres, others sequestered into the cooling minerals of a floating planetary crust. Trillions upon trillions of microscopic organisms have processed many of these atoms across the eons—perhaps carrying them around for a while, or simply plucking them up for the briefest instant of chemistry before discarding them.

Some atoms were incorporated into other living matter: insects, plants, animals—a wild array of trajectories and histories. Until now, today, when they've been passed on from your mother, her food, your food, the air you breathe, and the water you drink, to become a piece of your very corpus.

But, if a handful of fundamental physical constants and initial characteristics of the universe were slightly different, these pathways to galaxies, stars, heavy elements, the ubiquitous carbon molecules, and life itself, would be subverted. For example, the fine structure constant determines the size and behavior of atoms. If it were slightly bigger, or slightly smaller, objects like planets might not form, nor would chemistry operate the way it does. If the strength of gravity were a little greater all stars would be blue giants, and planets like Earth could not exist. If it were a little smaller, all stars would be red dwarfs and there would be few, if any, heavy elements.

There are other apparent coincidences. The manufacture of carbon in the bellies of stars relies on the existence of a specific, resonant, excited energy state of carbon-12 nuclei, the unusual stability of beryllium, and the nature of oxygen-16 nuclei. Without all these ducks lined up in a row, there would be no carbon. Without carbon there would be no life. There is also the remarkable coincidence of us being able to *discover* all of this. (See Middle ground on page 80).

Such observations have led to the Anthropic Principle[9]—the idea that our very presence is somehow relevant to the cosmos. (In truth it need not be our presence, since the presence of any life does the trick. So the 'anthropic' is a bit selfish and the principle slightly misnamed). This principle has different variants. A so-called 'weak' version is the most straightforward: it says that the apparent fine-tuning for life is a selection bias, since if it weren't this way we simply wouldn't be here to examine it. The weak Anthropic Principle was an early argument for the existence of multiple universes, which neatly avoids us having to explain why this universe ended up this way and connects with multiverse ideas emerging from fundamental physics. We simply exist in a universe suited for life. The strong Anthropic Principle goes further still, and argues that a viable universe is somehow *compelled* to produce life like us—it could not be any other way.

There is even a body of thought that supposes that life is the ultimate end or expression of our universe, the apotheosis of complexity in a vast space that can seem curiously suited for us to exist in it. In fact the late, great physicist John Wheeler mused on whether *information* is at the root of all physics. A consequence might be that consciousness itself, also built from information, is a key component of reality and that ours is a participatory universe in which consciousness affects reality.

In most respects, the connectedness of life to basic features of our universe, and the Anthropic Principle, are the polar opposite of the Copernican worldview, which can be an uncomfortable thing. But what these facts accomplish is to widen the circle of what we consider to be life "like us." Life beyond Earth may very well also be carbon-based, initiated by similar combinations of monomers into complex information-carrying compounds, evolving through similar processes of selection, enabled by the same cosmic coincidences. In other words, cut from the same fabric.

Indeed, there is a nagging doubt that any life we find will be truly independent of us. In our own solar system, asteroids have battered planets throughout the past 4.5 billion years, with each collision potentially launching microbe-harboring surface material into a variety of 'conveyor-belt' orbital pathways[10]. Pieces of Mars eventually end up on Earth. Pieces of Earth end up on Mars, and even on the distant moons of the giant planets. Nature may have already created an intermixed diaspora of life in our solar system. And it is also possible that life further afield is connected to our own, just through a more ancient bridge.

So if we find life off Earth, the Bayesians will have their work cut out for them. As for our sense of our own significance, we could argue that it would strengthen, by confirming the entrenched nature of life in our universe. On the other hand, we tend to take things personally, and a universe full of life might seem a lot smaller.

* Exactly how the young Earth went through its 'final' assembly is not completely understood (indeed, arguably it's still assembling incrementally today, by accumulating about 40,000 metric tons of interplanetary dust and muck a year). There may have been a period of intense bombardment 4.1-3.8 Gigayears ago known as the Late Heavy Bombardment, a hypothesis supported by what we see in lunar cratering, but still somewhat controversial. A final pounding has also been linked with a dynamical rearrangement of the outer planets—with Jupiter and Saturn shifting to their present orbits and Neptune and Uranus actually swapping order. These shenanigans would have perturbed large numbers of asteroid and cometary bodies, flinging them inwards to pelt the terrestrial planets.

Unique vs. significant

We are wrestling with two distinct questions: our uniqueness and our significance. Uniqueness is easier to approach. For the astrobiologist, uniqueness can be defined as the probability that Earth, and life on Earth, is different from anywhere else. Primatologists, on the other hand, may define uniqueness as the collection of characteristics that distinguish us from our evolutionary cousins. For computer scientists, uniqueness can be defined in terms of the specific way in which we process and store information. In each case, while the answer may not be simple, progress is being made.

In my own field, astronomers and exoplanetologists are actually beginning to construct quantitative measurements of our uniqueness, by evaluating the degree to which alien systems and worlds may or may not be suitable for life. Within 10 years, the James Webb Space Telescope may tell us if nearby terrestrial-sized planets exhibit the chemical signatures of a biosphere. Sniffing their atmospheres through the spectra of filtered starlight. And new giant telescopes that are starting to move from blueprints to reality will help do the same.

Significance is trickier and, also perhaps, a question that astronomy gives a unique perspective on. Certainly the frequency with which any kind of life occurs in our galaxy and in the universe as a whole is relevant. We are in the process of refining this question, asking what detailed properties correspond to what abundance of life and not just how little the universe need be different to prevent all life.

But will this be enough? Like it or not, significance is an emotionally charged question for us humans, and it can mean many different things. It can be about whether our home, our planet, our universe matters. It can also be about whether *we* matter, whether we're at all important in this vast cathedral of a cosmos. Or in other words, whether nature gives a damn. It doesn't seem science can help much with that, at least not yet, and one suspects its answers are unlikely to comfort us. Science has told us, though, that we belong to the universe in interesting and deep ways—that we should think carefully about the Copernican narrative of ever-diminishing importance.

Middle ground

It's important to realize that we humans also happen to occupy a position in space and time that allows us to piece this cosmic story together. The accelerating expansion of space itself, confirmed over the past 15 years, suggests that we exist at perhaps the only epoch whose inhabitants stand a chance of correctly understanding the nature of the universe. More than 4 or 5 billion years in the past and we'd not have been able to see this acceleration, and the growth of what's known as dark energy. A hundred billion years in the future and the expansion of space will dim the cosmos from view, blacking out other galaxies from our night sky and effectively removing even the cosmic background radiation. By then stellar evolution will have also profoundly altered the universal mix of elements, largely erasing evidence of primordial nucleosynthesis, as well as most reasonable hopes of deducing that a Big Bang had once occurred.

So has science sealed our fate? The answer is a resounding *no*. Whatever science tells us (and often *because* of what it tells us), we possess the capacity to take matters into our own hands, to *make* ourselves significant. Our solar system and the star systems beyond represent a huge terrain for exploration and habitation. Although there are enormous hurdles to traveling to our sister worlds, much less through interstellar space itself, there is nothing obviously impossible about it.

Even if we content ourselves with just sending robotic avatars out into the universe, by doing so we have the opportunity to alter the fundamental balance of the significance equation. By extending our presence we may not only find a way to extend our species' longevity, but also to modify the most fundamental precepts of the questions we have always asked about our place in the cosmos. We can become the significance that we are looking for.

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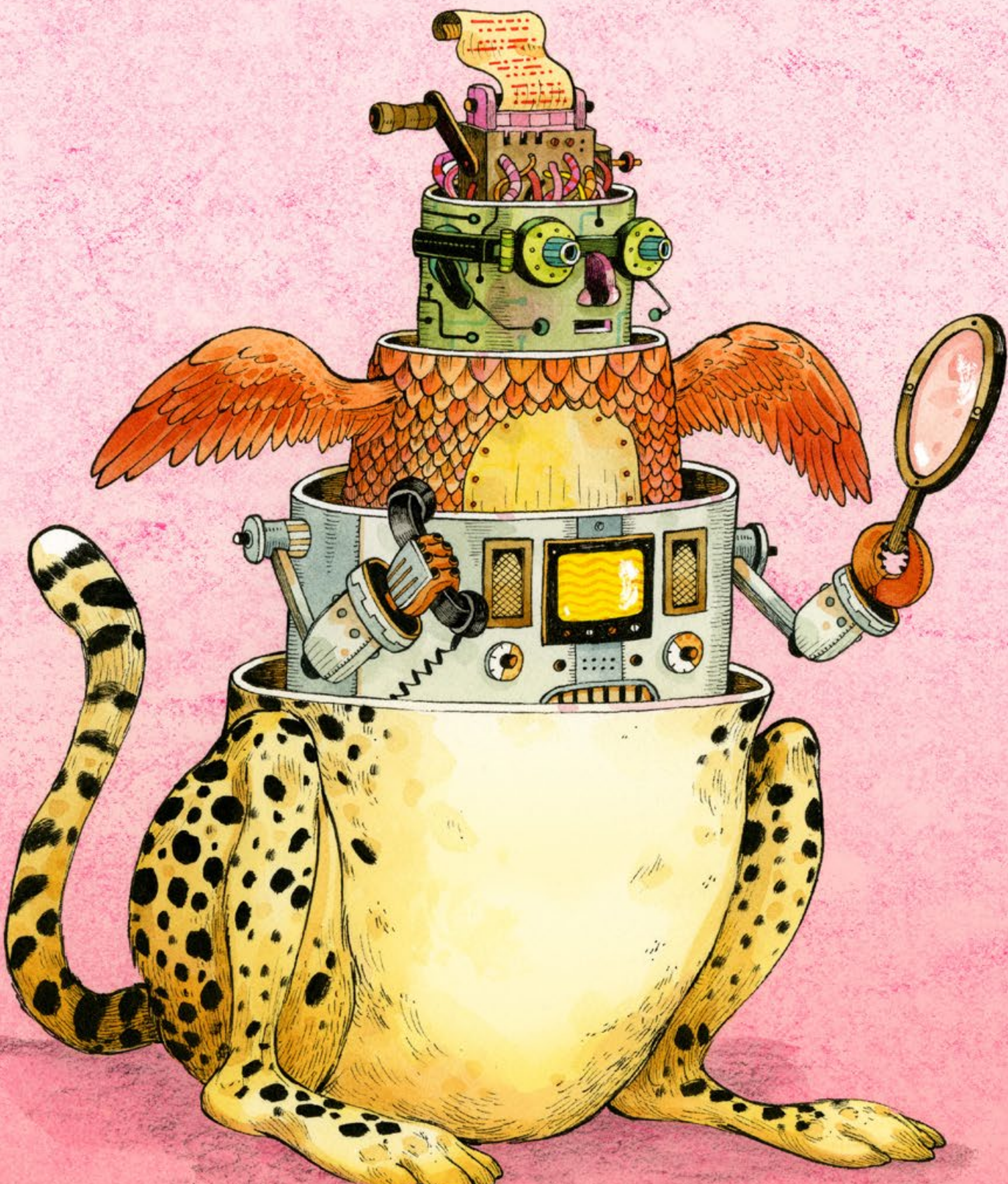

Encounters With the Posthuman

As bodies meld with machines, are we leaving ourselves behind?

BY SALLY DAVIES

ON THE SECOND BALMY day of the year in New York, Neil Harbisson, a Catalan artist, musician, and self-professed "cyborg," walked into a café in the Nolita district of Manhattan. The actor Gabriel Byrne was sitting at a table in the corner. Harbisson approached. "May I do a sound portrait of you? It will just take one minute. For nine years, I've been listening to colors," he explained.

Byrne eyed his questioner from under raised eyebrows. On a slight frame, the 30-year-old Harbisson wore a white T-shirt, deep-pink jeans, and black-and-white showman's brogues. His face was angular, with an aquiline nose and a chin smudged with grown-out stubble. A small plastic oval floated in front of his forehead, attached to the end of a flexible stem that reached around from the back of his head and over a sandy pageboy mop, like the light on the head of an angler fish. This "eyeborg," as Harbisson calls it, converts light into audible sound, with a pitch that varies according to the color of the light.

With a good-natured shrug, Byrne relented. Harbisson darted down next to his quarry, intent, but with a boyish smile that betrayed his excitement. He pointed the eyeborg first at Byrne's ear, then his lips, then his left eye, then the bridge of his nose,

ILLUSTRATION BY JOHN HENDRIX

Since having his eyeborg fitted, Harbisson has been thrown out of churches and department stores.

I AM CYBORG The artist Neil Harbisson, with his "eyeborg" that translates color into audible sound.

and finally his salt-and-pepper hair, scribbling down musical notes on the back of a cardboard coffee-holder. Byrne gave him his agent's email. When Harbisson got back to a computer, he would make a sound file that combined the notes from each bit of Byrne's anatomy, and send it back to the actor. Harbisson's collection already included Prince Charles, Nicole Kidman, and Al Gore.

Harbisson sees the world in greyscale. Born in Belfast and raised in Catalonia in northeastern Spain, as a child Harbisson was diagnosed with achromatopsia, a rare congenital condition in which his eyes' cone cells do not pick up color. He has worn a version of his eyeborg since 2004. It transposes color into a continuous electronic beep, exploiting the fact that both light and sound are made up of waves of various frequencies. Red, at the bottom of the visual spectrum and with the lowest frequency, sounds the lowest, and violet, at the top, sounds highest. A chip at the back of Harbisson's head performs the necessary computations, and a pressure-pad allows color-related sound to be conducted to Harbisson's inner ear through the vibration of his skull, leaving his outer ears free for normal noise. Harbisson, who has perfect pitch, has learned to link these notes back to the colors that produced them. Where once he had to rely on other people's descriptions of how colors looked and what they meant, now he can create his own web of meanings and associations. He even hears sound-color in his dreams.

Harbisson never takes his eyeborg off, even to sleep or shower. The device, he said, "is part of my body." This year, he plans to have it "osteointegrated," inserted into the bone in his skull. It is his feeling of oneness with a qualitatively new sense, rather than the expansion of the sensorium itself, that makes him feel like a cyborg—a word, he noted, that was coined in 1960 as a contraction of "cybernetic organism," in order to describe how astronauts could use drugs and devices to adapt their bodies for space travel. "If we can adapt ourselves to better live in space," he told me, "why can't we adapt ourselves to better live in nature?"

AT LEAST SINCE ARISTOTLE, Western cultures have defined the people that comprise them by drawing a line between humans and machines on the one hand, and humans and other living things, such as plants and animals, on the other. "It needs twenty years to

PHOTOGRAPHY COURTESY OF THE CYBORG FOUNDATION lead man from the plant state in which he is within his mother's womb, and the pure animal state which is the lot of his early childhood," wrote Voltaire, "to the state when the maturity of the reason begins to appear."

Now, however, advances in artificial intelligence, cybernetics, and genomics are blurring the outlines of the once-cozy categories of human, animal, and machine. Under the loose and shifting rubrics of "transhumanism" and "posthumanism," a growing number of artists, philosophers, and self-modifying "biohackers" are looking to redraw the boundaries of the self.

The idea of redefining humans can make people uncomfortable. Bioengineering plays into nightmares about the not-quite-human that have long haunted the West's historical imagination, from the Prague Golem to vampires, werewolves, the monster in Mary Shelley's *Frankenstein,* and the evil automaton David in Ridley Scott's 2012 film *Prometheus*. Harbisson receives angry emails from people who "don't agree that I should be using technology as part of my body, or see it as an anti-natural thing," he said. Since having his eyeborg fitted, he has been thrown out of churches, cinemas, and department stores, and has been attacked three times for wearing it. It is as though humans know that our boundaries are porous, and are horrified when our neat divisions and comparisons break down, and our own contingency threatens to make itself known to us.

In his 1966 book *The Order of Things*, the French theorist Michel Foucault wrote that the concept of "man" is "an invention of a recent date. And one perhaps nearing its end." It was during the European Enlightenment, Foucault claimed, that "man" came to connote a free, self-contained individual who could understand reality through reason and observation. If the tidy taxonomy of knowledge which arose in the 18th century, and which allowed humans to conceive

of themselves as distinct and knowing entities, was to crumble, so too would the human "be erased, like a face drawn in sand at the edge of the sea."

The Enlightenment raised the stakes of human self-definition, and now science is challenging its foundations. Today, technology may be washing away the outline of the human—or it may be reinscribing us upon the sand, just in a different and, perhaps, unrecognizable form.

ONE AFTERNOON IN APRIL, I visited an old box factory next to the Gowanus Canal in Brooklyn. Postindustrial and picturesque, the building had succumbed to its seemingly inevitable fate and was now an interdisciplinary art space. I was shown into a gray-walled backroom, with a single chandelier, where an exhibition of "bioart" was mounted. The work, according to the explanatory panel, stemmed "from recent developments in the field of biology, especially biomedicine, genomics, ecology, and synthetic biology."

Contemporary artists' fascination with genetic and bodily transformation is one sign of a profound cultural shift occurring in understandings of the human. Photographs by the British artist Revital Cohen hung in one corner, depicting people in domestic settings measuring themselves using fantastical arrays of pipes and beakers, under the title "Genetic Heirloom Series." The artist evoked how it would feel to live in a future where we could discern and modify the genetic destiny of ourselves and our family members—including our susceptibility to fatal or crippling diseases. The work appeared at once fabulist and prosaic; given the availability of genome testing today, it seemed infused with preemptive nostalgia for the present. On another wall, the Brazilian-born artist Eduardo Kac displayed a photograph of a vivid pink "Edunia"—a transgenic petunia that had been engineered with genes from the artist's own blood, so that each petal had a veiny red stain. The piece seemed to play on the idea of human identity and the origin of life, the Edunia neither fabricated nor totally natural, neither plant nor human.

No artist has explored the permeable borders of humanity and technology more intimately than the Australian performance artist Stelarc, who has used his body as a canvas for biological and electronic experimentation for more than 30 years. In works entitled "Ping Body," "Parasite," and "Fractal Flesh," Stelarc

SONOCHROMATIC ART The actor Gabriel Byrne sits for a sound portrait. Harbisson also performs on stage by plugging himself into loudspeakers, and playing back the sounds of colored socks or of the audience's faces. A secondary effect of his eyeborg is that he now associates notes with colors; he has translated musical scores and famous speeches into paintings.

Attaining a better form of humanity entails transcending the confines of the flesh.

adorned himself with a web of electrodes and allowed internet users to move his muscles from afar. "Technologies do not simplistically enable or extend us; we can't really separate the body from these systems," he said, in a conversation over Skype. Given his background, I was particularly conscious that our chat was happening across the cyber-ether, where we bridged the distance between us—or the entities I thought of as *us*, as *him* and *me*—by projecting our images and voices as binary bits of information.

"The self is a dynamic interactivity with the world, with others, with technologies—but it's one that's really unstable," Stelarc said. "We need to seamlessly shift from biological functions to machine augmentations to computational code and algorithmic functions." He rolled up his sleeve to reveal his most famous artwork: a partly constructed, partly cell-grown, ear planted in his forearm. He hopes to enhance it with a soft earlobe and an internet-enabled microphone for remote audio-streaming, allowing other people to hear through the ear.

Stelarc can properly be called "posthumanist." Through his art, he suggests that technology is now revealing what has always been the case: that the human subject is a convenient illusion, a gossamer web of interactions and relationships, and should be dismantled. "Identity is not such a meaningful concern anymore—nor is the self," he said. "The more and more performances I do, the less and less I think I have a mind of my own, or any mind at all in a metaphysical sense."

In place of the human, what remains, for Stelarc, is another set of questions. "I think the interesting realm is the realm of what's living and what's not, rather than what's human and what's not," he said. "There's such a blurring now—dead bodies used to disintegrate; now we can preserve cadavers indefinitely with plastination. We can sustain bodies on life support, or we can cryogenically preserve bodies such that at some point in the future they can be reanimated. The most important question is what kind of vocabularies of behavior generate aliveness: how can we define aliveness without necessarily referring to the human?" As the parameters of the human subject shift, this residue of aliveness may become the new battleground for debates about the acceptability and moral status of new technologies.

A DESIRE TO DECONSTRUCT the human is not the only reason to apply technology to the body. Some interventions are about enhancing our particularly human experience of the world. This is most obviously the case when it comes to certain disabilities, where devices can "restore" or "improve" people's functioning, according to what society deems "normal," such as with the use of bionic limbs.

A more extreme example is the futurism of Ray Kurzweil, the inventor and director of engineering at Google, who looks forward to a time when nanobots swarm to mimic living creatures, and when he can load the consciousness of his dead father into a computer. Ideas like Kurzweil's have come to be known as "transhumanism," the belief that humans are in a "transitional" period before we attain the next, qualitatively different stage of experience—possibly in "the singularity," when a new form of technologized, long-lived (or possibility immortal) super-intelligence will emerge. (When I Googled "Ray Kurzweil," a sponsored advertisement for books and vitamin supplements appeared at the top of my search results, informing me that "The Singularity is Near—Stay Healthy, the Kurzweil Way." Presumably Kurzweil hopes capitalism will survive in the singularity.)

A down-to-earth proponent of transhumanism is Tim Cannon, cofounder of Grindhouse Wetwares in Pittsburgh, Pennsylvania. Launched in January last year, Grindhouse is a "biohacker" workshop focusing on human modifications such as implanting magnets in fingertips—not software or hardware, but "wetware." It is part of a DIY, punk-inflected movement known as "grinding," informed by the open-source philosophy of hacker culture.

Cannon, who has a magnet implanted in his left ring finger, insists that his brand of "practical transhumanism" is about helping people to retrieve more information about the world and themselves. "I've started to look at the world as an extremely complex zoo," he said. "I'm watching people run around and participate on their natural data—never doubting their intellectual conclusions, never thinking that they're not getting the whole story."

Cannon sees himself at the start of a process that will, eventually, let humans rein in the damaging impulses we have developed under evolutionary pressure. "A lot of transhumanist people have this hazy notion that the future will drop in our lap," he said. "It will be iterative; even the cell phone was introduced in an iterative fashion." Grindhouse magnets, like Cannon's, allow their implanted "wearers" to feel the electromagnetic fields around live wires, and tingle in the presence of microwaves. The team is currently working on a device, with the working title "Circadia," which can be inserted under the skin and communicate vital information, such as body temperature and heart rate, to a smartphone or through the skin using LED lights.

For Cannon, the human self is a compilation of what we know. The body is fallible and only exists in service of its information-processor, the brain, where the real "self" resides. "The mind is the only thing that experiences the embodied," he said. "The embodied experience is a signal, to be replicated." So attaining a better form of humanity, claims Cannon, entails transcending the confines of the flesh. "Culture is a slapdash fix for trying to escape our animal nature," he observed. "I think there are better ways we can engineer around our animal nature and come to be what we should be." Despite the apparent trangressiveness of Cannon's projects, this urge to self-modify in search of greater knowledge is, in many ways, deeply traditionalist.

THE RISE OF THE cyborg does not necessarily spell our undoing. The assumption by some transhumanists that we can know what makes us human, and improve and refine it using technology, is the product of a distinctively Enlightenment-era sensibility about the progress and perfectibility of man. The inventors of the word "cyborg," Manfred Clynes and Nathan Cline, showed signs of this thinking when they wrote in 1960 that "adapting man to his environment, rather than vice versa, will not only mark a significant step forward in man's scientific progress, but may well provide a new and larger dimension for man's spirit as well."

Harbisson, too, does not see being a cyborg as signifying a break from humans' "organic" state. "It's very human to be a cyborg," he said. "We are constantly developing our senses when we are in our mother's womb, so we just can continue extending our senses when we are outside. I feel that becoming a cyborg is actually getting us closer to nature and to other animal species." Harbisson has extended his eyeborg to capture ultraviolet light,

> *"The self is a dynamic interactivity with the world, with others, with technologies—but it's one that's really unstable." —Stelarc*

which some birds and insects can already see; he also hears infrared, like snakes. Dolphins hear partly through bone conduction, as Harbisson does for color.

After bumping into Gabriel Byrne in Nolita, I strolled with Harbisson along the High Line, the converted railway track-turned-public park in Chelsea. A drill droned away beneath us. "Somewhere between blue and violet," he said, describing the dominant color of the machine's note. We stopped at a viewing platform to watch the traffic stream up Tenth Avenue. "He likes the sound of the yellow cabs," explained Moon Ribas, Harbisson's longtime artistic collaborator, who was walking with us. "Cars are like extreme jazz to him."

Harbisson and Ribas are unusually close. On the day I spent with them, Ribas was wearing a long-sleeved black dress with a rainbow of horizontal stripes down the front, corresponding to the notes for the song "Moon River," a pun on her name, as transposed by Harbisson's eyeborg. The pair grew up together in Catalonia and finish each other's sentences. They share an apartment in Barcelona, above the headquarters of the "Cyborg Foundation," which they founded in 2010 to promote the use of cybernetics in the arts and to protect cyborg rights. They are not romantically involved, although Harbisson's brother and Ribas' sister are a couple. Neither Ribas nor Harbisson want children or a long-term partner, saying that they are enough for one another.

Ribas has also been experimenting with sensory extension. Previously, she has worn earrings that allowed her to perceive the speed of people moving around her, and fitted a device to the back of her head that would alert her when someone approached. When I met her, I noticed that the back of each of her wrists had an egg-sized mass secured to it with black tape.

"It's an earthquake sense," Ribas explained. She had been wearing the bracelets constantly for three weeks. A chip in each device read off several Twitter feeds that monitored seismographs around the world. When an earthquake happened, Ribas would feel a vibration in her wrist with an intensity that depended on the magnitude of the quake. This occurred every four or five minutes. "I'm a choreographer, so I'm dedicated to movement," she said. "I was always looking for ways to perceive movement differently or to approach movement in a different way. And we realized that nature moved for itself, through earthquakes."

AN EAR FOR BEAUTY Harbisson listens to a Mondrian—although the best-sounding artists, he says, are Joan Miró, Andy Warhol, and Mark Rothko. Artists who use many different shades of the same color produce a lot of microtones and sound quite spooky, he says.

The motives behind this bioengineering seem to hew closely to a kind of post-Enlightenment Romanticism, striving for a harmonious union of the human with nature and the environment. I asked the pair whether it would concern them if Ribas were to feel an earthquake that she subsequently discovered had killed large numbers of people. "It's not the fault of the earth, but what we've built upon it," replied Harbisson. In 2001, before becoming a cyborg, Harbisson attracted national media attention in Spain when he camped for nine days at the top of one of the trees in front of a cathedral in his hometown in Catalonia, to protest a government plan to cut them down.

Harbisson and Ribas do not want to tear down the category of the human. Nor do they strive to generate more data about the world, or act more effectively within it. "You can use cybernetics to extend your mental or physical abilities, but we're not so interested in this," Harbisson said. "I think what's most interesting is the link between brain and software. I could use a machine that would say 'green,' and give me the information. This would be a use of cybernetics to extend my knowledge. But I want to extend my senses." For these two, being a cyborg is about enriching our capacity to appreciate the world for its wonder and beauty. Regardless of what form—if any—the human may yet take, perhaps this, at least, will be left to define us.

I joined Harbisson and Ribas as they made their way to the southern end of Central Park, where Ribas was to improvise a dance in response to the stimuli from her bracelets. Ribas slipped into a sleeveless white shift and set a blue compass on the lawn. Her dance was part of a series, and she wanted to begin each one facing north. Harbisson filmed, using a Steadicam device to stop the camera from shuddering. Ribas stood still, back straight, arms by her sides. The earthquake monitors were dark marks on her wrists. After about a minute, her bracelets vibrated and she began to move, rolling her shoulders and juddering, dancing as if to balance on undulating ground.

FEEL THE EARTH MOVE

Moon Ribas wearing a dress whose colors correspond to the notes from the song "Moon River," as translated by Neil Harbisson's eyeborg. The bracelets on her wrists monitor seismic movements around the world, and vibrate when an earthquake occurs. This happens every four to five minutes.

02

"The absence of foundation, whether infallible or probable, is no loss to anyone except tyrants and charlatans, because what the rest of us want from ideas is their content, not their provenance."

DAVID DEUTSCH,
Why It's Good to Be Wrong

Uncertainty

INSIDE OUR INDETERMINATE WORLD

The Deepest Uncertainty

When a hypothesis is neither true nor false

BY AYALUR KRISHNAN

GEORG CANTOR DIED IN 1918 in a sanatorium in Halle, Germany. A pre-eminent mathematician, he had laid the foundation for the theory of infinite numbers in the 1870s. At the time, his ideas received hostile opposition from prominent mathematicians in Europe, chief among them Leopold Kronecker, once Cantor's teacher. In his first known bout of depression, Cantor wrote 52 letters to the Swedish mathematician Gösta Mittag-Leffler, each of which mentioned Kronecker.

But it was not just rejection by Kronecker that pushed Cantor to depression; it was his inability to prove a particular mathematical conjecture he formulated in 1878, and was convinced was true, called the Continuum Hypothesis. But if he blamed himself, he did so needlessly. The debate over the conjecture is profoundly uncertain: in 1940 Kurt Gödel proved that the Continuum Hypothesis cannot be disproven, and in 1963 Paul Cohen proved that it cannot be proven. Poor Cantor had chosen quite the mast to lash himself to.

How is it possible, though, for something to be provably neither provable nor disprovable? An exact answer would take many pages of definitions, lemmas, and proofs. But we can get a feeling for what this peculiar truth condition involves rather more quickly.

Cantor's Continuum Hypothesis is a statement regarding sizes of infinity. To see how infinity can have more than one size, let's first ask ourselves how the sizes of ordinary numbers are compared. Consider a collection of goats in a small forest. If there are six goats and six trees, and each goat is tethered to a different tree, then each goat and tree are uniquely paired. This pairing is called a "correspondence" between the goats and the trees. If however there are six goats and eight trees, we will not be able to set up such a correspondence: no matter how hard we try, there will be two trees that are goat-free.

Correspondences can be used to compare the sizes of much larger collections than six goats—including infinite collections. The rule is that, if a correspondence

exists between two collections, then they have the same size. If not, then one must be bigger. For example, the collection of all natural numbers {1,2,3,4,...} contains the collection of all multiples of five {5,10,15,20,...}. At first glance, this seems to indicate that the collection of natural numbers is larger than the collection of multiples of five. But in fact they are equal in size: every natural number can be paired uniquely with a multiple of five such that no number in either collection remains unpaired. One such correspondence would involve the number 1 pairing with 5, 2 with 10, and so on.

If we repeat this exercise to compare "real" numbers (these include whole numbers, fractions, decimals, and irrational numbers) with natural numbers, we find that the collection of real numbers is larger. In other words, it can be proven that a correspondence cannot exist between the two collections.

The Continuum Hypothesis states that there is no infinite collection of real numbers larger than the collection of natural numbers, but smaller than the collection of all real numbers. Cantor was convinced, but could never quite prove it.

To see why, let's begin by considering what a math proof consists of. Mathematical results are proven using axioms and logic. Axioms are statements about primitive mathematical concepts that are so intuitively evident that one does not question their validity. An example of an axiom is that, given any natural number (which is a primitive concept), there exists a larger natural number. This is self-evident, and not in serious doubt. Logic is then used to derive sophisticated results from axioms. Eventually, we are able to construct models, which are mathematical structures that satisfy a collection of axioms.

Crucially, any statement proven from axioms, through the use of logic, will be true when interpreted in any model that makes those axioms true.

It is a remarkable fact that all of mathematics can be derived using axioms related to the primitive concept of a collection (usually called a "set" in mathematics). The branch of mathematics that does this work is known as set theory. One can prove mathematical statements by first appropriately interpreting the statement in the language of sets (which can always be done), and then applying logic to the axioms of sets. Some set axioms include that we can gather together particular elements of one set to make a new set; and that there exists an infinite set.

Kurt Gödel described a model that satisfies the axioms of set theory, which does not allow for an infinite set to exist whose size is between the natural numbers and the real numbers. This prevented the Continuum Hypothesis from being disproven. Remarkably, some years later, Paul Cohen succeeded in finding another model of set theory that also satisfies set theory axioms, that *does* allow for such a set to exist. This prevented the Continuum Hypothesis from being proven.

Put another way: for there to be a proof of the Continuum Hypothesis, it would have to be true in all models of set theory, which it isn't. Similarly, for the Hypothesis to be disproven, it would have to remain invalid in all models of set theory, which it also isn't.

It remains possible that new, as yet unknown, axioms will show the Hypothesis to be true or false. For example, an axiom offering a new way to form sets from existing ones might give us the ability to create hitherto unknown sets that disprove the Hypothesis. There are many such axioms, generally known as "large cardinal axioms." These axioms form an active branch of research in modern set theory, but no hard conclusions have been reached.

The uncertainty surrounding the Continuum Hypothesis is unique and important because it is nested deep within the structure of mathematics itself. This raises profound issues concerning the philosophy of science and the axiomatic method. Mathematics has been shown to be "unreasonably effective" in describing the universe. So it is natural to wonder whether the uncertainties inherent to mathematics translate into inherent uncertainties about the way the universe functions. Is there a fundamental capriciousness to the basic laws of the universe? Is it possible that there are different universes where mathematical facts are rendered differently? Until the Continuum Hypothesis is resolved, one might be tempted to conclude that there are.

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The Genome in Turmoil

Hope your week went well. It might have messed with your genes

NESSA CAREY

W**HEN PRESIDENT OBAMA** delivered a speech at MIT in 2009, he used a common science metaphor: "We have always been about innovation," he said. "We have always been about discovery. That's in our DNA." Deoxyribonucleic acid, the chemical into which our genes are encoded, has become the metaphor of choice for a whole constellation of ideas about essence and identity. A certain mystique surrounds it. As Evelyn Fox Keller argues in her book *The Century of the Gene,* the genome is, in the popular imagination at least, the secret of life, the holy grail. It is a master builder, the ultimate computer program, and a modern-day echo of the soul, all wrapped up in one. This fantasy does not sit easily, however, with geneticists who have grown more aware over the last several decades that the relationship between genes and biological traits is much less than certain.

The popular understanding of DNA as a blueprint for organisms, with a one-to-one correspondence between genes and traits (called phenotypes), is the legacy of the early history of genetics. The term "gene" was coined in 1909 to refer to abstract units of inheritance, predating the discovery of DNA by 40 years. Biologists came to think of genes like beads on a string that lined up neatly into chromosomes, with each gene determining a single phenotype. But, while some genes do correspond to traits in a straightforward way, as in eye color or blood group, most phenotypes are far more complex, set in motion by many different genes as well as by the environment in which the organism lives.

It turns out that the genetic code is less like a blueprint and more like a movie script, subject to revision and reinterpretation by a director. This process is called epigenetic modification ("epi" meaning "above" or "in addition to.") Just as a script can be altered with crossed-out words, sentences or scenes, epigenetic editing allows entire sections of DNA to be activated or de-activated. Genes can be as finely tuned as actors responding to stage directions to shout, whisper, or cackle.

ILLUSTRATION BY GÉRARD DUBOIS

These directions are encoded through what are essentially little deposits of specific chemicals onto our DNA and proteins called histones, around which our DNA is wrapped like Christmas lights around a tube. The most common form of epigenetic editing is called methylation, in which a methyl group (one carbon and three hydrogen atoms) latches on to either the DNA or the histone. DNA methylation switches off gene expression, while histone methylation may increase or decrease gene expression, depending on the type of methylation and where on a histone it happens.

These modifications don't change the underlying genetic code, but influence how genes are expressed. Some modifications can last a lifetime, keeping certain genes switched off forever, like whited out lines running through entire scenes of our genetic script. If you don't have a tooth growing in your eye or a liver in your knee, thank your epigenome: the differences controlling cell lineage are dictated predominantly by DNA methylation. Other modifications are more like Post-it notes, influencing incremental degrees of gene expression depending on environmental circumstances—allowing cells to react quickly to changes. Permanent changes often involve large amounts of methylation, which make the DNA cling so tightly to the histone that it can't be read, rather like glued-together pages of a movie script.

The long-running debate about nature versus nurture takes on a new complexion in light of this emerging understanding of how epigenetics affects organisms' form and function. The boundary between nature and nurture turns out to be rather porous. For example, when the dominant female in a school of clownfish dies, an epigenetic modification occurs in the male that increases the release of particular hormones and switches his sex to female. Similarly, the difference between male and female crocodiles is not encoded in their DNA; rather, incubation temperatures of 32-33 degrees Celsius will produce males, while females predominate at 30 degrees Celsius and below, thanks to a mechanism like that of the clownfish. Epigenetics has been offered as an explanation for why genetically identical mice kept in identical conditions can have a range of body weights, or why one of a pair of identical twins can develop schizophrenia, while the other remains perfectly healthy. Stress, diet, and exposure to environmental toxins are thought to be some of the common epigenetic triggers in humans, although the processes are still poorly understood.

All creatures, then, live in two histories at once: their inherited evolutionary history, built up by their ancestors over many thousands of years, and their personal organic history, lived through a single life cycle. Epigenetics is a bridge between these two domains, adapting evolutionary advantages to the demands of the present moment. It etches the uncertainty of our life experience directly onto our biology. In fact, philosophers of genetics Paul Griffiths and Karola Stolz have gone so far as to suggest that we abandon the idea of genes as fixed units of information and define genes instead as "things you can do with your genome."

Consider the example of alcohol. Inexperienced drinkers get tipsy fast. But later in life, if you continue down this dissolute route, your alcohol tolerance increases. To keep up with an increased drinking habit, the liver adjusts the epigenetic information on the genes that produce alcohol-metabolizing proteins, "turning them up" so that alcohol is broken down faster. If we cut back on our booze, the liver "turns down" those genes' expression, since it would be a waste of the body's resources to produce an excess of those proteins. Epigenetic modifications may also contribute to alcohol cravings: when alcohol is consumed over a period of time, it appears to prime a gene that is responsible for higher levels of neuropeptide Y, a neurotransmitter that helps manage anxiety. But if the drinker turns down her consumption, the gene that modulates neuropeptide Y switches off, leading to the anxiety associated with alcohol withdrawal.

As scientists learn more about these epigenetic acrobatics, new medical treatments are emerging. Research suggests that chronic diseases with no obvious genetic roots may be the result of genes locked into abnormal patterns of expression by epigenetics. For example, Zolinza is a new drug licensed to treat a blood tumor called cutaneous T cell lymphoma. Zolinza inhibits enzymes that remove acetyl molecules from epigenetically-enhanced histones, allowing acetyl groups to build up and switch on certain tumor-suppressing genes. Vidaza, a drug used to treat the preleukemic condition known as myelodysplastic syndrome, works in a similar way by inhibiting DNA methylation, which also turns on tumor-suppressing genes.

But many of the mechanisms underlying epigenetics continue to resist our understanding.

Among these is the heritability of epigenetic modifications. A strange phenomenon was observed among children who were born after the Dutch famine of 1944, known as the "Hongerwinter" or Hunger Winter. The occupying Germans had blockaded the northern and western regions of Holland as a form of collective punishment, and food became painfully scarce. After the war, scientists discovered that children conceived during the Hongerwinter had a higher than normal risk of obesity, cardiovascular disease, and other health problems, compared to their siblings conceived before or after the famine. Surprisingly, so did their children—even though the second generation hadn't experienced the original episode of malnutrition, even in the womb. Similar phenomena were observed among survivors of the Biafra famine in Nigeria between 1968-1970, and the Chinese famine of 1958-1961 during Mao's Great Leap Forward. The most likely explanation for these cases is that epigenetic changes caused by the original episodes of famine were passed from parent to child. Recently, scientists have found signs of methylation in the genomes of Hongerwinter survivors, including on those genes associated with cholesterol transport and aging.

When and why epigenetic modifications pass on to the next generation is unclear. Enzymes strip most of the epigenetic data from our DNA when it is funneled into producing sperm or eggs; those cells only contain epigenetic traces necessary for their own functioning, not for the phenotypes of the organism that they will go on to produce. When the sperm and egg merge to form a single cell, another wave of enzyme activity strips off epigenetic data specific to the egg and sperm, and replaces it with information which controls the gene expression required for the fetus' early development. But apparently there are tracts of DNA where epigenetic information from the parents stubbornly persists. But we don't know what that information is, or where it is stored.

The notion that creatures' life experiences could shape the next generation is actually a very old idea. The fabled Greek physician of antiquity, Hippocrates, wrote of a quasi-mythical race of people known as the Macrocephali that had succeeded in cultivating long heads by molding the soft skulls of their newborn babies. The French naturalist Jean-Baptiste Lamarck picked up on this concept in the early 19th century, proposing that organisms acquire characteristics during their lifetime that can be passed on to offspring, although his ideas were widely discredited by Darwin's successors. When evidence supporting complex patterns of epigenetic modification emerged in the 20th century, many biologists remained resistant.

It turns out that the genetic code is less like a blueprint and more like a movie script, subject to revision and reinterpretation by a director.

In part, this reluctance is a familiar story in every scientific field where new ideas challenge long-entrenched theories. But perhaps part of the initial aversion to epigenetics was motivated by something in our cultural consciousness. Epigenetics undermines age-old ideas of the organism, particularly the human being, as having a stable essence—whether it is a divine soul, a curled-up miniature being waiting to unfold into a fully formed adult, or a molecular program from which we can read off a biologically predestined future. The claim that "it's in our DNA," it seems, no longer offers the reassuring bedrock of certainty that we once thought it did.

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Epigenetics at Work

Four fun facts

BY YVONNE BANG

To petal or not to petal

LINARIA VULGARIS

Known for its layered and frilly blooms the color of butter and eggs, toadflax, a plant in the snapdragon family, can boast flowers of varied styles. Two genetically identical toadflax plants can grow petals of different shapes, depending on whether the gene LCYC, which controls petal symmetry, has been silenced or not. When the LCYC gene is switched on, the petals curl up and around the stamen and carpel like delicate tongues. When the gene is heavily methylated and, consequently, deactivated, the petals spike straight out like a ninja star.

Instant armor

DAPHNIA

Daphnia, crustaceans three times smaller than mosquitoes and also known as water fleas, are experts at building fortresses out of themselves. In dangerous times, when predators such as the common carp and yellow perch swarm around, the tiny fleas grow tail spines, helmets, or neck teeth from their cuticle, a shell-like layer of skin. “It makes them look bigger and, also, it’s harder for a small predator to physically eat them,” explains Mount Allison University biologist Vett Lloyd. The growth initially happens over the flea’s lifetime, but the physical trait can get passed onto the second and third generation if the environment remains unsafe. But Daphnia grandchildren won’t exert energy building the extra armor if there is no threat. “Assuming there are no predators for their offspring, they’ll cut back because it’s energy-expensive,” Lloyd says.

ILLUSTRATIONS BY KATIE SCOTT

Skinny Minnie

AGOUTI LAB MICE

Genetically identical Agouti lab mice can be brown, yellow, or spotted depending on the behavior of the "agouti gene," as scientists call it. Brown mice have the gene turned on only in the hair follicles, but in yellow mice it is switched on in every cell of the body, affecting, among other things, the rodents' ability to feel satiated. "They literally eat themselves to obesity, diabetes, and cancer," says epigeneticist Randy Jirtle at the University of Wisconsin. When a yellow mouse's diet is enhanced with methyl-rich supplements—such as folic acid, choline, betaine, and vitamin B-12—during pregnancy and until her offspring are weaned, the agouti gene will be controlled in the body via methylation. This results in more pups (but not all) turning out brown, slim, and with lower incidences of diabetes and cancer, Jirtle says.

Royal treatment

APIS MELLIFERA

Queen honeybees have the same genes as worker bees, but are double the mass, live two years as opposed to the worker's six weeks, and have the ability to reproduce. Who gets to be queen? Those who eat more royal jelly, the proteinaceous secretion worker bees produce with hypopharyngeal glands in their heads. Bees chosen to become queens are fed royal jelly all six days of their larval stage while other bees get the treat for just the first two. "The only difference between the queen and the worker is their diet," says Christina Burden at Gro Amdam's Arizona State University honeybee lab.


והו ילי סיט עלם מהש ללה
אכא כהת הזי אלד לאו ההע
יזל מבה הרי הקם לאו כלי
לוו פהל נלך ייי מלה חהו
נתה האא ירת שאה ריי אום
לכב ושר יחו להח כוק מנד
אני חעם רהע ייז ההה מיך
וול ילה סאל ערי עשל מיה
והו דני החש עמם ננא נית
מבה פוי נמם ייל הרח מצר
ומב יהה ענו מחי דמב מנק
איע חבו ראה יבם היי מום

The Hidden God

One man's path to knowing less about God

BY TODD PITOCK

D**AVID FRIEDMAN MOVED FROM** Denver to the Israeli city of Safed in 1979 to live as a Haredi, or ultra Orthodox Jew. At 29, he and his wife Miriam already had four children. He enrolled at a yeshiva where he drew a salary to study Talmud. It seemed like a splendid arrangement, a path into a life of spiritual consciousness. Friedman plunged into his studies headlong, mastering difficult texts in Hebrew and Aramaic. "It was my job," he told me. "I was pretty serious about getting there on time, spending the whole day studying like we were supposed to do, and also serious about prayer."

But as months and then years went by, he began to feel frustrated. "Everyone around me would rush through prayers and not get into it. Where were they going? They were staying in the yeshiva the whole day, so why rush?" Prayer started to feel less like a spiritual experience. Friedman believed that the mitzvoth, the commandments in Judaism, would lead him to spiritual experiences. But those experiences weren't happening. He felt himself becoming alienated from the people around him. Something was missing.

72 HOLY NAMES by David Friedman. Each of the three-letter sequences read right to left, from blue to green, comprises one of 72 Names of God. Reading down the columns—starting first with the blue letters from the upper right corner, then next the red starting at the upper left corner, and finally the green characters back at the upper right—are the three 72-character verses (19, 20, and 21) of Exodus Chapter 14.

PAINTINGS BY DAVID FRIEDMAN

His spiritual struggles suddenly gained a physical dimension. Seven years after arriving, he was diagnosed with stage three non-Hodgkins Lymphoma. Friedman moved back to Denver for chemotherapy with much to consider. He had followed the strictest prescriptions of his faith to the letter. But he had not yet found God in Safed, at least not the way he'd expected. And, by letting him get cancer, God had apparently not found Friedman.

Friedman's ideas of God changed dramatically around this time, he would tell me years later. God became an unknowable entity. "I know people who think their beliefs have been proven scientifically," he told me. "But it's more like shooting an arrow and then painting the bull's eye around it. I don't think that's what we're supposed to be doing. You have to learn to accept what you don't know, what you can't know." The devotee has to arrive at a kind of knowledge that one medieval philosopher described as a "cloud of unknowing."

The history of the idea of God has consisted of two equal and opposite themes: a God in man's image (God creating man, or vice versa), and God as pure abstraction. A man-like God makes God relatable. He has personality, and sometimes even a chance to make a flesh-and-blood appearance. The abstract God, on the other hand, embodies the unreachable ideal, pure goodness, and origination. This tension is visible across Abrahamic religions. In Christianity, a physical son of God is balanced against ideas like the Holy Spirit. Islam prohibits representational art, even of people, because they might suggest an image of God in the worshipper's mind. The Islamic tradition presents a paradox: man cannot know God, but also should approach God through cultivating a consciousness of the "face of God". A hadith quotes God telling Muhammad, "I was a hidden treasure; I wanted to be known."

The Jewish biblical tradition goes through a linear evolution between these themes. Adam, Eve, Cain, Abel, and Noah all encounter God. He comes in person to tell Abraham and Sarah that they'll be nonagenarian parents, and then demands that Abraham offer his child, Isaac, as a sacrifice. But by the time Moses appears and witnesses the Burning Bush, God has changed in character.

"The image of the Burning Bush captures that God is material and non-material at the same time," Harvard University history professor Peter Gordon told me. "Then it evolves so that by the time you get to the prophetic books there's a pronounced emphasis on God's abstraction, and then by the medieval period God's incorporeal nature solidifies into a dogma." Alan Mittleman, professor of modern Jewish thought at New York's Jewish Theological Seminary, the leading institution of Conservative Judaism, said, "the classic text is Exodus 33. Moses asks to know God's ways. Moses says, 'If I have found favor in your eyes, let me see your substance, your being', and God says 'no man can see my face and live. So I'll show you my goodness and it will all pass before you.'"

The duality of the concrete and the abstract God naturally sets up a difficult boundary. The faithful needed some kind of definition—a dotted line around a set of characteristics, no matter how broad. But the development of an uncertain God made even this a challenge. "There's always a kind of struggle to sustain the idea of a pure God as Other," Gordon notes. "It's inherently unstable. The minute you begin to think about it, and imagine the relation between the divine Other and humanity, you compromise it. Some other relation bridges the relation between us and the unknown God."

In Judaism, one of those bridges was the development of Kabbalah.

ALONG WITH JERUSALEM, TIBERIAS, and Hebron, Safed is one of the four holy cities in Judaism. Set in stone atop Mount Canaan, the clear air, shimmering blue skies, and hills that ripple like waves into the horizon remind you of the Rockies. Jewish mystics associate Safed with the primordial element of air (Jerusalem, Tiberias, and Hebron are earth, water, and fire). When the weather turns, mist envelops the mountain and surrounding forest like a shawl, a phenomenon that must surely have encouraged the mystics who have made Safed famous—though they preferred the nighttime, when they would study and gaze at the profusion of stars and ponder eternity.

The old part of Safed is a warren of stone passages connecting houses of worship and religious institutes, homes, shops, galleries, and studios. The city has been destroyed by earthquakes, rebuilt, and grown well beyond its medieval boundaries. The use of similar materials on newer structures gives them an ancient

Creation was not a revelation; it was an act of concealment.

look almost as soon as they're finished. A late Mamluk postal station, one of a number of 400-year-old buildings still in use, is the Rimon Inn. Street lamps, ensconced on smooth stone walls, cast a pale light at sundown, like medieval torches.

Safed's heyday was in the 1500s, following the cataclysm of the Spanish Inquisition and the subsequent expulsion of Jews from Iberia in 1492. Bringing the flourishing Jewish society in Moorish Spain to an abrupt end, the disaster convinced some Jews it was the End of Days. As ravaged communities dispersed from Spain, many went to Palestine. At the time, Safed was a thriving textile center about 13 miles north of the Sea of Galilee, and Jerusalem was a backwater.

Prosperous and free, Safed also held the graves of the great rabbinic figures of the second century. Medieval Jews saw this as a reflection of their own situation—they had flourished under Roman rule until it ended catastrophically in exile and dispersion. Drawn to Safed by these practical circumstances, and the connection to their past, the gathering of Jews in Safed in the 1500s gave it the greatest concentration of rabbis and scholars since Roman times. It was in this climate that the Jewish mystical tradition of Kabbalah took root. Stretching back to 12th century Spain and France, and to other forms of mysticism further back still, Kabbalah concerns itself with the relationship between an infinite God (or *Ein Sof*, which means no end) and a finite universe.

As with any mystical tradition, defining exactly what Kabbalists believe is a tricky business. Matthias Riedl, an intellectual historian who serves as director of the Center for Religious Studies at Central European

"ALEPH SUNRISE" by David Friedman. The first Hebrew letter, Aleph, is inscribed on the image of the sun, fixed between the red sky of Heaven and the blue waters of Earth.

The divine is something that can only be understood in paradoxes.

University in Budapest, describes it this way: "the mystical theologians say the divine is something that can only be understood in paradoxes. The basic idea is that God is beyond any knowledge that can be conceived in any analogy to visible things or the sensual world. But they would never say therefore we cannot have any knowledge of God at all. Instead, you need a different type of knowledge, a non-linguistic knowledge."

After his cancer diagnosis, Friedman left Safed for eight months of intensive chemotherapy in Denver. A friend gave him books on meditation and visualization. There had been a time when he was so sure of what he knew, he wouldn't have bothered. One book was by a Jewish rabbi and philosopher, Arye Kaplan. Although he was learned in Judaism, Kaplan wrote in English, not Hebrew—a strike against it, for the typical Haredi. As Friedman began to practice the visualization techniques, he began to feel much less certain. A new space opened up. As his physical recovery progressed and he worked on meditation techniques, he read, and he found that he could deepen his concentration and contemplation. He found that ideas associated with Eastern mysticism had a long tradition in Judaism. But that also meant that other traditions were equally valid. "I realized that I'd been mistaken and judgmental and ignorant," Friedman said. "When I read about Eastern mysticism, I saw that we say the same things, and that a lot of traditions say the same things."

The chemo caused his hair and beard to fall out, and it hadn't grown back by the time Friedman returned to Safed. The change in his appearance belied the internal change that he was undergoing and, at first, people allowed him the space—until his hair grew back in. Once he looked familiar, they expected him to fall back into line, as if he'd been on a vacation and now it was time to get back to work. He felt their impatience and disapproval. One day he went to the mikveh, the Jewish ritual bath, and stood on the edge of the water unable to get in. Instead of the spiritual cleansing exercise it was meant to be, Friedman saw dirty water, the potential for infection when his body was still vulnerable. He got dressed and left.

He looked around and saw how his identity was tied up with people who dressed as he did, but with whom he no longer really identified. "I wanted to make a statement," he told me. "First I tried to make it by changing my clothes. I'd worn Hassidic garbs to fit in, but now I changed that. I went from a long black suit to a short one and a different hat. A lot of people began to avoid me."

Friedman stopped studying Talmud and began practicing yoga. "When I first started, I learned the corpse pose where you go into deep relaxation. Until then I'd probably never experienced deep relaxation. It was very healing, and it gave me new insight into something like Shabbat: deep rest is healing and really important. And yet, the way I'd been living, it was possible to keep Shabbat to the letter of the Law and not experience that deep rest."

From this new line of thinking, Kabbalah was a short distance away. "I came to see the dual aspect of spirituality, that God is both unknowable but we

Fragments of divinity, then, were everywhere.

also experience God in the known," Friedman said. He opened an art studio, painting and drawing Kabbalist shapes and patterns—his expression of faith was, in the words of Riedl, overcoming language. One painting of his, "A Tapestry of Holy Names," features Hebrew letters arranged in rows, repeating patterns that invite the viewer to reflect on ideas connected to *Gematria*. This is a system of Jewish numerology that assigns each letter numerical values that in turn have spiritual associations. To Friedman, the different spellings of the same names represent the different levels of how we understand the manifestation of God. For the Kabbalist, God makes Himself known by 'clothing' Himself in the ten attributes of primordial man—the *sefirot*. The numerology is tied to stories and metaphors that are meant to help explain these attributes, another way of approaching the ineffable ideal.

IN 1569, RABBI ISAAC Luria joined a Kabbalist community in Safed. By the end of his life, through oral lessons given to his students, he had changed the tradition permanently. Most modern Kabbalah reflects these lessons—the Lurianic Kabbalah. Luria was a charismatic figure who had spent years living as an ascetic, barely communicating with his own family. He also was a well-known mystical poet. He challenged his followers to dedicate themselves to revelation and self-purification through fasting, prayer, and study; they often gathered in forests and open fields for stargazing. Luria claimed to be reincarnated from Shimon Bar Yochai, the second century rabbi whom Jews believed had unearthed sacred knowledge while hiding from the Romans in a cave for 13 years. Jewish tradition credits Bar Yochai with the authorship of the foundational Kabbalist text, the Zohar, although scholarship points to Moses Ben Leon, a thirteenth century sage.

Luria's thinking built on that of earlier Kabbalists, and on Aristotle and Plato. His most radical idea was that God had withdrawn to make space for the world. Creation was the result of God contracting his divine and infinite light to create space for finite, independent spheres. The "empty space," the vacuum, he called the *tzimtzum*. Creation was not a revelation; it was an act of concealment. "God had thus created a place where he was not, an empty space that he could fill by the simultaneous process of self-revelation and creation," writes Karen Armstrong in *A History of God*. "It was a daring attempt to illustrate the difficult doctrine of creation out of nothing: the very first act of En Sof was a self-imposed exile from a part of himself."

Deeply ingrained in the Kabbalist tradition, then, is the idea of a God that is inscrutable—that he has, in fact, hidden himself. And from this starting point emerges a whole system of ethics. That's because, according to Luria, God's withdrawal was a catastrophe. The original harmony of creation was destroyed, and the divine sparks it contained scattered into the formless waste of *tohu u-bohu,* or exile from the Godhead. The task fell to humanity to retrieve the sparks through devotion to God and love of fellow man, or in the language of

“CHAOS AND ORDER” by David Friedman. According to the Kabbalah, the world existed in a state of chaos at the beginning of creation. This choas then collapsed to create order.

DAVID FRIEDMAN'S practice of Jewish Meditation and study of Kabbalah influence his painting.

PHOTOGRAPH BY TAL SHAHIR

the Kabbalists, deeds of loving kindness. The universe could be repaired, and it was up to us.

Fragments of divinity, then, were everywhere. God was in the world—and out of it, at the same time. In this way Kabbalah bridged the everyday with the unknowable. It also addressed other vexing issues. For example, how could God let evil exist? It's because his original harmony was destroyed. In his wholeness, God was good and only goodness could exist. But evil could exist in pieces. Why did God create man? Because God depended on man to be made whole again. And so on.

"It is something integral to the Jewish tradition: the distinction between God's being and his ways," Mittleman told me. "The uncertainty of what God is does not, though, leave Jews directionless or confused or adrift in what they do with their lives, or how they see their lives in covenant with this unknowable God."

Just as Kabbalah teaches that God cannot be known, so Kabbalistic art tends to be abstract and conceptual—even vaguely reminiscent of the Islamic mosaics, which take the place of representational art. "Negative theology works in a way that you speak about God in concepts that are totally inadequate," Riedl told me. "You think of him as a father or you think of him as a shepherd or as a lord or as a creator. You talk yourself into ever more abstract concepts until you overcome language and you only experience. There you have a knowledge that is not knowing in any common understanding of the word but is still somehow knowledge."

I read Riedl's analysis to Friedman.

"I agree with that," he said. "The Hindus say 'neti, neti,' meaning, 'It is neither this nor this.'"

THE CRYPT OF BAR Yochai, the purported author of the Zohar, is in a stone building with a modest white dome and blue gates in a village not far from Safed, called Meron. Lag B'Omer, the anniversary of Bar Yochai's death, draws hundreds of thousands of visitors. Men and women daven, or pray, in two different sections of the complex, their eyes sometimes focused on an open book, sometimes closed, their prayers either personal or committed to memory. Their lips move; words spill in a firm murmur, so the place acquires a kind of rumbling hum. Many of the men genuflect, and some rub their faces on the velvet curtains that veil the marble structure over the grave itself. Beggars are everywhere, asking for change, usually successfully. The Kaballah calls for acts of loving kindness, so giving to a beggar takes on an aspect of divinity.

The pilgrimage reflects the deep echoes of Kaballah across Judaism. Kabbalist teachings suffuse Jewish liturgy and practice. And their spiritual heirs, the Hasidim, are a powerful presence in the Jewish community. Talking to them, I am reminded of why so often in Jewish history the rationalists have been dismissive of such scenes. The line between mysticism and magical thinking can become easily blurred. Friedman is one who sees Meron through the lens of a skeptic. "Who even knows who's buried there?" he said. "A person's value is in his teachings."

I visited Friedman early this spring in Safed. He is a content 56-year-old grandfather and successful artist, and less of an outlier within his community. When I first met him about 15 years ago, he and his neighbors were in a state of hostility over his change and his rejection of their values. He observed the Sabbath and kept kosher. But his presence was a threat.

Now, though, all of that seemed to be behind them. He and his wife Miriam, who herself went through epiphanies, from a secular upbringing to ultra Orthodoxy to her husband's viewpoint, have five children and 11 grandchildren. They get along with their neighbors, even if they don't agree on everything. Safed is much more relaxed and tolerant than many communities in, say, Jerusalem. Friedman's gallery is successful, and his art is shown in international galleries.

He reflected on his own journey. "You get sick and you wonder why it happened. You can't know. As humans, we can only know a certain piece. Kabbalah means 'accepting,' and one of the things it challenges us to do is to accept that there is a curtain between God's knowing and our not knowing," Friedman said. It sounds simple. But simplicity, Friedman says, "is hard, not easy."

TODD PITOCK, a writer in Philadelphia, has reported stories from across the Middle East.

The Coin Toss and the Love Triangle

There are two flavors of uncertainty in our lives. Math helps with both

BY SIMON DEDEO

"I returned, and saw under the sun, that the race is not to the swift, nor the battle to the strong, neither yet bread to the wise, nor yet riches to men of understanding, nor yet favour to men of skill; but time and chance happeneth to them all." *Ecclesiastes 9:11* (*King James Bible* [*Pure Cambridge Authorized Version*]).

CHANCE APPEARS TO NAME a single, unitary thing. But its genealogy, its family history, turns out to be a tangled one. One way to understand its branching origins is to turn to literature: We may look, in turn, to two very different novels.

Anton Chigurh, the antagonist of Cormac McCarthy's novel *No Country for Old Men* forces his victims to guess the outcome of a coin toss, taking their life if they guess in error. McCarthy's villain forces blind chance into his victims' lives in the most brutal way. That chance is entirely contained, not in Chigurh, but in the toss—in nature itself. This is one source of uncertainty.

To understand the second source, we travel as far as possible from McCarthy's American Southwest. The first volume of Henry James' *The Wings of the Dove* ends with Milly Theale, a wealthy American heiress, visiting the National Gallery in London. To her surprise, she sees an acquaintance, Merton Densher, in the company of her best friend, Kate Croy. The plot of the book from this point forward hinges on a single question: Will Milly learn what the reader already knows—that Merton and Kate are in love and secretly engaged to be married.

In the sequence, told from Milly's point of view, we see how Kate—caught sharing an intimate afternoon—acts in such a way as to generate an alternate hypothesis for her friend: that Merton may well be keen on her, but that she, Kate, is not keen on him.

Here are uncertainties not otherwise found in nature: probabilities about probabilities, beliefs about beliefs held by others.

For many of us, the material world of the coin toss may be a byword for chance. But the cognitive world of the love triangle is just as fraught and, at its limits, just as much a form of chance as a tumbling coin. We humans are capable of introducing a degree of uncertainty both dizzying and unavoidable.

Therefore, Ecclesiastes was right twice over. Uncertainties—both natural and human—must be dealt with even by the swift, strong, wise, and able. Our objective

ILLUSTRATIONS BY GÉRARD DUBOIS

is to demonstrate the depths of each kind of uncertainty and to introduce mathematics that can help us come to terms with both.

I. The Coin Toss

> *"What's the most you ever saw lost on a coin toss?"*
> No Country for Old Men, *Cormac McCarthy* (2005).

Sufficiently many fictional murderers have toyed with their victims that, today, the idea borders on cliché and parody. But Chigurh's game chills us still, perhaps because of the concentrated form of his message. His impartial, deadly coin toss is a reminder of the dominance of chance in our own lives.

From the accidents we have avoided or been met with, to the relationships we have formed and the institutions we have come to be associated with—each fact about ourselves appears to depend on a series of events, any one of which could have gone another way. To stand on top of a tower of such coincidences and look down gives us a hint of vertigo. Which aspects of life are real, we ask, and which simply luck?

This question is, on the one hand, at the heart of much literature and art; on the other, it is a hardheaded question in the mathematical sciences.

In particular, the branch of mathematics known as *information theory* concerns itself with how to describe chance and uncertainty. It reconciles the unlikeliness of any particular life with the intuitive sense that the shape of one's life is not simply a matter of chance.

To see how, let us begin at the beginning, at the base of the tower of coincidences. Suppose Chigurh's coin toss is fair—equally likely to come out heads or tails. What are the possible strategies his victim should consider? Always guess tails? Heads? Some alternation?

Should the toss be fair, no strategy is better than another. Indeed, strategies are indistinguishable from each other. This is due to the symmetry of the problem: We can swap the labels on each side of Chigurh's coin at any time and thereby convert any prescription into any other. In McCarthy's desert landscape, strategy and reason are meaningless. The vertigo of chance is upon us.

This, of course, doesn't describe the world we normally confront. In our world, there is predictability, with a preference between outcomes* and the possibility of rational choice. Broken symmetries makes reason relevant to our lives.

But this doesn't rescue us from the vertigo of chance. Suppose, for example, Chigurh's coin is slightly more likely to come up heads. Now strategies are distinguishable. For a heads-biased coin, the preferred and most rational strategy is to always to guess heads.

But, in the course of your life you need to make many decisions. What if you had to guess the coin toss more than once? Consider tossing the biased coin a thousand times. Since each toss is independent of the one before, the most likely outcome is the repeated occurrence of the most likely outcome of each one separately. And thus, of all the possible histories we could foresee, the strangest sequence of all, an unbroken run of heads:

HHHHH ... H, 1,000 times

is the single most likely. Our intuition is that such a sequence will never, in fact, occur.

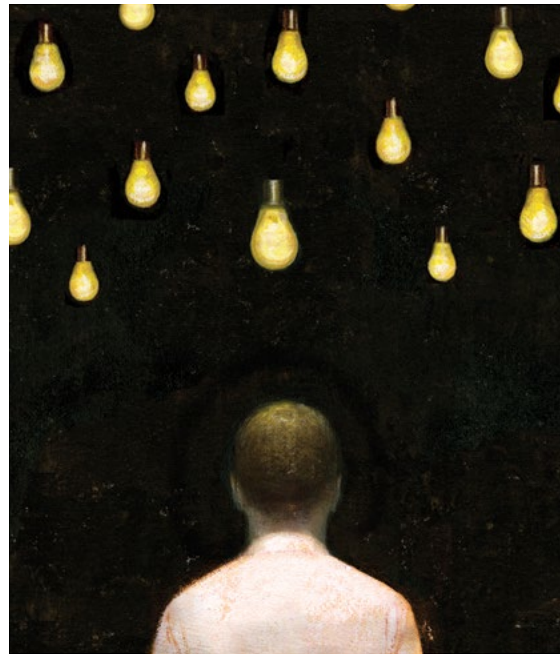
And of course we are correct. Fix the bias of the coin at 60 percent heads. The chance of heads on a first toss is (by definition) 6 in 10; of two heads in a row, a little over 1 in 3. The chance of three heads in a row is only a little better than 1 in 5.

The chances of an unbroken run decrease exponentially; the chance of ten heads in a row is less than 1 percent, and a few more doublings suffice to place the chances beyond the astronomical. It is unlikely to see an unbroken run of heads in 80 tosses, even if one completes such a sequence once every second for the 13 billion years the universe has existed.

We've established that a string of unbroken heads is extremely unlikely. But any other history is even

* The inscriptions on the two sides of a coin have different forms and weights; this difference imprints itself on how coins behave in the real world, as can be seen by balancing a dozen pennies on their edge, and thumping the table to make them fall. A tossed coin is less sensitive to these effects, but (more seriously) is sensitive to the side facing upwards at the beginning of the toss—the bias is roughly 51-49 in favor of the coin showing the side that faced upward at the start.

In McCarthy's desert landscape, strategy and reason are meaningless.



more so. As time passes, every narrative becomes an extreme rarity. Despite the existence of a "most rational" choice, the particulars of your life describe a very unlikely path. The biased coin, which signifies the possibility of reason, does not relieve our vertigo after all.

Yet we also know that some things *are* routine, expected—even, at times, part of our birthright—and others less ordinary. A friendship might depend on having shared a freshman seminar, but is it so unlikely to have made a friend in college?

This intuition has a mathematical grounding, in what is called the *typical set*. The typical set is the mathematics behind our feeling of normalcy. It reconciles reason and chance by linking the nature of the singular event to the properties of the history it belongs to. More than biased probabilities, it challenges the vertigo of pure chance.

Consider the space of all possible histories: an exhaustive list of every sequence of events that might have occurred. Every coin toss, every decision ever made. The typical set bounds a very small region in this space and describes the path that we, as time goes on, are increasingly likely to follow. Given a prescription for the probabilities of individual decisions, the typical set picks a list of histories whose rates of uncertainty accumulation become increasingly close to each other, and match, on the average, the intrinsic rate of the probabilities themselves.*

* The relationship between a history in the typical set and the underlying chance events that produce it is somewhat akin to the train conductor who makes up time along his route. In the short run, one might be delayed—or arrive ahead of schedule; but on the longest journeys, one finds the train pulls in exactly as expected.

Let's return to the freshman seminar. Your college life is a series of chance events whose probabilities are set by a finite list of constraints: your major, your age, and so on. As your college days run on, the set of possible histories you are likely to experience converges with those found in the typical set your constraints define. Each individual history is rich in idiosyncrasy while being drawn from a narrowly circumscribed set of possibilities that is much smaller than the space of all that might happen.*

We are left in a profoundly ambiguous place. The typical set rescues normalcy but also dictates typical lives, common stories: boy meets girl, dog bites man. This wisdom was also known to the author of Ecclesiastes, who wrote that there was "nothing new under the sun." To the swiftest, the race might go once, or even twice, but on the longest scales of time no streak is left unbroken.

At the same time, our pasts and our futures—even our most likely futures—are, in their details, profoundly unlikely things.

An information theorist may not know the exact world we live in, but she does know that, in the long run, it's a world in the typical set. And she also knows that she *doesn't* know anything else.†

So much for coin tosses and freshman seminar assignments: things external to ourselves, driven by the chances of the physical world.‡ These material things, however, are not the only—or even the most important—sources of life's uncertainty. To see that we turn from Cormac McCarthy's American Southwest to Henry James's London.

II. The Love Triangle

> *"Little by little indeed, under the vividness of Kate's behaviour, the probabilities fell back into their order."* The Wings of the Dove, *Henry James* (1909).

It is a remarkable fact about the structure of our reasoning that probabilities can be understood to represent not only chances of outcomes in the physical world, but the strength of the convictions we hold within our minds.§ This has been known explicitly only since the 1940s, when the physicist Richard Cox derived the laws of probability from a set of logical postulates. His work was then adapted by key figures such as Edwin Jaynes (another physicist) to found an account of chance based on *degrees of belief*—to go from biased coins to biased thoughts about them.

It is under this latter understanding of chance that James' narrative best shines. Milly must make sense of the unexpected: Merton and Kate together in the National Gallery. Under the influence of Kate's posturing, she must form a set of beliefs—a set of "probabilities," concerning beliefs about beliefs. James'

* How to best adapt the mathematics of probability to the cognitive and social worlds remains a challenging problem and places us at one of the major research frontiers. Two assumptions in particular, technically known as *stationarity* and *ergodicity*, play central roles here. My colleague Ole Peters, at the London Mathematical Laboratory, has been at the forefront of asking what we might need to do if these simplifying assumptions fail, in part by careful study of the *St. Petersburg paradox*, an apparent failure of human reasoning to abide by mathematical principles.

† Leibniz introduced us to the idea of possible worlds, and was memorably parodied as Dr. Pangloss in Voltaire's *Candide*, who teaches his student that we live "in the best of all possible worlds."

‡ The "chance" in the King James Version translation uses the original Hebrew word, pega, which is etymologically derived from the word for "impact."

§ It is not difficult to describe games where the mathematically rational choice is at odds with the sensible one we would make ourselves. One example is the Allais paradox. Question one: Which would you prefer? A million dollars guaranteed or an 89 percent chance of $1 million and a 10 percent chance of $5 million? (And thus a 1 percent chance of nothing.) Question two: Would you prefer an 11 percent chance of $1 million or a 10 percent chance of $5 million? If you prefer the first option for question one and the second option for question two, your choice-making violates some of the basic assumptions that underlie the mathematization of reason presented here.

Our pasts and our futures are, in their details, profoundly unlikely things.

self-reflexive prose abounds with difficult-to-track higher-order thoughts—perhaps this is why it was once said of James that he chewed more than he bit off.

Although remote from the raw chance of the physical world, mathematics can also help us understand how to describe these beliefs and show us how they can start to resemble raw chance.

To begin with some notation, let us represent the fact that person X believes sentence s in the form B_X (s), which is read as "X believes that s".*

The recognition that takes place between Milly and Merton and sets the narrative in motion can be described this way. Merton sees Milly first; he is, of course, aware of this, and so we can write:

$$\mathrm{B}_{\mathrm{Merton}}(\text{“Merton sees Milly”}).$$

Or, in words, "Merton believes that Merton sees Milly" (it will save us a great deal of trouble if we avoid pronouns for a spell).

Milly then sees Merton. As she is also self-aware,

$$\mathrm{B}_{\mathrm{Milly}}(\text{“Milly sees Merton”}).$$

When, as the narrative tells us, she can see that Merton can see her, we have

$$\mathrm{B}_{\mathrm{Milly}}(\mathrm{B}_{\mathrm{Merton}}(\text{“Merton sees Milly”})),$$

or that "Milly believes that Merton believes that Merton sees Milly". Not only is this recognition mutual, but so is the recognition of this recognition, so that

$$\mathrm{B}_{\mathrm{Milly}}(\mathrm{B}_{\mathrm{Merton}}(\text{“Milly sees Merton”})).$$

And, indeed, this recognition itself is also known to Merton, so that

$$\mathrm{B}_{\mathrm{Merton}}\,(\mathrm{B}_{\mathrm{Milly}}\,(\mathrm{B}_{\mathrm{Merton}}\,(\text{“Milly sees Merton”}))).$$

Aided by the mathematical notation, one can see that these towers are potentially infinite in extent, with true and false beliefs possible at each point.

Game theorists—in a beautiful simplification—use the term *common knowledge* to refer to cases where sentence s is true, and any arbitrarily nested belief functions referring to the state of knowledge of individuals concerning s, are also true. Common knowledge is often associated with social norms such as obeying traffic lights and being polite, but here we can see the infinite tower emerge, at once, in the meeting of gazes.

* Here we adopt the semantic approach of the Interactive Epistemology notation given by Aumann, *Int. J. Game Theory* **28**, 263-300 (1999).

Not all forms of belief are commonly held; indeed, it is the failure of common knowledge that drives many narratives (including *Othello*, *Hamlet,* and nearly all of Shakespeare's comedies).

It is only *after* Milly and Merton have recognized each other, in other words, that the games begin. After the awkward encounter, Milly invites both Merton and Kate to her hotel so as to *appear* to take Kate's hint that the encounter must seem to Milly "queer," but that it has a simple interpretation. Milly does this in part because she believes the best solution is to adopt and emphasize her "native wood-note," her own spontaneous, American attitudes. This, she feels, will ease the strain of her stumbling on a scene of unrequited (that is, Merton's) love.

In short: Milly believes that Kate believes the scene has induced a belief in Milly; Milly, holding beliefs about her own beliefs, attempts to induce a new belief in Kate. Such patterns of thought are real, if delicate; they are difficult to represent properly in English (though of course James tries) but more than amenable to the formalism above.

Milly reasons that, because

$$B_{\text{Milly}}(B_{\text{Kate}}(B_{\text{Milly}}(\text{“something's queer”})))$$

and

$$B_{\text{Milly}}(B_{\text{Milly}}(\text{“one should be straight-forward”} \text{ is the best response}),$$

the awkward predicament can be resolved by acting such that

$$B_{\text{Kate}}(B_{\text{Milly}}(\text{“with time, an innocent explanation will emerge”})).$$

Milly is proud of the complexity of her reasoning,* motivated by a noble desire to be a good friend to Kate. She is unaware, of course, that the English girl, nesting all of Milly's beliefs one level deeper and responding appropriately, is able to conceal the essential truth: that Merton's love is in fact requited.† At each stage, these belief functions carry with them probabilities—degrees of belief—that multiply together in increasingly complex ways.

The typical set was the star of Section I: It gave us a handle on the nature of uncertainty. The sources of that uncertainty were drawn from the material world. Here in Section II we have seen how to describe the emergence of uncertainty among thinking, competing agents. The extension of chance to the social world requires a new set of mathematical tools. These tools show us plainly the potential for spiraling complexity, for reflexivity, which we can now name precisely:

$$B_{\text{Milly}}(B_{\text{Kate}}(B_{\text{Milly}}\ldots$$

III. The Limits Of Reflexivity

At sufficient complexity, social and natural uncertainty, both in principle and in practice, become indistinguishable. While readers might find *Wings of the Dove* difficult (if rewarding), they are not alone if forced to rely on the Merchant-Ivory version of James's subsequent, and even more oblique novel, *The Golden Bowl*.

Put another way, our cognition, so limitless in the development of the natural sciences, seems the most fallible when, in walking down the street, we meet a stranger coming from the other direction, and, symmetrically polite, both move to the left and right in a frustrated attempt to make way.

It occurs to us that the best solution can often be the leaving of things to chance. When our social environment demands we take into account too many reciprocal beliefs about beliefs, we become—against our better knowledge—mystics. We attribute chance and randomness to others even as we fail to attribute it to ourselves. The minds of others become too

* We assume, as James does in this passage, that Milly can alter her own beliefs at will. Not a trivial assumption: A common human predicament is the desire to change a detrimental belief. Such desires are familiar in the religious realms—the struggle for faith—as well as the social ones, where self-help books encourage one to practice staying positive (i.e., holding certain beliefs about the future) against one's prior, learned inclinations. Such struggles are not uncommon in science, either: Scientists often report a frustrated desire to reconcile their "naive" beliefs with their scientific ones.

† Merton Densher has very little idea what is going on and spends most of his time in the nested belief functions of the two ladies. Whether this represents an amusing comment on the powers of Edwardian-era male reasoning or a failure of imagination on the part of Henry James is left as an exercise for the reader.

Pardon Me

A common problem, particularly among the English, is allowing a colleague to pass you in a narrow corridor. This kind of friendly *anti-coordination game* contains the seeds of much of our discussion in the main text.

We'll use Cox's theorem (Section 2) to turn talk about beliefs into talk about probabilities. In particular, we'll write "my belief about what to do, given what's come before" as $p(x\,|F)$, or "the probability of action x given the facts, F." For example, we can represent "I'm reasonably (70 percent) confident that I should move to the left, given that the last time we both moved to the right" by setting $p(\text{left}_{\text{me}}|\{\text{right}_{\text{me}}, \text{right}_{\text{him}}\})$ to 0.7.

The solution is to do the opposite of whatever your colleague is doing. We can represent this as the belief that what you should do next is the opposite of your estimate of your colleague's beliefs about what *he* should do next:

$$p(x_{\text{me}}(t)|F) = 1 - p(x_{\text{him}}(t)|F)$$

where we assume that "all facts are common knowledge"—*i.e.*, you and your colleague both know F. How should you estimate $p(x_{\text{him}}(t)\,|\,F)$? To *zeroth* order, you can set it to 100 percent when $x_{\text{him}}(t)$ is equal to $x_{\text{him}}(t{-}1)$; in this case, assuming you bumped into each other the last time, you'll now switch sides. To first order, you can model his reasoning process,

$$p(x_{\text{him}}(t)|F) = 1 - q_1(x_{\text{me}}(t)|F)$$

where q is your model of his beliefs, and assume that he's working to *zeroth* order, *i.e.*, $q(x_{\text{me}}(t)\,|\,F)$ is equal to one only when $x_{\text{me}}(t)$ is equal to $x_{\text{me}}(t-1)$. In this case, you'll stay on the same side as last time. As before, if you're at the same level of cognitive sophistication, you'll never be able to pass.

One solution is to be unsure about the level your opponent is working at: you might believe that works to first order with a confidence of only 80 percent, so that

$$p(x_{\text{me}}(t)|F) = 0.8[1 - q_1(x_{\text{me}}(t)|F)] + 0.2[1 - q_0(x_{\text{me}}(t)|F)].$$

This is not *quite* the full solution, since the most rational thing is to choose the action with the highest probability (Section 1). If you both do this, and have similar estimates of each other, you're back to awkward alternation. The full solution is to go from the "rational" maximum likelihood to something like "probability matching," where you act with the probability given by your belief strength. After a little time, you'll both get lucky (and get back to work). Research in the laboratory shows that both adults and children prefer to probability match, a solution that allows for greater exploration (at the cost of occasional inefficiency).

complex, and we treat the social world as we do the natural one—as fundamentally unknowable, fundamentally subject to chance.

Navigating the limits of our ability to judge the degree of certainty in our own beliefs and those of others is a defining human characteristic. With this understanding, the point at which one crosses from theories of mind to theories of chance is a balance of innate ability and a philosophical choice about what it means to lead a good life.

One might imagine a science fiction device—a probability meter—that would measure the differential contribution of nature and humankind to the uncertainty of an outcome. How much uncertainty in the average corporate boardroom is due to nature (e.g., the chances of bad weather delaying a shipment of parts) and how much to the strategic creation of uncertainties by human participants (e.g., the refusal to disclose final production targets to one's suppliers)? Of course, such a meter could wreak havoc in any real boardroom—and itself be a source of its own readings.

Social and natural uncertainty are like natural and anthropogenic sources of carbon dioxide. When CO_2 reaches the atmosphere, its source makes little difference. But there are essential differences in our ability to manage social and natural uncertainty. Our modern world of technology and planning has transformed many natural uncertainties into near-certainties. The same, however, cannot be said of higher-level aspects of human interaction.

Not that we aren't trying. Today, machines manage much of our response to chance. They do so often by a low-level approximation of our own ideals of reasoning. Modern algorithms respond not only to inputs from their environment but also to degrees of belief in those inputs.

Machine learning systems that use this so-called Bayesian approach not only monitor the antilock brakes on modern cars and fly-by-wire passenger jets, but have spread far into the social domain. Among other things, they provide estimates of (and degrees of belief in) a student's scholastic abilities (as part of automated essay-grading algorithms used by the Educational Testing Service for the SAT exam) and the romantic compatibilities of couples (as part of the algorithms developed by the online dating service eHarmony).

Computers, however, have shown far less ability than humans in the modeling of higher-order systems. While they can estimate with high accuracy the optimal move in a game of chess, they have performed poorly in games such as poker that require estimation not only of the facts at hand but of the beliefs of other players concerning those facts.

Machines that play a naively "optimal" poker—folding with poor hands and persisting with better ones—can beat a simple-minded human player by better estimation of the odds. But they lose disastrously to a more expert player who can learn the underlying strategy and, by reference to the machine's tolerance for risk, bluff more precisely.

Since we have allocated to machines reasoning tasks that far exceed our own abilities, since each successive limit to the power of computers relative to those of human reason has fallen, we might ask: Can we expect this last domain in which properly thoughtful humans remain the unchallenged experts to remain inviolate?

We treat the social world as we do the natural one: fundamentally unknowable.

Will machines eventually diagram *The Golden Bowl* for us? And perhaps—let us speculate—produce new solutions to the dilemmas faced by its characters?

More lucrative avenues than literary criticism suggest themselves. Will corporations someday put supercomputers into boardrooms as well as their research labs to better anticipate and maneuver against their competition?

Though few have gotten rich betting against technological progress, this final step to fully automated reflexive knowledge of other minds seems far off. There are even reasons to believe that the search would amount to the construction of a conscious being or would pose questions fundamentally unanswerable to man and machine alike.* Should such a thing occur, our world would become, in an instant, unrecognizable. But the words of Ecclesiastes would still remain: Time and chance shall happen to them all—machine and creature alike.

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* A machine capable of reasoning about reasoning—capable of forming beliefs about its beliefs, as is necessary for the kind of higher-order reasoning seen in the writing of Henry James—also becomes subject to one of the most mysterious mathematical results of the 20th Century: the so-called Incompleteness Theorems, first explicitly formulated by Kurt Gödel in 1931. One can see this informally in the self-referentially that the $B_X(s)$ formalism allows and imagine sentences that refer to, for example, the believability of sentences that deny their believability; more rigorously, one can note the possibility of modeling a primitive arithmetic with the syntactic rules available.

When Photographers Are Neuroscientists

Artists who manipulate photos capture the ambiguity—and beauty—of vision itself

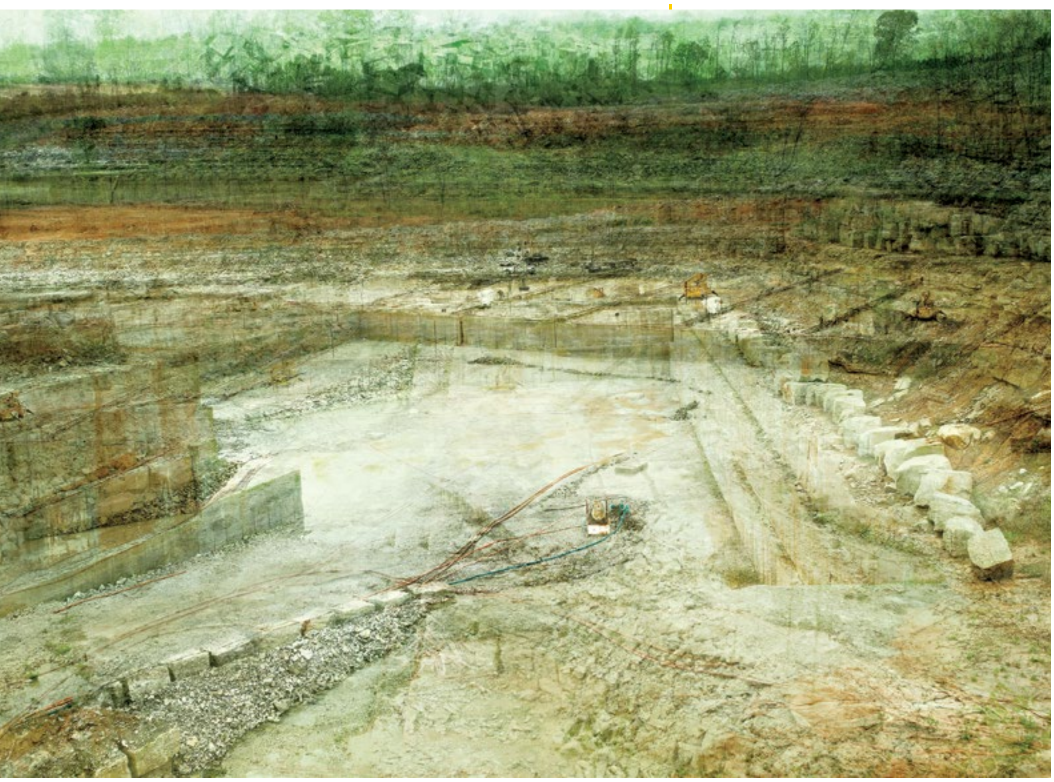
BY JONATHON KEATS

IN THE SUMMER OF 1867, American photographer Carleton Watkins hauled a mammoth wooden camera through the wilderness of Oregon, taking pictures of the mountains. To prepare each negative, he poured noxious chemicals onto a glass plate the size of a windowpane and exposed it while still wet, developing it on the spot. Even then, his work was not complete. Because wet-plate emulsions are disproportionately sensitive to blue light, his skies were overexposed, utterly devoid of clouds. Back in his San Francisco studio, Watkins manipulated his photos to resemble the landscapes he'd witnessed. His finished prints were composites, embellished with a separate set of cloud-filled negatives.

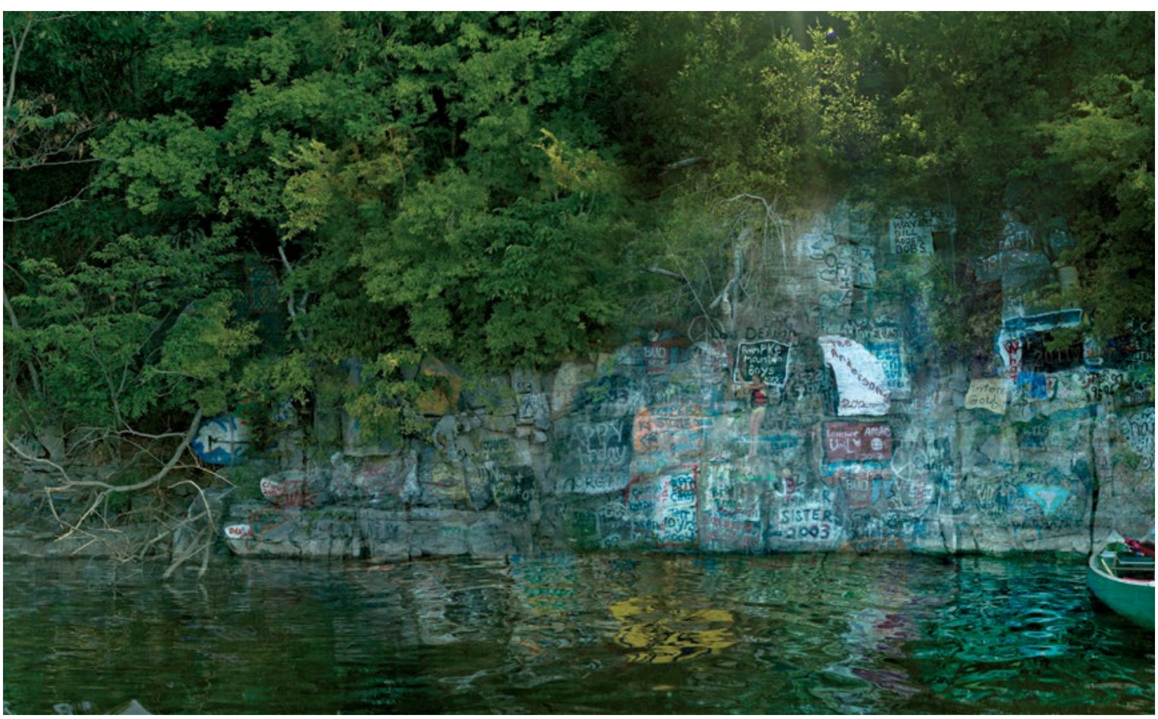
Nearly a century and a half later, Elena Dorfman—another American photographer porting a large-format camera—spent several summers in the rock quarries of Kentucky and Indiana, landscapes as dramatic as Watkins' Oregon. Dorfman had none of the old limitations. Her digital Hasselblad instantaneously captured 32-megapixel photos in full color. But it didn't satisfy her. In postproduction she created composites on her computer, layering as many as 300 images to obtain effects unlike anything seen in nature.

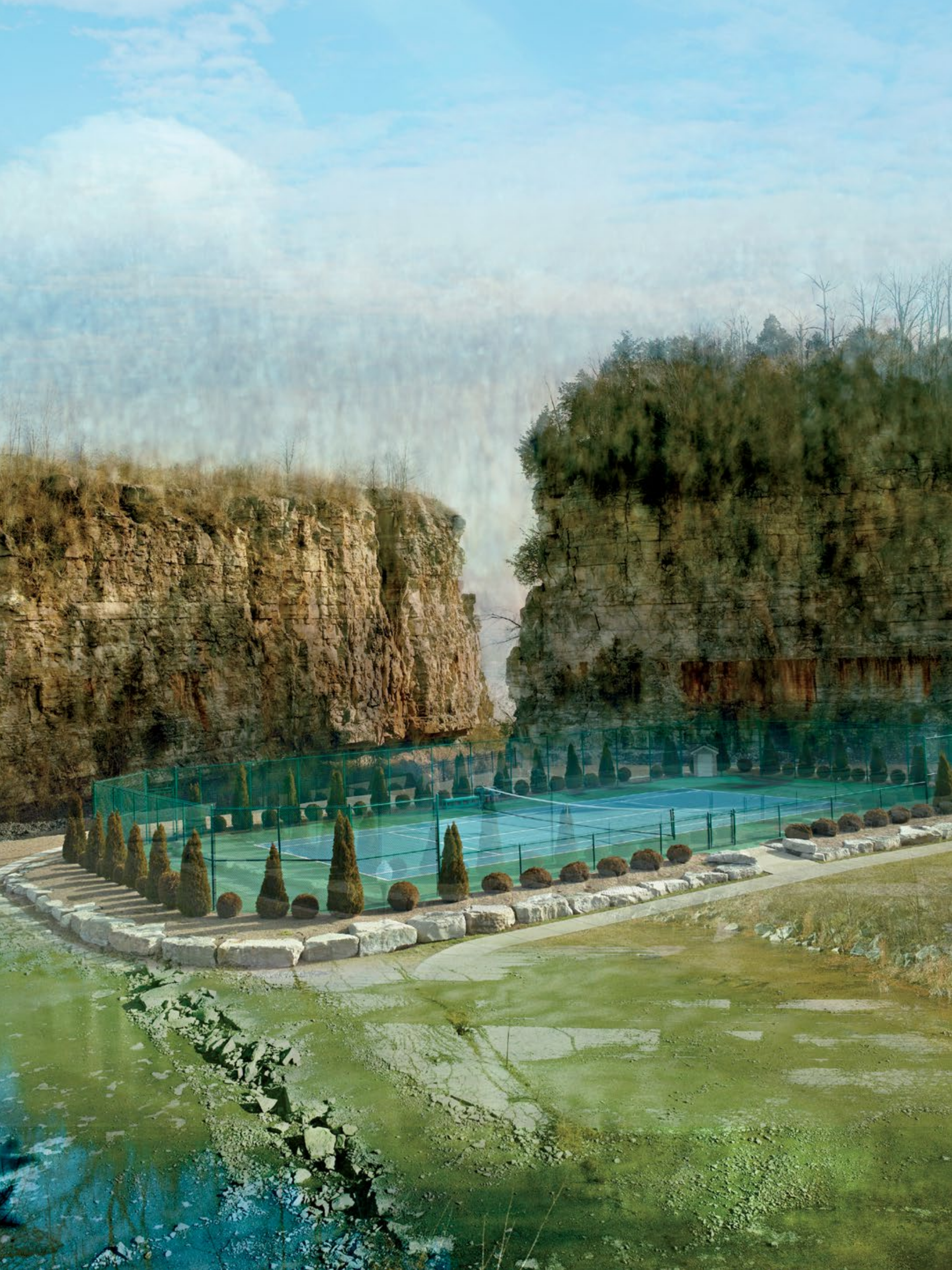
In one sense, Dorfman was doing the opposite of what Watkins achieved with his library of clouds. While his intervention made the mountain vistas more meteorologically accurate, she intentionally introduced physical impossibilities, from conflicting perspectives to rearranged geology, much as a painter might fictionalize a scene. Yet in another sense, each photographer was artfully striving for truth about how we experience the natural world, laboring against the inadequacies of the camera. For Watkins, the constraints were physical. For Dorfman, they're neurological, a discrepancy between photomechanical depiction and how the brain processes what the eyes perceive. Like many modern artists, she has a strong intuitive grasp of how the visual brain works and understands that her pictures can be made more stimulating by seeding them with

PHOTOGRAPHY BY ELENA DORFMAN



ART OF THE QUARRY
Elena Dorfman shot photos at rock quarries in Kentucky and Indiana, and layered as many as 300 images to create the final effect. Photos are a selection from the series and monograph *Empire Falling* (Damiani Editore and Modernism Gallery, San Francisco, 2013).





conflicting perspectives.

Examining Dorfman's trickery—and the artifice of other photographers from Weegee to David Hockney—provides a valuable way of learning about how the brain handles contradictory or uncertain visual information. Equally important, the neuroscience of vision helps elucidate what makes these photographs so artistically compelling. Enlisting photomanipulation, these photographers achieve one of the most oft-praised qualities in art—ambiguity—in ways that neuroscience is now beginning to understand.

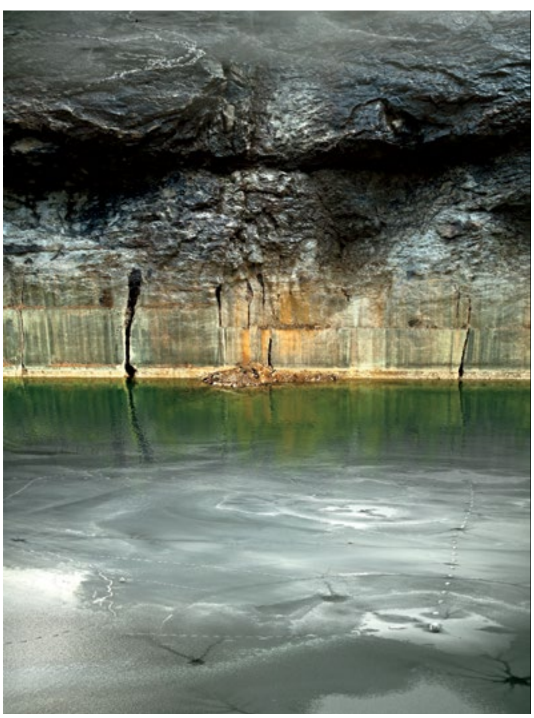
In a 2004 paper titled *Consciousness and Cognition,* University College London neurobiologist Semir Zeki argued that the brain experiences ambiguity as the "certainty of many, equally plausible interpretations," much like an optical illusion alternately seen as approaching and receding. Zeki holds Johannes Vermeer's paintings as supreme examples of artistic ambiguity, citing *Girl with the Pearl Earring* to support his aesthetic judgment. "She is at once inviting yet distant, erotically charged but chaste, resentful and yet pleased," he writes. And, as Zeki notes in his 1999 book, *Inner Vision,* Vermeer's art is widely admired because the artist is able to express all of that "in a single profound painting, profound because it is so faithfully representative of so much."

Too bad Vermeer didn't have a camera. Photography may be more suited to capturing multiple conflicting certainties than painting. A painting can only blend visual information that has been preprocessed by the unreliable brain. Each photograph, on the other hand, is an independent fact. In layering them without resolving

In layering images without resolving their contradictions, photographers approach the tenuous quality of truth.

their contradictions, as Dorfman does, photographers approach the tenuous internal quality of truth.

On the surface, *photographic ambiguity* is an oxymoron. The camera sees the world with total fidelity to physical laws. It's a deterministic system, the performance of which can be perfectly predicted, given the optics and the chemistry or necessary electronics. Human perception is far messier, hacked together by a visual system riddled with inconsistencies, as Zeki documents in *Inner Vision*. Perception is a product of evolution rather than engineering. Nobody thought out in advance how all the parts would work together. It isn't really a system so much as a Rube Goldberg contraption where the parts just manage to interact. For instance, every eye has a blind spot where the optic nerve passes through the retina, carrying signals to the brain, yet this blind spot isn't noticeable to the viewer. As National Institute for Physiological Sciences neurophysiologist Hidehiko Komatsu details in a 2006 *Nature Reviews Neuroscience* review, the brain fills in the blank in what is perceived by interpolating visual information from areas of the retina surrounding the hole: The resulting sight is an approximation.



In fact, most everything about how we see comes down to heuristics. In a 2005 *Nature* paper, Harvard neuroscientist Patrick Cavanagh observed that "our visual brain uses a simpler, reduced physics to understand the world." In other words, we aren't using all the complex mathematics of textbook optics to analyze the relative position and characteristics of objects. We're taking a few imperfect cues and improvising. The visual information isn't totally accurate, but it's good enough to get by and can be more useful than perfect knowledge. (You don't need to calculate the velocity of a falling rock to know that you should step aside. In fact, if you start making measurements from where you're standing, you probably won't survive to complete them.)

Painters have an intuitive grasp of these heuristics, taking visual shortcuts such as showing more of an object than can be seen in a single glance or muddying insignificant background details. Those distortions and uncertainties make their pictures less true to life but more true to us: They reflect how we see. On that basis, Cavanagh claimed that "artists act as research neuroscientists," informing us about how the brain works.

That may be inevitable for painters, since their paintings derive from the perceptual apparatus of their own eyes and brains. The heuristics of the mind guide the naive hand. The reduced physics can be circumvented only with intense effort. For instance, achieving unflawed one-point perspective, in which all objects recede to a single vanishing point (like a converging set of railroad tracks) requires rigorous training in overcoming the eyes' constant movement and refocusing. A geometrical system must be superimposed on the canvas, and even Renaissance masters were notoriously hazy about the correct projection of shadows. Photographers have the opposite problem. One-point perspective comes in the box. The camera's view is too absolute. To be neuroscientific—and to make pictures that resonate in painterly ways—photographers must actively emulate the distortions and uncertainties inherent in vision by purposely making their pictures deformed or ambiguous.

In 2006, MIT neuroscientist Pawan Sinha and colleagues showed that faces with exaggerated features are more immediately recognizable than straight depictions—despite being less accurate—because they deviate more from average human appearance. Paradoxically, you increase the intelligibility of the image by decreasing the verisimilitude. Pablo Picasso instinctively exploited this phenomenon by selectively distorting facial features, intensifying the presence of portrait sitters such as Gertrude Stein. In the mid-20th century, the American photographer Weegee applied a similar tactic in his caricatures of public figures, including Lyndon Johnson and Marilyn Monroe, whose features he twisted by physically warping his negatives and using trick lenses. Johnson's sloping

Distortions and uncertainties make their pictures less true to life but more true to us: They reflect how we see.

nose was obscenely elongated; Marilyn's luscious lips were puffed up to become positively lascivious.

Ambiguity has also taken cues from modern painting. David Hockney, a painter by training, has revisited Cubism with a camera in photo collages constructed from dozens of snapshots. The snapshots are all close-ups of the same subject—say, a city street or a swimming pool—each taken from a different angle and all overlapped to render the contours of the original scene inexactly. As in a Cubist painting, no single point of view can account for all the visual information. Yet the ambiguity about where you're standing and the uncertain positioning of the scenery don't make the image confusing: They make it all-encompassing.

Visual research by Harvard neurobiologist Margaret Livingstone and colleagues helps explain why Hockney's method works. When we encounter an unfamiliar setting, our eyes dart around, acquiring snapshots of everything in sight before we begin to analyze what we're seeing. This tactic maximizes our acquisition of information before we know what we want to know and prevents us from prematurely filtering out details that may later prove important in terms of how we handle a crisis. But as a consequence, each snapshot is independent. That means that, while we're looking, we aren't aware of any inconsistencies between images. Evolutionarily, noticing discontinuity simply wasn't important. As Livingstone and Wellesley College neuroscientist Bevil Conway wrote in a 2007 review in *Current Opinion in Neurobiology*, "Perspective and reflections change second to second as we move our eyes across a scene. Therefore, there would have been little biological benefit to incorporating the rules for global perspective or illumination into our visual computations." Hockney's photocubism embodies and exploits our obliviousness to show us more than can possibly be captured with the camera's one-point perspective. We have the sense of being right there with him.

Dorfman's layered photographs work on the brain in a similar way, though they have less in common with Cubism than with the post-Impressionist paintings of Paul Cézanne. Instead of kaleidoscopically fragmenting the picture plane, Cézanne fused the visual information gleaned from multiple disparate perspectives. In his still lifes, for instance, a bowl of fruit might be shown at an impossible tilt that allows you to see all the apples *and* the bowl's contact with the table. The reduced physics lets the artist accentuate the scene's essentials, even if his place of observation is ambiguous. It's a naive point of view, the naturalness of which is proven by how commonly it's found in drawings by children.

In her most ambitious pictures, Dorfman takes this power of synthesis to an extreme by transparently layering scenes viewed from completely different directions or up close and at a distance. In a single two-dimensional image, Dorfman presents the visual information we'd glean by exploring a three-dimensional landscape over many hours or days. Looking at one of her pictures, we feel as if we've actually *experienced* the place.

And in a sense, we have. Dorfman's photographs give us access to her experiences and her ambivalence toward a place that's at once beautiful and ruined. Through her photographs, we feel her ambivalence. We don't only *observe* the multiple incompatible certainties that Zeki describes—we internalize them.

Critic and artist JONATHON KEATS is most recently the author of *Forged: Why Fakes Are The Great Art of Our Age* (Oxford University Press).

Why It's Good to Be Wrong

Nothing obstructs access to the truth like a belief in absolute truthfulness

BY DAVID DEUTSCH

THAT HUMAN BEINGS CAN be mistaken in anything they think or do is a proposition known as *fallibilism*. Stated abstractly like that, it is seldom contradicted. Yet few people have ever seriously believed it, either.

That our senses often fail us is a truism; and our self-critical culture has long ago made us familiar with the fact that we can make mistakes of reasoning too. But the type of fallibility that I want to discuss here would be all-pervasive even if our senses were as sharp as the Hubble Telescope and our minds were as logical as a computer. It arises from the way in which our ideas about reality connect with reality itself—how, in other words, we can create knowledge, and how we can fail to.

The trouble is that *error* is a subject where issues such as logical paradox, self-reference and the inherent limits of reason rear their ugly heads in practical situations, and bite.

Paradoxes seem to appear when one considers the implications of one's own fallibility: A fallibilist cannot claim to be infallible even about fallibilism itself. And so, one is forced to doubt that fallibilism is universally true. Which is the same as wondering whether one might be somehow *in*fallible—at least about some things. For instance, *can* it be true that absolutely anything that you think is true, *no matter how certain you are*, might be false?

What? How might we be mistaken that two plus two is four? Or about other matters of pure logic? That stubbing one's toe hurts? That there is a force of gravity pulling us to earth? Or that, as the philosopher René Descartes argued, "I think, therefore I am"?

When fallibilism starts to seem paradoxical, the mistakes begin. We are inclined to seek foundations—solid ground in the vast quicksand of human opinion—on which one can try to base everything else. Throughout the ages, the false authority of experience and the false

ILLUSTRATIONS BY GÉRARD DUBOIS

Have we now gotten lost in the paradox of being wrong about being wrong?

reassurance of probability have been mistaken for such foundations: "No, we're not *always* right," your parents tell you, "just usually." They have been on earth longer and think they have seen this situation before. But since that is an argument for "therefore you should *always* do as we say," it is functionally a claim of infallibility after all. Moreover, look more closely: It claims literal infallibility too. Can anyone be infallibly right about the *probability* that they are right?

But wait. Have we now gotten lost in the paradox of being wrong about being wrong? There really is such a thing as existing knowledge—including a vast amount of useful, salutary truth. Parents really do know more than children about everyday dangers; your physician does know more than a passing hobo about your illness. Although, certainly,* all concerned are fallible—they could be wrong—isn't it rational to play the odds? To defer to the opinion of the experts who have a lot more knowledge about the matter? In other words, isn't it better to act as *if* one considered them infallible about it, even though they are not?

No. That is not only an irrational answer but, catastrophically, the wrong question. I'll return to it below. But first, consider infallibility itself.

Ascribing a sphere of infallibility to a parent or expert has the same logic as the Roman Catholic Church's doctrine about the pope: It likewise considers him infallible only under certain narrowly defined circumstances, called *ex cathedra* (metaphorically "from the throne"). So, consider this thought experiment: You seriously believe in papal infallibility. One day, an atheist friend gleefully tells you that the pope has said something which, after due consideration, you decide must be false: "There is no force of gravity." Immediately, it becomes vital for you to know whether the pope declared this *ex cathedra*. For if he did, you would have to accept that you are mistaken about gravity, and act accordingly, even if you never managed to understand the mechanics of how that might be so. Because for you, ideas are *about* something—important precisely because they have consequences for how you think, feel, and act. And so you would have to drop some assumptions that you hitherto considered true incontrovertibly—or even infallibly.

* See what I did there?

Furthermore, one cannot seriously believe that the pope is infallible while also believing any rival religion, or atheism. So the implications of papal infallibility, even more than parental infallibility, are sweeping. Despite its narrow nominal scope, it is functionally equivalent to the entire gamut of Roman Catholic doctrine. But there is another class of implications—even more sweeping—in the opposite direction.

Consider the steps you are obliged to follow, from hearing of an *ex cathedra* declaration to believing its content.

A passing hobo tells you that he saw the pope making the declaration *ex cathedra*. Do you therefore accept that there is no force of gravity? Obviously not: That would involve assuming that the hobo was infallible—which would *contradict* the church's teachings. And the same would hold even if an archbishop were to visit you and swear that he had witnessed it too, and stated his expert opinion that it met the requirements for being *ex cathedra*. Since the doctrine does not ascribe infallibility to archbishops, you would still not be required to accept the claim about gravity. Thus the doctrine of *in*fallibility has made you take the *fallibility* of archbishops more seriously than you otherwise might. Even if the pope himself were to swear that his claim about gravity was strictly *ex cathedra*, you would not be forced, by your faith, to believe it. The doctrine of papal infallibility does not say that the reminiscences of a pope are infallible—unless they are *ex cathedra* reminiscences.

So your very faith in papal infallibility has led you to within touching distance of one of the cornerstones of scientific rationality: *nullius in verba*—"take no one's word for it"—the motto of the Royal Society.*

But now, what if you personally witnessed the *ex cathedra* statement?

So, there you were, visiting the Vatican and you took a wrong turn and found yourself witnessing the pope as he solemnly declared that there is no force of gravity. You happened to have purchased, from the souvenir shop, a checklist of the official requirements for a declaration to count as *ex cathedra*, and you took the trouble to verify that each one was met. None of this constitutes direct observation of what you need to know. Did you observe infallibly that it was the pope? Did you do a DNA test? Can you be certain that souvenir checklists never contain typos? And how is your church Latin? Was your translation of the crucial phrase "no force of gravity" infallible? Have you never mistranslated anything?

So, there you were, visiting the Vatican and you took a wrong turn and found yourself witnessing the pope as he solemnly declared that there is no force of gravity.

The fact is, there's nothing infallible about "direct experience" either. Indeed, experience is never direct. It is a sort of virtual reality, created by our brains using sketchy and flawed sensory clues, given substance only by fallible expectations, explanations, and interpretations. Those can easily be more mistaken than the testimony of the passing hobo. If you doubt this, look at the work of psychologists Christopher Chabris and Daniel Simons, and verify by direct experience the fallibility of your own direct experience. Furthermore, the idea that *your* reminiscences are infallible is also heresy by the very doctrine that you are faithful to.

I'll tell you what really happened:† You witnessed a dress rehearsal. The real *ex cathedra* ceremony was on the following day. In order not to make the declaration

* Britain's National Academy of Sciences, founded in the 1660s at the dawn of the Enlightenment.

† I can do that infallibly because a thought experiment is fiction, and the narrator in fiction is infallible.

Whether the idea was originally suggested to you by a passing hobo or a physicist makes no difference.

a day early, they substituted for the real text (which was about some arcane theological issue, not gravity) a *lorem-ipsum*-type placeholder that they deemed so absurd that any serious listener would immediately realize that that's what it was.

And indeed, you did realize this; and as a result, you reinterpreted your "direct experience," which was identical to that of witnessing an *ex cathedra* declaration, as not being one. Precisely by reasoning that the content of the declaration was absurd, you concluded that you didn't have to believe it. Which is also what you would have done if you hadn't believed the infallibility doctrine.

You remain a believer, serious about giving your faith absolute priority over your own "unaided" reason (as reason is called in these contexts). But that very seriousness has forced you to decide *first* on the substance of the issue, using reason, and only then whether to defer to the infallible authority. This is neither fluke nor paradox. It is simply that if you take ideas seriously, there is no escape, even in dogma and faith, from the obligation to use reason and to give it priority over dogma, faith, and obedience.

The real pope is unlikely to make an *ex cathedra* statement about gravity, and therefore you may be lucky enough never to encounter this particular case of the dilemma. Also, the real pope doesn't just pull *ex cathedra* statements out of a hat. They're hammered out by a team of expert advisors trying their best to weed out mistakes, a process structurally not unlike peer review. But if your faith in papal infallibility depends on reassuring yourself of things like that, then that just goes to show that for you, reason takes priority over faith.

It is hard to contain reason within bounds. If you take your faith sufficiently seriously you may realize that it is not only the printers who are fallible in stating the rules for *ex cathedra*, but also the committee that wrote down those rules. And then that *nothing* can infallibly tell you what is infallible, nor what is probable. It is precisely because you, being fallible and having no infallible access to the infallible authority, no infallible way of interpreting what the authority means, and no infallible means of identifying an infallible authority in the first place, that infallibility cannot help you before reason has had its say.

A related useful thing that faith tells you, if you take it seriously enough, is that the great majority of people who believe something on faith, in fact believe falsehoods. Hence, faith is insufficient for true belief. As the Nobel-Prize-winning biologist Peter Medawar said: "the intensity of the conviction that a hypothesis is true has no bearing on whether it is true or not."*

You know that Medawar's advice holds for all ideas, not just scientific ones, and, by the same argument, to all the other diverse things that are held up as infallible (or probable) touchstones of truth: holy books; the evidence of the senses; statements about who is probably

* In *Advice to a Young Scientist.*

right; even true love.

How should this no-exceptions fallibilism play out when the physician suggests a treatment? The right question is not "who is more likely to be right, the physician or I?" but "has this idea been judged rationally, by its content?" Which means, in particular, has it been subjected to sufficiently severe attempts to detect and eliminate errors—both by explanatory argument and by rigorous experiment? If you think it has, then your opinion and the physician's should become the same, and the issue of deference should not arise, nor should the need for anyone to claim effective infallibility.

On the other hand, if you suspect that the physician has not given enough thought to some feature that makes your case unusual, it would be irrational to defer. The physician's greater knowledge is irrelevant until you are satisfied with the way that idea has been taken into account. And whether the idea was originally suggested to you by a passing hobo or a physicist makes no difference, either.

This logic of fallibility, discovered and rediscovered from time to time, has had profound salutary effects in the history of ideas. Whenever anything demands blind obedience, its ideology contains a claim of infallibility

Headline writers should not call every failed military strike "botched," and courts should not call every medical tragedy "malpractice."

somewhere; but wherever someone believes seriously enough in that infallibility, they rediscover the need for reason to identify and correctly interpret the infallible source. Thus the sages of ancient Judaism were led, by the assumption of the Bible's infallibility, to develop their tradition of critical discussion. And in an apparently remote application of the same logic, the British constitutional doctrine of "parliamentary sovereignty" was used by 20th-century judges such as Lord Denning to develop an institution of judicial review similar to that which, in the United States, had grown out of the opposite doctrine of "separation of powers."

Fallibilism has practical consequences for the methodology and administration of science, and in government, law, education, and every aspect of public life. The philosopher Karl Popper elaborated on many of these. He wrote:*

> The question about the sources of our knowledge . . . has always been asked in the spirit of: "What are the best sources of our knowledge—the most reliable ones, those which will not lead us into error, and those to which we can and must turn, in case of doubt, as the last court of appeal?" I propose to assume, instead, that no such ideal sources exist—no more than ideal rulers—and that *all* "sources" are liable to lead us into error at times. And I propose to replace, therefore, the question of the sources of our knowledge by the entirely different question: *"How can we hope to detect and eliminate error?"*

It's all about error. We used to think that there was a way to organize ourselves that would minimize errors. This is an infallibilist chimera that has been part of every tyranny since time immemorial, from the "divine right of kings" to centralized economic planning. And it is implemented by many patterns of thought that protect misconceptions in individual minds, making someone blind to evidence that he isn't Napoleon, or making the scientific crank reinterpret peer review as a conspiracy to keep falsehoods in place.

Popper's answer is: We can hope to detect and eliminate error if we set up *traditions of criticism*—substantive criticism, directed at the content of ideas, not their sources, and directed at whether they solve the problems that they purport to solve. Here is another apparent paradox, for a tradition is a set of ideas that stay the same, while criticism is an attempt to *change* ideas. But there is no contradiction. Our systems of checks and balances are steeped in traditions—such as freedom of speech and of the press, elections, and parliamentary procedures, the values behind concepts of contract and of tort—that survive not because they are deferred to but precisely because they are not: They themselves are continually criticized, and either survive criticism (which allows them to be adopted without deference) or are improved (for example, when the franchise is extended, or slavery abolished). Democracy, in this conception, is not a system for enforcing obedience to the authority of the majority. In the bigger picture, it is a mechanism for promoting the creation of consent, by creating objectively better ideas, by eliminating errors from existing ones.

"Our whole problem," said the physicist John Wheeler, "is to make the mistakes as fast as possible." This liberating thought is more obviously true in theoretical physics than in situations where mistakes hurt. A mistake in a military operation, or a surgical operation, can kill. But that only means that whenever possible

* In "Knowledge without Authority" (1960).

we should make the mistakes *in theory*, or in the laboratory; we should "let our theories die in our place," as Popper put it. But when the enemy is at the gates, or the patient is dying, one cannot confine oneself to theory. We should abjure the traditional totalitarian assumption, still lurking in almost every educational system, that every mistake is the result of wrongdoing or stupidity. For that implies that everyone other than the stupid and the wrongdoers is infallible. Headline writers should not call every failed military strike "botched"; courts should not call every medical tragedy "malpractice," even if it's true that they "shouldn't have happened" in the sense that lessons can be learned to prevent them from happening again. "We are all alike," as Popper remarked, "in our infinite ignorance." And this is a good and hopeful thing, for it allows for a future of unbounded improvement.

Fallibilism, correctly understood, implies the possibility, not the impossibility, of knowledge, because the very concept of error, if taken seriously, implies that truth exists and can be found. The inherent limitation on human reason, that it can never find solid foundations for ideas, does not constitute any sort of limit on the creation of objective knowledge nor, therefore, on progress. The absence of foundation, whether infallible or probable, is no loss to anyone except tyrants and charlatans, because what the rest of us want from ideas is their content, not their provenance: If your disease has been cured by medical science, and you then become aware that science never proves anything but only disproves theories (and then only tentatively), you do not respond "oh dear, I'll just have to die, then."

The theory of knowledge is a tightrope that is the only path from A to B, with a long, hard drop for anyone who steps off on one side into "knowledge is impossible, progress is an illusion," or on the other side into "I must be right, or at least probably right." Indeed, infallibilism and nihilism are twins. Both fail to understand that mistakes are not only inevitable, they are correctable (fallibly). Which is why they both abhor institutions of substantive criticism and error correction, and denigrate rational thought as useless or fraudulent. They both justify the same tyrannies. They both justify each other.

I must now apologize for trying to trick you earlier: All the ideas that I suggested we might know infallibly are in fact falsehoods. "Two plus two" of course *isn't* "four"* as you'd discover if you wrote "2+2" in an arithmetic test when asked to add two and two. If we were infallible about matters of pure logic, no one would ever fail a logic test either. Stubbing your toe *does not* always hurt if you are focused on some overriding priority like rescuing a comrade in battle. And as for knowing that "I" exist because I think—note that your knowledge that you think is only a memory of what you *did* think, a second or so ago, and that can easily be a false memory. (For discussions of some fascinating experiments demonstrating this, see Daniel Dennett's book *Brainstorms*.) Moreover, if you think you are Napoleon, the person you *think* must exist because you think, doesn't exist.

And the general theory of relativity denies that gravity exerts a force on falling objects. The pope would actually be on firm ground† if he were to concur with that *ex cathedra*. Now, are you going to defer to my authority as a physicist about that? Or decide that modern physics is a sham? Or are you going to decide according to whether that claim really has survived all rational attempts to refute it?

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* Though that does depend, as a U.S. president once wisely remarked, on what "is" is.

† Just kidding.

03

"My trip to Chile was one of many I took around the world to observe astronomical events. But more than any other, it would shake my vision of what science meant to me."

KELLY CLANCY,
Buried in the Sky

In Transit

THE ELEMENTS OF MOTION

Buried In the Sky

Looking up to the sky, a young astronomer finds truths at her feet

BY KELLY CLANCY

OUR GROUP OF ASTRONOMERS took in the naked mountains by the sea. We had flown into the La Serena airport at noon, and found a parched landscape. What sparse vegetation there was survived by drinking coastal fog. Sleeping dogs melted in the sun and dotted the sidewalks beneath knotted telephone wires. In the busy town bazaar, an ancient man stood stooped by his cargo, dripping sweat, while two wolfish dogs sat on top of his empty car, a kind of primal security system.

We drove four hours inland on a road veiled in sand to reach the Las Campanas observatory. Shanty villages lined the highway, built around whatever water sources could be found. Buses were the only other vehicles we'd see. Sometimes people would get off nowhere in particular and walk into the perfectly empty desert. Children in layers of tattered sweaters watched our gleaming van drive by, their mothers calling to them from inside scraps of metal leaned up against wooden posts: These were their homes. Others lived in rusted-out school buses on blocks, fitted with grimy curtains. As we drove higher, the villages disappeared and there was nothing save a handful of llamas wandering the verdigris-flecked hills, chewing brittle scrub brush. *Las Campanas* translates to "the bells," some say because its rocks, composed of volcanic material, sing when struck.

The domes housing the telescopes were gorgeous, radiant with the setting sun. Telescopes cost tens of millions of dollars to build, and more than a million a year to maintain. The stark contrast with the villages below unsettled me. My trip to Chile was one of many I took around the world to observe astronomical events. But more than any other, it would shake my vision of what science meant to me. Within a year, I would abandon science altogether.

I loved astronomy because it allows us to look backward to our origins. Eugene Wigner spoke of the "unreasonable effectiveness" of mathematics in describing the natural world, calling it miraculous, a "gift we neither understand nor deserve." And perhaps

ILLUSTRATIONS BY THE AUTHOR

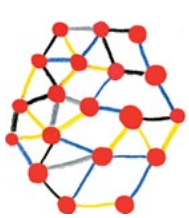
it is fair to call it a miracle: Math has made possible the scientific and technological progress that has revolutionized human life. But it also enables us to peer into the past, to reverse the trajectory of physical objects. I'd always had a special love for the beginnings of things: the Big Bang, stellar nurseries, the protoplanetary disk. I hoped that understanding these beginnings might give us a better sense of our purpose.

My father, who believed that understanding the *how* of the universe would make clear the *why* of it, had kindled this obsession. He had traded in the Catholicism of his upbringing to raise us on Stephen Hawking books and nature documentaries. I immersed myself in physics from a young age; I never got the memo that college was supposed to be the best years of your life—immersed in my studies, all I ever thought about was math. This delighted my father, but my grandmother, a truck dispatcher from Pittsburgh, never understood my passion. She was proud of me, of course, but it felt as if she thought my academic interests were a betrayal. "Why don't you just open a restaurant?" she advised. "You're a pretty good cook!" Despite her sage counsel, I became a wandering nomad for those years, looking to the skies for answers.

I worked for the late astronomer Jim Elliot and, though his lab was based out of MIT, we bounced around the world—Arizona, Chile, Hawaii, Australia—to work at various observatories. The nomadic lifestyle suited me—I was a loner and, apart from my family, had no ties at home. We were in Chile that year, 2002, chasing Pluto's shadow. There hadn't been a Pluto occultation—when a planet passes in front of a star—since the first one was observed in 1988. But that summer there would be two, the first visible from the Las Campanas observatory in Chile. The way that starlight gradually or abruptly cuts away in occultation data is rich in information about a planet and its atmosphere. A body with no atmosphere blocks the starlight like a light switch—light, no light. But a gradual extinction with a softer shoulder suggests an atmosphere, and we could even get the atmosphere composition from the wavelength-dependence of the curve. Anomalous dips betray the presence of rings or moons (Jim had discovered the rings of Uranus in a 1977 occultation, and took great pride in the toilet humor afforded by this distinction). Sharp spikes in the shoulder are caused by starlight refracting from variations in the atmosphere; an abrupt change in the slope of the shoulder suggests a blanket of clouds or a layer of murky haze.

Occulting planets cast their shadow on only a thin swath of Earth, and it takes months of preparation to predict the exact location of this shadow. Like the trajectory of a human life, an orbit is predictable—save in its detail. Larger planets merely wobble, but smaller bodies can fluctuate wildly. Observing a Pluto occultation requires extreme precision: Calculating the alignment of Pluto with a star is akin to lining up two bacteria from a distance of 80 meters. We'd been working in preparation at Lowell Observatory in Flagstaff, Ariz., gathering last minute data to perfect our predictions of Pluto's shadow. We worked such long hours that I kept a bag of clothes in my office and slept beneath my desk instead of going home, thinking I might go unnoticed until I realized that, in an office of astronomers, foot traffic happens at all hours of the night. Every morning, with fresh data, we updated the map of the shadow we were chasing. To cover our bases on these expeditions, Jim would organize a massive effort to send teams to record the event—both along the expected path and areas flanking it—in case our predictions were off. For very small bodies, the prediction uncertainty can be huge: In 2009 Jim sent 18 teams out across 6,000 miles to observe the occultation of a Kuiper Belt Object. Only two teams ended up observing the event.

Jim had learned in 30 years that there were certain countries to be avoided. Some colleagues had been kidnapped and held hostage briefly, and others robbed of their expensive equipment at gunpoint. Each team carried a portable telescope, tripods, a desktop computer, and a low-read-noise frame-transfer camera rugged enough to endure rough handling, locked to a GPS timing system. Observing in the field was tough on a telescope—ours had been customized with smooth motors for tracking the stars and heated baffles to keep the lenses free of dew and frost. Jim had perfected these portable systems over the years, and we carried them in the kind of suitcases that movie villains keep their guns in, which never ceased to draw scrutiny from TSA agents. Nevertheless, Jim refused to check this baggage: He used to, years ago, but it had once been misdirected and he'd lost a night of once-in-a-lifetime data.



Like the trajectory of a human life, an orbit is predictable—save in its detail.

The morning after we arrived at Las Campanas we woke to an unrelenting fog. The moisture felt strange in that arid atmosphere, oily. We'd slept in sterile dormitories one hill over from the telescopes, a few doors down from the cafeteria. Despite the inauspicious weather, Jim was anxious to get to the control room, so we wolfed our meals and trudged up the hill to the telescope, huffing from the high altitude. The anise used in the kitchen to prepare rice perfumed the whole mountaintop. We stayed up all night despite the fog, in the vain hope that it would lift and we could make observations.

José, the telescope operator, kept us entertained. He was Chilean, and recounted to us the history of the Atacama desert, the driest in the world. Its population exploded in the 19th century––and the natives began to die out––when vast riches were discovered in the rocks: silver, copper, gold, saltpeter. But apart from its mining towns, the vast majority of the desert was uninhabitable. Thus, when Augusto Pinochet led his successful military coup in 1973, toppling a democratically elected socialist government, the Atacama was where he hid his misdeeds. He turned its abandoned mining towns into internment camps and buried the dead in its barren sands. It's estimated that he imprisoned 80,000 people without trial, of which 30,000 were routinely tortured and 3,500 killed. Two hundred thousand people fled the country as political refugees—more wanderers of the universe.

Deep in the Atacama desert, a handful of elderly women have been digging through the sand for decades in search of the bodies of their family members. One mass grave was discovered in 1990, but Pinochet's regime had moved the bodies several times in hopes of concealing their crimes. As a result, the skeletons were shattered beyond identification, unless a team of scientists was willing to dedicate years to the task. Bereft family members were looking for narratives, but they would find none. Instead, they improvised, imagined, buried a bone shard they hoped might belong to their brother, or their son.

These women and I took shifts in the high desert panning for memories: they in the blistering daytime, I in the barren night. I was stuck in the past too—an abstract past, one hypothesized out of light curves and mathematical models, temperature estimates and spectral analyses. The subject of our trip, Pluto, was just part of a larger story of the outer solar system. It belongs

SKETCHBOOK Stray dogs in La Serena.

These women and I took shifts in the high desert panning for memories: they in the blistering daytime, I in the barren night.

to the Kuiper belt, the largest observable structure in the solar system, discovered only 20 years ago. Scientists now estimate there are about 70,000 large Kuiper Belt Objects. For me, the most interesting thing about them is their composition: Most of them appear to be covered in a goopy layer of complex organic molecules. Some scientists claim that, based on its current complexity, life must have begun 9.7 billion years ago (Earth is only 4.5 billion years old)—perhaps it got a head start on small bodies swinging through space. The idea's not totally outlandish: There is evidence that comets, slathered in ice and organic compounds, crashed into and seeded our hot young world with their payload of life, delivering the chemicals necessary to generate biomolecules. Even the cosmic dust surrounding stars appears to contain organic matter. The building blocks of life seem to be *everywhere*.

At the time of our Las Campanas trip, very little was known about the Kuiper belt. We were explorers, building a map of the distant plane, surveying the skies for dim planetesimals, peering, maybe, into the narrative of life. Keeping tabs on the trajectories of smaller bodies is also a necessary precaution for avoiding potential extinction events on Earth. The sky's wandering objects are, perhaps, both Brahma and Shiva: creators and destroyers. Every time I submitted the observation of a new body to the Minor Planetary Center, I was excited to think that, in some years, if this object were observed enough to confirm its orbit, as its discoverer I would get to help name it. If it turned out to be a comet, it would even be named after me, like a strange sort of offspring—a son that would bear my legacy for thousands of years. A son who never needed or disappointed me—and who never died—but spun silently through the universe, far from home, ignorant of my ownership.

Far from home because, from their composition, Kuiper Belt Objects are believed to have formed much closer to the sun than they are now. Hulking Jupiter flung them to the edge of the solar system as it cleared all in its path, scattering the solar disk's debris into the icy reaches. It's lucky, in a way, that they migrated: If they had remained so close to the sun, their ice would have long ago melted off—and with it, many secrets from the early days. I, too, was far from home. In fact I was discovering that the ivory tower could not be a more apt metaphor for an astronomer's life. Observatories are built in some of the most remote locations

I found a messy system that defused my purposive bias, that asked me to humbly serve a mystery I had no hope of solving.

on Earth: on the slopes of volcanoes in Hawaii, in the Atacama desert in Chile. Astronomers, already isolated from humanity by their work hours, are even more isolated by their work location. It didn't bother me much, at first. I was glad to live alone in the mountains, glad to be distant from messy human relations. I had my work and my solitude, and that was enough. But I was finding there was no real escape: I was bumping up against human tragedy even in this desolate desert. That first night in Las Campanas, the fog on the mountain persisted until morning, and we collected no data. I walked back to my room in the gray of early morning burdened with José's stories—stunned, weary, bumping shoulders with the moon.

It was on our second night in Chile that I received an email from my father: My grandmother had died. The funeral would be in two days. She had checked herself into a hospital, refused her many medications, and died the next day. Fiercely independent, and fiercely lonely, she lived for her children's visits. Her family had made it out of the steel mills, but the better lives she'd dreamed for them also took them far away from her. I hated to imagine her dying alone in a hospital. I looked up plane tickets to Pittsburgh for the funeral, but couldn't afford them, so I worked through the night, excusing myself to the bathroom to cry during particularly long exposures. My mother had taught me to splash cold water on my face to hide tear-swollen eyes.

A few days later, my trip was over. We drove back down the mountain, silent most of the way, a glut of survey data on our hard drives. The shantytowns pressed even more glaringly on my conscience. A month later we would successfully observe another Pluto occultation from Mauna Kea Observatory in Hawaii, discovering that Pluto's atmosphere had expanded since 1988. Pluto's atmosphere puffs up when the dwarf planet is closer to the sun and freezes out as it moves away, making its surface a particularly interesting chemistry lab. Jim was elated, and we landed a major publication. But I was left cold. Whom did this new knowledge help? I thought of the women sifting the desert for bones. I thought of the empty chair at my grandmother's funeral.

Had I been there for my grandmother, I thought, she might still be alive. Would I find myself someday alone, like her, hunkered down in an empty house full of relics, buried alive in the past? My travel made me miss other funerals, too, and weddings, births, graduations. My aim, I tried to rationalize, was still very human: this primal human instinct to explain, to know. Yet there was a part of me—seeded by grandmother's pragmatism, no doubt––that never quite bought this. "Why's your head always buried in a book?" my grandmother would ask, "What more you gotta learn?" My career in astronomy had been driven by the desire to dominate the great mysteries. There were so many questions in the world, so many fundamental truths to be uncovered. But the women digging through the desert suggested a different approach. What would they gain, once they found their skeletons? They weren't looking for the why, not really. It wasn't a DNA test that would fulfill them: It was the act itself that was meaningful, their tireless devotion. Each shovelful of sand was an offering to the bones they sought. I realized that it is hopeless to think we might eradicate mystery—all we can do is serve it.

I left science and joined the Peace Corps. I asked to be assigned to Central Asia, the place in the world I knew least about. I'd steep myself in unknowing, I'd dedicate myself to the children of strangers, living in a Turkmen village no one's ever heard of. There's no way for me to give a fair account of the poverty and daily heartbreak I witnessed there. Yet it was this very tragedy that drew the community together. They were fiercely proud of their heritage, their tribe. Their ability to make a home in even the most devastating circumstances humbled me, and inspired me to try to do the same. Though I'd gone in the clichéd hope of making a difference, I quickly learned that it wasn't the work I did that was satisfying, it was the relationships I built, my engagement in the community, alive and in front of me, not hidden among the stars.

I had no intention of returning to science. I felt infinitely removed from my former conviction, and my father's belief, that science could answer the whys of the world. But a friend in Turkmenistan asked me why I'd pursued physics so devoutly. As I recounted my love of the subject, I recalled that Eugene Wigner spoke of another miracle besides the laws of nature: the human mind's capacity to divine them. Though we like to think of physics as the foundation of the sciences, perhaps it is the mind that is the more fundamental principle: the universe's most elegant solution to itself. I began to read about the brain. I discovered something full of mystery, impossibly complex, resistant to glib mathematical laws. Borderline lawless, even. I found a messy system that defused my purposive bias, that asked me to humbly serve a mystery I had no hope of solving. Here was science that asked for a different kind of devotion.

When I returned to the United States, I began Ph.D. work in neuroscience. I've since found a community of likeminded people, bound by curiosity. We make our home in ideas, collectively telling stories we hope have truth in them. It is our dedication to asking questions that matters. But there is something else, too. We are fascinated by life. Among all the human tragedy we try to ignore, calloused by media, myopically nationalistic even in our sympathies, perhaps there is hope in this great unlikelihood: Of all the planets that might have formed, Earth did, and it stayed dancing in an orbit whose conditions life loved. Life, which seems desperate to take hold, wandered from the sea onto land, across Pangaea, across the Bering Strait, perhaps even across the Milky Way. Life that bubbled up on icy rocks 4 billion miles from the sun and made a home for itself in every lost corner of the Earth. Life that is never satisfied—ever shifting forms, it tries and tries and tries again.

The solace this offers is pitifully inadequate: a drop of water on a forest fire of suffering. It will not heal the hearts of those women in Chile. It will not feed the poor or shelter the homeless. It will not keep anyone's grandmother company at night. I cannot pretend that curiosity is enough, that awe is enough. But the tenacity of life might be.

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The New Flight Of the Ibis

How a determined scientist taught an ancient species to migrate again

BY CHELSEA WALD

IN 2007, ON A fine summer day in rural Austria, a flock of northern bald ibises followed two paraplanes, gondolas with prop engines, held aloft by yellow and blue parachutes. Although the ibises looked like vultures on the ground, the resemblance disappeared in the air. In flight their long, curved bills jutted forward, their black wings shimmered purple and green.

The scientist piloting one of the paraplanes was leading the ibises to a mountain pass in the Alps and a wintering ground in Tuscany. For centuries, ibises had been plentiful in Europe. They summered north of the Alps in today's Austria, Germany, and Switzerland, where they nested on cliffs and castle walls and fed from meadows. By the early 1600s, the sociable animals, vulnerable to hunting, had been wiped off the continent. If this group of 20 learned the route to Tuscany and returned on its own, it would be the first colony of northern bald ibises to migrate in Europe in 400 years.

But the birds were not sticking to the script of their historic mission. After shadowing the paraplanes for about five miles, they turned around and flew back to where they started that day. The birds landed in a field and started preening and making deep-throated squawks.

ILLUSTRATION BY ANDREA KALFAS

PHOTOGRAPHY BY JOHANNES FRITZ

They looked like an aging, addled punk band, rings of black feathers around receding red foreheads. “Scheisse,” said Johannes Fritz, the scientist, cursing in German.

FOR FOUR YEARS FRITZ had been trying to do something he had never even heard of in zoology—teach an ancient bird to migrate. He had been a doctoral student in biology at the Konrad Lorenz Research Station in Austria, founded in the 1970s by Lorenz, the Austrian zoologist who demonstrated some types of young birds “imprint” on the people who raise them, accept them as foster parents, and follow them everywhere. Fritz got the idea to lead the birds in the air from the movie *Fly Away Home*, about a girl and her father who teach a wayward brood of Canada geese to migrate to a North Carolina bird sanctuary behind a “microlight,” or engine-powered hang glider. Fritz had worked with dozens of hand-raised ibises in captivity. But he knew that if the birds were to flourish in the wild, they would have to learn to migrate on their own.

By 2007, his optimism was fading. Did he understand enough about migration to make the reintroduction work? Princeton University professor of ecology and evolutionary biology James Gould, co-author of *Nature’s Compass*, has called animal migration “one of the greatest mysteries of science.” And no scientist had ever tracked a migration of the ibis in Europe. There was only one tiny, dying colony of migrating northern bald ibis left in the wild. And that was in Syria, where little was known about them.

For the past six years, Fritz has never stopped trying. Since 2003, he has led eight migrations with the ibises. In 2011, a female ibis flew the first new migratory route on her own, an extraordinary achievement. Subsequent migrations have brought surprising new insights that will help scientists work out how birds navigate, learn, and conserve energy during their journeys. Scientists marvel at the new migration of the ibis. Martin Wikelski of the Max Planck Institute of Ornithology said tracking the flights “is like following the walk of mankind out of Africa.”

ON A RECENT EVENING at his ibis colony in Burghausen, Germany, Fritz, 46, who heads the "Waldrappteam" (*Waldrapp* is the German name for the species), explained that he never set out to be a flight instructor for the ibis. He arrived at the Lorenz station, a field station of the University of Vienna, in the '90s to study the social traditions of the greylag goose, a common European species. The northern bald ibis, he said, "dropped out of the air" into his life, his voice accented with the harsh but likable consonants of his native Austria. This May, the nonprofit Waldrappteam received its biggest donation: a grant worth more than 4 million euros from the European Commission and other sponsors.

By the 1990s the northern bald ibis was not only long gone from Europe but also critically endangered around the world, namely in the Middle East and North Africa, where it once flourished. In the 1950s, Turkey used DDT intensively, killing many hundreds of birds while also interfering with their reproduction. Conservationists caught more than 40 of the remaining wild birds in the '70s and '80s, preventing them from migrating but allowing them to breed on site. The hatchlings did well, but the wild flock continued to decline and was declared extinct in 1990. Their migration tradition died with them. Without experienced migrators to show them the way, the descendants of the captured birds remained in Turkey, cared for by humans, unaware of where their ancestors had spent their winters.

In the meantime, zoos figured out how to breed the northern bald ibis using descendants of a North African population. There were soon more than zoos could handle. Some conservationists experimented with releasing them into the wild to form colonies, but the young birds didn't cohere into a group and instead wandered off.

IN 1997, KURT KOTRSCHAL, director of the Lorenz station (who had taken over the station's leadership from Lorenz, who died in 1989), acquired birds from the Alpenzoo in Innsbruck. He thought the station could establish a non-migratory colony by imprinting new ibis chicks. Just after hatching, the helpless chicks, kept from their natural mothers, bonded to human foster parents. (Students and young scientists usually take the role.) The chicks depended on their foster parents for food and protection and stuck close by them. So it

If this group of 20 learned the route to Tuscany and returned on its own, it would be the first colony of northern bald ibises to migrate in Europe in 400 years.

was surprising that in August of the first year all but a handful of the birds suddenly flew off. Where had they gone? Luckily, Kotrschal said, people who see odd birds often try to find out where they came from. He got calls, mainly reporting dead birds, from as far away as the Netherlands, Lithuania, northern Germany, and Russia.

What compelled the birds to cut their ties with their foster parents and fly off? One likely possibility, which turned out to be the scientists' first key insight into the ibises' migratory habits, was *Zugunruhe*: Seasonal migratory restlessness caused by sudden physiological changes, such as an increase in the hormone corticosterone. This nervous energy convinces birds to leave their breeding grounds for warmer places that will provide them food for the winter. In the spring it pushes them north to breed, where predators are fewer thanks to harsher winters, and where the first flush will provide a dense food supply.

"It was hilarious. In the morning you wouldn't know where you would end up in the evening. Sometimes it was the middle of a field in northern Italy."

Some birds, like geese, are happy to give up their migratory traditions if the conditions are right, jaunting from pond to pond. But the ibises' extreme August journeys indicated that they were seized by an overwhelming drive to go, in spite of the fact that they didn't know their destination. This continued to be a problem for Kotrschal, who eventually succeeded in establishing a sedentary colony at the station. But it also represented an opportunity. If someone could harness the ibises' restlessness and teach them where to go, the species' lost migration traditions could be recreated.

ENTER FRITZ. HE FIGURED migration was a social tradition in the ibis, as it was in geese, cranes, and other water birds. Those types of birds followed adults on their first migration, and seemed to learn the route by memorizing visual landmarks in a sequence—a sort of mental photo album. That was different from many other birds, especially migratory songbirds, which are known to have a powerful innate migration vector that tells them which way to fly—no learning needed.

Although the ibises had an innate migratory impulse, their sense of direction was clearly lost. When they flew off their first year at the station, most of them flew roughly north, following the valley, when they should have flown south for the winter. Given the ibises fall "on the extreme side of the socially learned," Fritz remembered thinking, he figured it would be relatively easy to teach them a new tradition. Knowing the imprinted birds would follow their foster parents anywhere, Fritz had the idea of having foster parents sit behind pilots in two-seat microlights, calling out to the birds, "Come! Come!" to fly with them.

In 2001, Fritz got start-up funds from the Vienna zoo to buy his first "rather old microlight," which, like the one in the movie *Fly Away Home*, had a rigid wing over the cab instead of a parachute. He enrolled in a pilot school in Spain but quickly discovered that flying made him queasy. His instructor warned him not to tell the doctor, since that would disqualify him. Fritz chewed motion-sickness gum, kept his lunch down and mouth shut, and went home with his license.

There were no historical records of where the species would have wintered in Europe, but Fritz guessed that Tuscany would be about right. He consulted with Italian ornithologists, who assured him many bird species winter in the famous Italian wine country. Fritz found a nature preserve in Tuscany, run by the Italian branch of the World Wildlife Fund, on the western coast of Italy. He was allowed to establish an aviary, which his team would use to care for and monitor the birds.

In August 2003 he mapped a 680-mile route through a pass in the Alps, down the Tagliamento River to the Adriatic Sea, along the coastline, then across the Apennine mountains to the nature preserve. He wanted to follow big landmarks that the birds would remember.

The first flights didn't go well. The old microlight was too fast for the ibises. Its slowest speed was 37 miles per hour, while the birds' maximum speed was 27 miles per hour. Fritz had to keep circling around, waiting for them. But the biggest problem was that the imprinted ibises refused to fly much of the time. "We thought the birds have to follow when we want them to follow," Fritz said. But it turned out that the ibises had different ideas. Even if they did agree to follow on any given day, they often gave up and landed before they reached the place the team had intended to spend the night. Fritz often had to beg landowners to let them set up camp.

"It was hilarious," said Kotrschal, who accompanied the migration on the ground. "In the morning you wouldn't know where you would end up in the evening. Sometimes it was the middle of a field in northern Italy. One time it was at the location of the original international airport of Venice, at the Lido di Venezia. You wouldn't know if you would leave the place the next day or only a week later." But Fritz didn't think it was so funny. He had no knowledge of how a northern bald ibis would naturally migrate, and it showed. He and the birds were simply out of sync.

The birds' longest flight that year was about 19 miles in one day—a qualified success. On the other hand, the team was forced to load the birds in vans and drive them several stretches when they refused to fly. But the birds eventually got to Tuscany, one short segment at a time. The next years went better, as Fritz acquired slower microlights and allowed for more rest time. But getting the birds to fly over the Alps, the most direct route, was a struggle. He never made it through a pass without taking the birds some of the way in a van. After 2007, he called it quits for the Alps. He figured the birds simply couldn't cross the range.

Fritz also doubted his expertise as a pilot and enlisted Walter Holzmüller, an Austrian paraplane champion, as a second pilot. Holzmüller brought new paraplanes, the team's slowest aircraft yet, and finally a good fit for the birds' speed. Fritz hoped their new route would also be a better fit: The fastest way to the nature preserve without

The ibises found completely new and better ways home via places they had never been before.

Goja, the trailblazer, didn't learn the shortcut from another bald ibis but invented it herself.

crossing the Alps was to the east through Slovenia.

Those changes turned out to be the right decisions. All of a sudden the human-led migration started to click. Holzmüller noticed that the birds got bored if he just flew straight, so he wove to keep their attention. But what the birds really wanted was to soar in thermals. Studies had shown that large birds like storks and vultures conserve energy when they spiral up in hot air currents and glide down to the next one, barely moving a wing. But nobody had ever taught the ibises that soaring would be the best way to migrate. Wikelski of the Max Planck Institute of Ornithology marveled that the hand-raised birds "still have the ability and knowledge of how to fly in thermals and use streaming air efficiently."

The new technique meant the paraplanes and the birds could go all day. One summer day in 2010, the birds flew almost six hours and more than 160 miles, similar to the distances that conservationists had observed the Syrian birds fly. (It was "by far the longest flight of an airplane in company of hand-raised birds," Fritz would later boast in a press release.) Fourteen birds made it to Tuscany in only seven flight days. They stayed there for the winter, where the eating was good. Hopping from field to Tuscan field, they picked up grubs with the tips of their beaks and threw them into the back of their throats.

IN JULY 2011, FRITZ had the success he had long been waiting for: a lone bird named Goja returned on her own from Tuscany to the breeding grounds in Burghausen. Other birds arrived soon after. Global Positioning System trackers on the birds sent periodic locations to the scientists, showing that the ibises had taken shortcuts directly over the Alps.

The ibises had overturned Fritz's assumption that they would follow the route that he had taught them, having memorized a sequence of landmarks. They seemed to start out that way, following the learned route over the Apennines and up the Adriatic coast. But then they deviated. A statistical analysis showed that they chose straight-line paths through passes in the Alps. In short, they found completely new—and better—ways home via places they had never been before. It seemed that all Fritz had to do was show them where the wintering area was. "Everything else is in their genetic background," he said.

Fritz started spreading the word to other researchers. They were amazed. "We know other animals do these things on a small scale," said Wikelski. "Desert ants can go on a curly road trajectory, and then at some point when they decide to go back, they go straight back." But Fritz's birds, Wikelski said, were the first natural vertebrate population—at least one scientists had observed—to show that skill. Gould said the ibises' migration was "certainly news." It proved they were sophisticated navigators, more similar to migratory birds with no social tradition, which can find "a kind of planetary shortcut" with an internal, GPS-like map sense.

Because he tracked every single member of this new migrating population, Fritz knew that Goja, the trailblazer, didn't learn the shortcut from another bald ibis but invented it herself. She also taught a new generation, leading a young male bird directly south to the wintering area. Fritz had done it. He had put the ancient ibis back in touch with its natural instinct. In 2012, Goja bred. Fritz was thrilled. "Goja is basically the first breeding migratory bald ibis in Europe in almost 400 years," he said. "It's a big success. It's a concrete indication that we can give this bird a second chance in Europe so that it can return back to the wild."

The ibis, however, remains susceptible to an ancient practice out of its control. During one of her migrations last year, Goja was shot and killed by hunters in Tuscany. Fritz's team estimates that as many as 49 of the 102 ibises they have led to Tuscany have been killed by illegal hunters. The new European Commission grant includes money for an anti-hunting campaign, focused on ending illegal hunting in Europe.

ON A SUMMERY DAY in May, the air still electric after a storm, Fritz drove up to the Burghausen colony to check on his brood of ibises. On the top ledge of a two-story aviary were seven nests, seven parents sitting on them. At the start of the breeding season a few weeks earlier, the birds quarreled, stealing each other's nesting materials and sparring with their beaks. But now they seemed oddly peaceful.

Fritz was proud the ibises were offering scientists new insights into avian migration. Franz Bairlein, director of the Institute of Avian Research in Germany, was studying the birds to learn about long-distance migration, how birds alternate quickly between two opposing physiological states: intensive energy use during flight and intensive energy storage during stopovers. He analyzed blood samples taken daily before the ibises' takeoff and after landing, something that had never been possible before. By matching the ibises' blood chemistry to their flight behavior, Bairlein hoped to learn how the birds regulate these physiological changes. Another group was studying the aerodynamics of the ibises in flight. Their "V" formation was giving scientists new clues into how birds conserve energy over long hauls by "drafting," or reducing the drag in front of them, by flying in a precise angle.

The results of these studies could help Fritz be a better leader, equipped with hard data instead of educated guesses, when he begins human-led migrations again in 2014 to increase the number of migrating birds in Europe to a sustainable number. He plans to try to go through the Alps again. But this time he will take routes that the birds have chosen themselves. He might also figure out the physiological underpinnings of why his birds need so much rest, a problem that's plagued him since the very first migration. "They have food, they have a good body weight, they have everything, but sometimes they do not want to continue," he said. "That's still something we don't understand."

This year, seven new chicks were born at the Burghausen colony. Fritz made a prediction. In five years, he said with a grin, Europe could be home to more than 100 "free, wild" northern bald ibises, breeding north of the Alps and flying south for the winter.

CHELSEA WALD is a freelance science writer who contributes to *Science* and *New Scientist*. She migrates between the United States and Austria.

On the Wilderness Continent

Building new lands requires sacrifice

BY SCOTT GEIGER

T**HE CONTINENT HUNGERS TO** be realized. Each day adds a new increment to the frontier," I said, "and behind that expansion is the flux of towns darkening into cities to be threaded along newly spun highways. We will put up the mountains. We will lay out the prairie. We will cut rivers to join the lakes." This year's externs had arrived, and I gave them my orientation talk.

Seated about the displaybank before me, they flipped through intro folders. Clean frames of pure color, these were an electric, metal blue—the color of the company. We were just a bank when they had selected the color, back before the opportunity came to erect the Continent. I informed the externs that a more ambitious development has never been planned: all-new country, elevated and secured from downstairs, with a growing complement of landforms, clean waters, ecologies, wilderness. From what I've always understood, too, the Continent is still in the earliest phases of its construction. Two, maybe three, lifetimes may go by before substantial completion can be declared. But the Continent is too far along now and too valuable to be abandoned.

Faces above the displaybank followed me around the room. "We are alive at a crucial moment in the course of this project," I continued. "It's a voyage of generations. Our company has leveraged itself many times over to carry the design even this far." Mine was a message they had heard their whole lives. If not at home, then on the wireless; if not discussed in classrooms, then rumored in dormitories. They must understand that our work at the Activities Estimate, their work now, contributes significantly toward the Continent's fulfillment, one day at a time. But who at age twenty will readily consider the scale of time required to complete our project?

Twelve came fresh from the regional academy. The thirteenth was older, retraining after a tour in the field. He was maybe Vivian's age, so not quite old at all. He wore his hair wilderness length and had shaped a blond

ILLUSTRATIONS BY MATT TAYLOR

beard to reach from his smile to the open collar of a dark plaid shirt. They listened in earnest. Solid authority is celebrated up here. Often our externs are the children of subscribers who took out financing to move here, so they're required to work for the company in some capacity, like civil service. Some are new employees of the company who officially reside downstairs. You don't hear stories about pioneer grandparents who came up when the parts that are supposed to be Michigan and Illinois opened. The beautiful youth who grow up on the Continent, if they work for the company at all, become soil technicians or aquarists and rise to regional VP commissioners or principal scientists. Our own young men and women will sit at displaybanks like this one and wield vast sums of data to reconcile the Continent to its investors and the world.

"The work we do offers the only measure by which the Continent can be evaluated," I said, cueing Joost. "Without our work, the company gropes blindly." The Activities Estimate rose across the displaybank. Before each extern, case documents served up like a meal. I backed away as Joost and Erin Vesey came forward to take over from me. Eight weeks out of the year we had externs in the bureau, and it fell on Joost to coordinate them. He assigned their portfolios. The externs dealt only with the smaller, better towns, some still in their first generation. Less than six-thousand, seven-thousand subscribers. These consisted of new buildings with hot water and good, efficient equipment. A few even had historical downtowns. Modest but novel entrepreneurs flourished. Retail was lively with small local businesses and one or two major international brands from downstairs. Entertainment came in different formats. Meaning happy people. Meaning no incidents. Easy work for externs. Of course the happiness of these towns was no less essential to the sustainability of the Continent.

"Good luck to each of you." And I meant it.

Joost read off towns to which the externs were to tune. The man from the field was named Everett, and his assignment was a place called Venusberg, way down south where they were jacking up mountains into place. The start of Tennessee or thereabouts, I think. I watched him enter the name into his displaytop. Artificial light warmed his full blond beard. It looked like not so long ago his nose had broken.

SUCCESSFUL EXTERNS WORK QUICKLY to grasp the Activities Estimate and all its tools. They correspond with commissioners and field observers to learn how things are on the ground. They study how towns are administered, how they are structured, what they contribute locally and Continentally. Some settlements are so small, so remote, they are universes unto themselves. As Joost introduces new tools or new ways of approaching scenarios, complex techniques become more applicable. Ethics are introduced in the context of Continental policies. Most externs can cite Dymond and Balboa. They know *A Horizontal Babel* by Ober and the latest Monica Helix arguments, the ones about designing indigenous communities for the frontier. Something usually happens to ruin an extern's assumptions. A house fire kills a mother and a daughter. The collapse of a flyway pancakes a team of construction workers. Even rarer, a small incursion from downstairs. Terrorists strike at symbolic targets from time to time. Smugglers move contraband up and downstairs, feeding the parallel black markets. Joost allows externs emotional and mental space to adapt. Some cannot. Which externs are capable of continuing to work within the Activities Estimate is quickly evident.

During our weekly meetings together, Joost discussed the externs with me. Two were exceptional this year, he thought. One had an executable autobiography written in Buffalo. When Joost asked why he had chosen Buffalo, Nathaniel said that it was because among the languages permissible for publishing within the Activities Estimate, Buffalo was the best for detailing abstract emotions. The Activities Estimate tends to attract inward people.

"Take a look at this one, too," said Joost. "Everett came from Environmental Integrity. He was stationed on the frontier four years, patrolling the part we're calling Wisconsin."

"The broken nose?"

"Older than the others, yeah."

Everett had been pushing a lot of the figures for new construction at Venusberg. The town was way out there, but it burgeoned. A steady stream of new subscribers. There wasn't much to his submittals. Our assets on the ground were still limited. To get a town going for us took some time, and Venusberg was relatively young.

When you're young, you don't really see how life keeps hurtling you along. There is no place to rest.

"Everett started a little behind everyone else and he's fallen further back, I think. There might be a little reluctance on his part because of the transfer."

I said, "There's a known problem mixing former frontierspeople into design and ops. It's too hard to go behind the curtain. How did he transfer to us?"

"That's just it. The transfer issued directly from Trevor Rus."

"Shit," I said. "Then there are no questions to ask, Joost."

Trevor Rus was everywhere. He interfaced with the whole company, from the janitors to the town commissioners, all the way up to the Directors and their Board. He was the face of the company, a presence so ubiquitous as to require neither name nor mark. Not even a tiny logo stamped microscopically on the leaves of our trees. Internally, he played the reckoning angel. He came once for Darcey, my company wife, and she had to go. I wondered if Everett had also traveled on the special service sandwiched inside the Continent, a rail-like system that's more bullet than train. It moved company assets and resources as quickly as the Activities Estimate moved our eyes and ears. The Continent remains a wilderness for subscribers with the company whisking its people invisibly beneath the horizon.

"Everett stays. Can Nathaniel tutor him?"

As he stood up, I reminded Joost that Trevor Rus can't know any better. He only knows what's necessary for the Continent.

ON FRIDAY NIGHTS, I rode the shuttle to the port of entry. Wearing subscriber clothing, as many people from the Pyramids do on the weekends, I gave my name and password at the stiles. If I knew how to code in Buffalo I would describe the moment of seeing Vivian there across the lot, leaning against the silver light post in her flats, her patterned black leggings, her great gray coat with leather hooks and wooden buttons. She wore the black sunglasses then in fashion with subscribers because of the UV at this elevation. The sun reached her through the parking lot. Red-blond hair curled in a nebula behind Vivian. A rule of ours: no kissing in public. We shook hands, we spoke formally, at least near the port of entry.

Vivian and I were never official for four reasons. One was Darcey. Our request to be reunited was still pending, after years. Neither of us had ever canceled it, so far as I knew. I had not. Two, Vivian was a subscriber, a graduate student at the company's regional academy. As a bureau chief, I really had no business dating a subscriber who paid good money for her quality of life. To her I should have been as thin as air. I should have been appreciated out of sight, like plumbing. But Vivian handled species migration to the Continent, work that brought her into contact with a lot of design and ops people, even the Activities Estimate. Three, she had a thing for company contacts, and I knew a few of them. That's how we met. And four, the delicate little light we shared now felt unusually larger and more magnificent than it should have, as if a younger and brighter universe hid within our daily lives. Downstairs, the Continent is continuously advertised. One famous video is all pewter-and-white film, a collection of scenes with a lot of people presumably traveling up to the Continent. A man boards an elevator. A woman in high heels steps onto a helicopter. A tiny expensive jet takes off. It was like all that with Vivian and me.

Enclosed in her car we caressed, my hand on her cheek, Vivian's lips at my ear.

When Darcey was transferred, her whole economic development team was redeployed to the other end of the Continent. Who was she without her work? she had asked. I had the option to give up my bureau, but who was I without the Activities Estimate? "I've been so short with you these past weeks," Darcey said in the company car that took us from our place in the Pyramids to a distant corner of the campus. At the edge of the woods, a long hillside rose up from the forest. One side had a flat glass façade. Grasses all around had gone to seed. I pushed a cart of her luggage into the lobby of the station where agents took it. For security reasons, I could not continue with her beyond this checkpoint, the agents said. At the lip of a staircase that fanned down to the special service system, surrounded by the rest of her economic development team, Darcey turned to hold a hand up toward me. I only signaled back.

Everything happens for the best on the Continent, we believed together.

JOOST COORDINATED WEEKLY presentations for the externs in a dining room off the canteen. They ate at solid terrazzo tables under a polished ceiling element. The day I ate with all of them, this ceiling loomed its fractal geometry above presentations by Erin Vesey, our lead programmer, and Matthew Vowell, legal counsel in the bureau. The ceiling appeared to listen in on our lunch. Externs Sophie, Boyce, Li, and Darwin sat with me. Everett joined too. I remembered Paul Reiss aloud. Jesus. I told them all what it was like when Paul led the bureau, when I was just an analyst. I have tried to keep some of his traditions, but it has been years and years. I said, "It's probably not interesting for you to hear about the past. When you're young, you don't really see how life keeps hurtling you along. There is no place to rest."

At the next table over, Joost was between Nathaniel and Erin Vesey, laughing about the macaroni salad sprinkled with tiny colored dicings. I overheard Erin say, "It will be another ten years before the food is entirely figured out."

After the lunch we traveled the long way back to the bureau, across the skybridge, along the windows, not on the moving walkway. With Sophie and Darwin and Everett, I brought up the group's rear, all talking about the north. Joost stopped them along the windows midway across so everyone could have a look at the grounds. Some distance out, men were working from a white boom lift. Where the browned-out meadow met the treeline, at the beginning of the forest that cloaks the Pyramids campus, they were inspecting trees. One was a surgeon with a chainsaw extended into the canopy of an alder. The subtracted branch fell in silence and bounced as if the ground were a mattress. Joost told them how expensive this particular forest is. From right to left, traveling across the glass in front, came and went the reflections of figures on the moving walkway.

Sophie said to us, "There are trees now that allow you to select pretty much what form you want ten, fifteen, twenty years down the road."

Everett shook his head at the idea of destiny trees.

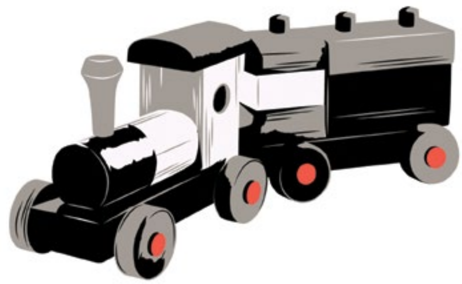
As the group started off over the second half of the skybridge, I saw Joost let everyone file by. Finding myself beside Everett, I asked, "Did they ever work on the trees where you were?"

"It was live and let live," he said. "It's one of the older parts of the Continent, and now it's a preserve."

"But they're all real trees, you said? No designer trees?"

"We have the real trees up north. Old ones so dense you can climb them and walk from tree to tree, as easily as you go between the buildings here with the skybridges linking everything. I know they have been up there for a long time. My own specialization is the watercourses and lake-like bodies feeding the trees."

Then Joost was with us. We walked well behind the group.



“Those lakes are pretty realistic,” Joost said. “Aren’t they, Everett?”

“They are real. There are real fauna too. Birds, reptiles, fish, mammals, insects, real everything, down to the bacteria and algae.”

I said if it were so real, I would have to move up there myself.

“You can’t. That’s just it. The land is a preserve. That’s how this happened,” Everett said, touching his broken nose. “A group of surveyors came. They were lost, I think, and their site specs were all wrong. I confronted them, physically. Which was wrong. They worked for the company. Which was why they moved me here, I think, as a temporary punishment.”

“Sometimes the Continent asks you to sacrifice,” I said. “As the Continent holds us up, we are called on to hold it up.”

He and I followed Joost around the terminus of the skybridge where escalators carried our colleagues off into the upper floors. Flush against the window-wall hung the mezzanine, a floor between floors, home to our bureau. The externs marched up the cantilevered stairs as if boarding a vessel. I watched Everett return to his dark displaytop. Before him wrinkled colors and shapes and words that made up Venusberg.

WHAT HAPPENED WAS BEYOND prediction. Early in the morning, Everett’s voice punctured the bureau. “No,” he shouted from his seat at the displaybank. “This can’t be happening.”

I came out to see all heads raised, work chandeliered indeterminately, mid-thought on the displaybanks. People in the mezzanine were looking up toward us. No one ever shouted in our bureau. Everett scrolled forward and back through his overnights.

In Venusberg, the overnights read, a seven-year-old boy, Joey B., had come into the Venusberg Care Clinic with an illness resembling advanced influenza. His condition was critical. The two doctors in town, a Donald Schuykhill and a Frances Deveroux, had agreed on the diagnosis. They signaled to the regional VP their desire to transport the boy to a city with a larger medical facility via special service. Everett captured part of Deveroux’s audio from the displaytop, “We have a clinic here with only fifteen beds. This town is three-thousand eight-hundred and twenty-seven souls.” The company rejected their request.

Erin Vesey went around the bureau, putting people back to their work.

“I don’t see what the trouble here is, Everett,” Joost said, his voice steady. “Just code it a ‘medical alert.’”

It looked like not so long ago his nose had broken... Joost allows externs emotional and mental space to adapt. Some cannot.

The next category tier was epidemic.

Deveroux appealed the decision. Everett and I read the VP's rejection, which came with a reference to the Subscriber's Agreement subsection on "at-risk" communities on the frontier. Like so many of these new settlements and towns, Venusberg was remotely placed. Small town life set in the robust wilderness appeals to the top subscriber market. Because of its remoteness, highways were still some distance on provisional roadways. They had no airfield. No hospital. The company would not break the realism of the Continent. No concession for Joey B.

Everett asked to code the correspondence between the town and the company, but Joost raised a hand. "No, all that stays out. This will run its course."

I touched Joost at the elbow to let him know that I would lead, but before I could start up, Everett said, "We were on our own up north. I don't think anyone ever expected help from the company. But this is for a boy, and it's the doctors asking."

"There's a lot of reluctance to use the special service, you know," I stated.

Everett's fingers coaxed his beard. He said, "I traveled on the special service, when I transferred cross-Continent. They moved me for my own good, I heard."

A second patient, the boy's aunt, appeared the morning of the second day. We caught the exchanges flurrying between the town commissioner, the regional VP, and a few offices even above that. Outrage manifested in Venusberg. More patients came into the Care Clinic. Satellite photography late in the second afternoon picked up large piles of debris spelling out the name JOEY with an incomplete delineation of HELP. "Oh no," Everett said, sorting these. The two or three people he had on the ground began worrying. Anxiety spiked. While Schuykhill worked with the influenza victims, Deveroux began agitating. She made noise. "Where do we live?" read one sign she held up to the street cameras. "Why won't you help us?" read another. She raised flags. She kicked up dust. Her organized following took off just in time for Joey B. to die in the Venusberg Care Clinic.

Everett coded diligently, trying to order Venusberg for the Activities Estimate. "What can we do for them?" he asked.

"The Activities Estimate only sees, hears the Continent. We cannot do."

"How can I enter that the company is just not responding? How can we represent the trauma people are experiencing? I've experimented with different code and tags."

Joost frowned. "Please don't try that. Venusberg could adversely affect the company's pricing any way we code it. But novel interpretations sure might make things worse."

Everett suffered, I could tell. He would not go home.

Sixth and seventh patients entered the clinic on the third day. Schuykhill diagnosed himself with the influenza. This was the end. The town commissioner disappeared. The administration began to decompose. Families fled out onto the prairie. Then Deveroux's protestors raided and burned the Continental Bank branch. This at last brought out the company troopers—via the special service—to read everyone the Subscriber's Agreement. He watched troopers from satellite, from a few surveillance points. Anonymous riot helmets, translucent shields stood in dusk light. Quarantine was imposed.

"Goddamnit," Everett said, hands on his head. "We broke the rules anyway. But instead of breaking them earlier to save Joey, they sent in police to shut Venusberg down."

"That's how the Continent goes sometimes."

I walked Everett to the edge of the mezzanine near the window-wall. I leaned against the rail with my back to the sun. We stood close to the glass, where it was possible to look up the slope of the entire building, floor after floor of design and ops studios, all working on the construction of the Continent.

"I hope, Everett, someday very soon if not right away, you'll find yourself working as an analyst. Maybe you'll have your own listening post." I imagined a facility surrounded by prairie grass, collecting from new towns along the frontier. "That's why you're here at the Pyramids."

"I'm here because I have to be, if I want to stay upstairs. I had to come."

If you're not a subscriber to the Continent, there is always the hazard of deportation—downstairs—even for established company members like me, like Darcey. I said I always worried about being let go.

Everett said, "They moved me to the Pyramids, but they won't move a sick subscriber, a kid?"

"They moved my wife away too," I explained. "We're pieces of the Continent, its instruments."

Passion softened Everett's big eyes.

"Look, this is a romantic period. Growth depends on the romantic power of the Continent. Do you remember Monica Helix in *Design Principles for Truth in Wilderness*?" It had been a long time since Environmental Integrity classes, maybe too long for her theories of a protected transit infrastructure supporting a super-landform.

"I'd like you to succeed here, Everett."

We returned to the displaytop, brought up the case materials. We did the entire case through four o'clock that day. Deveroux surrendered herself. The commissioner ordered everyone to shelter in place for the duration of the quarantine. The company was interviewing and evaluating residents, worried about a subscriber revolt. No further deaths came. I coded a vigil underway with all the suffixes and tags I knew to communicate unity and well-wishing.

The case saved, locked, and dissolved into the displaytop before Everett. I put my palm against the warm sculpture of his back. It was almost evening now, so I suggested he take the rest of the day for himself. Maybe tomorrow too.

"Who will monitor Venusberg?"

"The logs will have everything for you in the morning."

Everett put on his coat. He straightened his cobalt tie.

We walked down from the Mezzanine and across the lobby to the little plaza outside the Pyramids where shuttles run to the port of entry and transit hub that goes to the housing blocks of the pop-up charter city we called Soon City.

"On cases like this, we often work in teams to preempt misinterpretations," I said. "It's not easy to stay objective on your own."

Everett looked at me from the corner of his eye. In profile, the bridge of his nose bent drastically. The shuttle's electric motor whirred. Then we were moving, the two of us alone in the enamel white and air-conditioned chamber.

"Why not record events in the Activities Estimate just as they come in?" he wanted to know.

"I like information a lot. Probably the way you like a well-planned lake up north."

"So why warp it?"

The shuttle crawled counterclockwise around the plaza. The sky previewed evening.

"What's helpful for you? I think of it as a wall or a building going up, not unlike everything here at Soon City. Each day gathers another layer of information about the Continent."

Everett soured. "Then what lives in the building? What does the wall protect?"

"OK, take for granted that it's a parallel realm of infinite data. We could keep on building it forever with richer levels of realism. Like the Continent itself, right? The two are inseparable, almost, except that the Activities Estimate is the clean copy. If everything is known to be going smoothly here, continued growth is assured. Value escalates."

Everett made no acknowledgement. The shuttle entered the dense forest that wraps the Pyramids campus from outside view. I think the existence of the Pyramids nearby is widely known throughout Soon City, but it remains at some distance, shelled in these woods. The Continent has many such built-in illusions. Now we were speeding up over the barren and unplanted moor, pulled toward our destination rather than propelled. I braced one elbow against the upholstered wall. I said, "Think about the investors and subscribers. Think of the waiting list full of people hoping for a place like Venusberg."

Everett only stared into the moving distance.

When the shuttle arrived at the transit hub, near the port of entry, Everett stood to get off. As he did, I moved to tell him to take tomorrow too, if he needed it. Through the open doors, Everett said: "Can you help me transfer back north?"

The shuttle turned around empty.

THE WEEKEND BEFORE I was to file Everett's request, which would invite some risk for me, Vivian took me away to wash out my head. One of her contacts somehow had placed a little cabin out near an unfinished part of the Continent, and she got it for two nights. Vivian said it wasn't the frontier proper, but the landscape was that TBD unplanted moor you get a lot of around here. She even drove us out in a sports car she had borrowed from a downstairs friend who kept one place

They had no airfield. No hospital. The company would not break the realism of the Continent.

below, another above. From the highway spilled a thin unnamed roadway that wove over the topography. Rain fell all day Saturday, so we stayed in bed. But the Sunday that followed started with a hot, orange sun. Mist crept up from the lawn a while, hiding the unfinished ground, the missing earth where it was possible to plunge into the Continent, possibly falling the whole way through. I had never driven so far from the Pyramids.

"There's no one around for miles," Vivian said, touching her temples. "You can actually perceive it."

"Originally, Dymond and Balboa had strict rules," I said, crinkling the map's digital pages. It zoned this area "Completion Pending." This wasn't how the Continent should be seen, and it put me on edge. "There should be barricades," I said.

Vivian found one of the gaps in the lawn and set one of the cabin's folding chairs down beside it, like it was a swimming hole. Approaching the gap on my hands and knees, I studied how the landscape made an uneven skin over the structure. Workers would return to make adjustments. They would need to solder somewhere, to align different pieces. Then they would earth it up and meadow over the hole. The Continent would advance.

Seated beside me, Vivian tied back her bright hair. She dropped her ankles into the gap but drew them right out again. "It's freezing!"

I squatted in the mist.

"This reminds me of four-dimensional dioramas," she said from the chair. "My students made them this semester for Advanced Ersatz Ecologies. Have I told you about them?"

Another rule held that from time to time, Vivian and I deliberately put each other aside for a few weeks at a time. This made days like Saturday great, but we would forget where we were with each other, what had been said. My hand on the small of her back, for example, Vivian had restated a thought from childhood, that the two dimples there symbolized womanhood. She had said so twice, maybe three times. What else did Vivian forget?

"The dioramas contain an entire day with at least three hotpoints to fly through, all at different hours during the day. I can't even get over some of the scenes." Vivian described a capybara trapped in a river, bobbing endlessly up and down, fixed there as if in some underworld torment. And then there was a taiga forest where a storm snowed so apocalyptically it should have smothered the entire biome. The fingers of her right hand had worked into the sod while she spoke. She peeled a hunk of it up and held it in the palm of her hand. Vivian was taken, however, by a diorama about a California-like desert. Tarantulas and lizards lived beneath a series of highway billboards that ran all night long. "You would have thought it was a desperate place, but no. Organisms were thriving by the artificial daylight."

Vivian extended her arm out over the gap and turned her hand. The sod disappeared into the Continent.

I wondered aloud, "If we were in a diorama for a day, where should it be?"

"Easy," Vivian said. "A tropical island." She spoke as if she were already there, her chin up in the air, her eyes closed. The sun lit her throat.

I said that sounded so nice.

"I guess the Continent itself is a kind of island in the air."

"A beach is what makes the kind of island you're talking about," I said.

My diorama, I thought, was Everett's north. Vivian would pull herself up onto boulders along the shore and shout to me across a cold lake. We would strip naked. We would chase each other between real trees, feet kicking up fir needles as we leapt. We would become expert inventors of fire. There would appear a wilderness camp with timbers arranged around the fire as benches. Children would line the timbers, staring into the fire. They would believe every word of stories about Pyramids and escalators and listening to the acts of strangers miles and miles away. And out in the dark at the edge of the forest, like a ring around our planet, would come Darcey. But I did not discuss.

We had the day. Then she and I packed the sports car at about three o'clock in the afternoon. Big clouds buried the sun. We departed for home in a chalky light. It wasn't more than a few minutes before we came to the missing piece of road—a portion of land that had been squarely there on Friday. Neither of us spoke. She backed up while on foot I guided the car wide of the gap and onto the road once more. What if it had been raining? What if it had been dark?

"The frontier is a dangerous place," Vivian said at last.

"I thought this wasn't technically the frontier."

Rains did come as we reached Soon City. Vivian parked way out in the lot, where we kissed beneath a dim, mercurial windshield. I told Vivian let's break the rules. My right hand came up her inner thigh. I would come to her place in Soon City for the night. "There are hard limits," she whispered. "We have boundaries." Minutes later I watched from within the port of entry as the sports car dissolved into the rain.

FIRST THING, I HAD to scramble analysts Tom Huizinga and Catherine Uhle over this terrible highway crash outside Galesville. We have a model that can slow an accident the way molecules at low temperatures decelerate; events crystallize into injury and death and destruction of property. Upcoming places such as this Galesville are regional, stitched to other places by roadways and shuttle routes, hoping for a critical mass of economics, of population. There are no guarantees. The second nature we inhabit on the Continent established vast physical distances, as experienced by people of centuries past, in contrast to the sprawl and knotted highways accrued over time downstairs. This Galesville accident happened inside a mattress of fog on a lonely road between towns. Almost no telling what happened, but Tom and Catherine started working it.

Echoes of voices carried to the mezzanine. I made it to the top of the steps when Trevor Rus appeared at their foot. He was calling me by name, rushing up, shaking my hand. Daylight through the walls of the Pyramid caught in his blue irises. "Gorgeous day upstairs," said Trevor Rus, joking cheerfully. "Such a view. A-E bureaus often have the best views, don't they?"

I had yet to complete and file Everett's request to transfer. After the weekend with Vivian, I had simply forgotten.

Trevor Rus said, "Your bureau has a place called Venusberg in-scope, right? The company observed the trouble thereabouts."

"Cases like Venusberg come up on the frontier from time to time," I explained.

"Venusberg received a great deal of attention in your submittals, perhaps even too much. Then that all collapsed."

I saw Erin Vesey raise her left hand in front of her eye, pinching the air with finger and thumb to capture the scene. Our whole bureau looked on.

Trevor Rus pitched his head, a gesture saying let's talk out there, in the lobby.

Joost and I joined Trevor Rus across a low hexagonal table of glass and aluminum off to the side of the lobby. We sat in a wedge of amber light. Never had I dreamed

"The frontier is a dangerous place," Vivian said at last.

of such a conversation. But surely Darcey's transfer must have begun this way, a friendly communication between company and employee. I couldn't say. I started out describing Everett on Venusberg. The three days of the influenza medical alert when he would not get up from the displaybank, when he would not go home.

At this Trevor Rus huddled forward, coach-like, elbows on knees. A young, fit-looking edition, he was a warm and alert Trevor Rus with none of the coldness described in complaints I've heard.

"Where is Everett now? Up there?"

Joost said, "I have him auditing the other externs now. Taking notes. I took over Venusberg myself."

"A sad story pre-quarantine. That's the frontier for you. What's happening there today?"

Right now, I had no idea. Neither did Joost.

"There are followers downstairs and within the company. There's interest in the influenza. There's interest in the doctors, Deveroux and Schuykhill. We'd like to see Venusberg back on the Activities Estimate ASAP."

"I need to get an analyst working it," Joost explained. "The hiatus started when Everett wouldn't code the situation correctly. Then he wouldn't code at all."

I said, "Without knowing your original parameters for his re-training, I can't be certain, but it's our feeling that Everett's externship really went off track."

"Across criteria," Joost added.

Trevor Rus suggested we get Everett. Joost climbed back upstairs. Cheer quickly darkened out of Trevor Rus.

"Sir," I said. "I apologize about bringing this up now. I feel very responsible. Everett asked me to prepare a transfer request last week after the incident. I agreed, but here you are today."

"Good," he said, hand on the glass table between us. "That's the plan."

"He belongs back north."

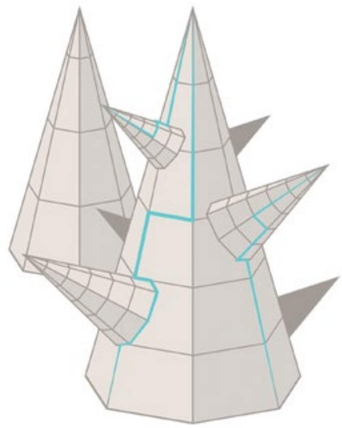
Trevor Rus blinked hard. "The area where Everett was stationed has been discontinued."

I repeated the word.

"Your nose looks healed, Everett," said Trevor Rus. Recognition coursed over the frontiersman's face, a brilliance. He sat between me and Joost at the six-sided table. He held a pen and a small spiral notebook at the ready.

"Trevor Rus is here to discuss your externship in the Activities Estimate," I said. "First I want to tell you, though, that I haven't had a chance yet to do your transfer request. I let you down. I'm sorry."

Everett's eyes searched the three of us for a key to what was happening.



Trevor Rus very sensitively explained that the company approved the transfer request unseen. Again, brilliance. But he continued: Everett would go via special service tonight—to a hydrology outpost at the edge of Oklahoma, where he would assist and support on an aquifer under construction. Trevor Rus said, “It’s really cutting-edge stuff.”

The north of my diorama, the pristine lakes, fir trees.

Everett said, fearlessly, “I guess I had hoped that the transfer request would identify my previous station up north. I’d like to head back there.”

Trevor Rus was peremptory.

“You know, Everett, the Continent makes changes,” he said. “We’re thinking far ahead. Value has been identified in sharing the preserve where you worked with the good people downstairs, opening it to a new class of subscribers, like weekenders, tourists.”

Everett weighed into the sofa. His notebook closed.

“Let me show you,” Trevor Rus said. He unfolded a piece of digital paper from his coat pocket. Searching with a finger through the contents, he played a video for us. A cylindrical glass elevator rose through shadowy orange air, through the superstructure of the Continent to open in a misty forest. A girl and her father exit into sunlight and mist. “In the past we prioritized horizontal expansion of the Continent,” Trevor Rus said. “That’s changing. Verticality is in vogue. The preserve will be the garden terrace of a ladder city.” The girl’s expression replayed in the paper.

“You must have known,” said Trevor Rus. “You must have known that you weren’t patrolling the land to preserve for its own sake.”

This was Everett’s exit interview.

BECAUSE I FELT MORE and more responsible for him than ever, that night I rode with Everett off to the edge of campus to the special service. Joost stayed behind. The shuttle buoyed the two of us alone, rolling through rush hour in the opposite direction of the analysts and engineers wanting the port of entry and Soon City. Everett’s face with its broken nose looked down. Twin heavy-duty suitcases angled under his arms. The shuttle slipped into the woods, over a stream, and uphill to the crest of meadow that concealed the arching glass of the special service station’s entrance. I had wanted to see the station again, but never allowed myself to make the trip.

Everett said he apologized, said he had let us down with his unwillingness to figure out the Activities

Estimate. It was all so different from what he had known.

"Joost and I only want to protect you from yourself," I said.

That semi-ellipse of glass facade parted to accept us. The capsule of lobby beyond was freezing cold. Sentinel agents in the lobby now steered me through security with him, even without the travel visa he had from Trevor Rus. He was an extern in my custody. I stood at the staircase where I had last seen Darcey. We descended into the Continent's special service, which was only a thin, illuminated isle of concrete suspended into darkness like a pier into the sea. "The Oklahoma," Everett told the platform engineer who scanned his travel visa.

"We'll bring it up," said the engineer. "Just wait."

Everett did not know what would happen to him in hydrology.

"You'll find your way to contribute, I know it."

"Another move," he said. "I'll shave my beard. I'll cut my hair."

"To be safe, Everett," I said. "You don't have to accept the Continent. You just have to not stick out so badly."

Everett asked me if I could go to Trevor Rus again for him, get him back north. He said he'd work there, even after the changes. "They wouldn't trust you," I told him. "Not with your record. What if hydrology's really your mission?"

Out of the dark below us began some strange light. The rails of the special service lit everywhere around us, like burners on an old stovetop. The surface whorled continuously in a way that reminded me of fingerprints, running as far into the dark as I could see, an artificial horizon. Everett's face shone in the orange light, his fractal nose lit. Shadows reached from our feet then withered. It was twilight inside the Continent. "OK, standby," said the platform engineer.

The vehicle that came for Everett wasn't much larger than the shuttle from the Pyramids, but without wheels, without a front or a back. And it spun silently toward us, rotating until it clicked against the pier. A single door opened to the empty car. It came exclusively for Everett.

"Is it difficult traveling like this?"

Everett shrugged. "You feel it much more than you think you would."

Before he left, I had something for Everett, an old-time gift that came to me from Paul Reiss. It was a 30x loupe in a slate leatherette sleeve. Paul kept magnifiers around his desk to use for studying images, transcript texts. There were printers then. I had selected this from a few other things I thought might work for Everett. Shyly, he accepted the loupe, loaded it into the pocket of his dark plaid shirt.

"OK," he said with a smile, bags over both arms like wings. "I'll use it."

Everett boarded the special service. The engineer told the door to close, and the vehicle floated free from the pier. He had barely the chance to wave before the car rotated from view. I saw that it was not the vehicle that moved inside the special service, but this volume of space positioned the cars from place to place inside the Continent. Everett appeared to fall away from me, like Vivian's sod, flashing from sight.

I had been the bureau chief at the Pyramids for seven years, yet Darcey and I were still cleft, apart but together, for this greater good of the Continent. I had thought long about our one-page request for re-union, so feeble compared to the vast, invaluable Continent, the last new place on Earth. Now I saw that the special service folded space, collapsed distances. Via special service, by its impossible speeds, could Darcey and I really have been more than minutes apart? A few hours at most? And Darcey would have known after her transfer. The rails dimmed from orange to pink. The horizon went dark.

I shouted to the platform engineer: "As the Continent holds us up, we are called on to hold it up."

Above ground again, I had no way home but on foot through stirring trees.

SCOTT GEIGER'S fiction has received the Pushcart Prize and a 2012 New York Foundation for the Arts (NYFA) Artist Fellowship for Fiction. He edited *Man-Made Lands*, a special edition of the literary journal, *Ninth Letter*, featuring architectural and landscape proposals alongside prose and graphic fictions to explore how storytelling can inform city-making.

A Seven-Month Wait For Lunch

Why food aid needs to overhaul its delivery system

BY JONATHAN M. KATZ

LAST FALL, THE UNITED States government bought lunch for some hungry schoolchildren in Mozambique. Though the students lived in their country's best farming region, where deep green hills cover rich, red soil, their benefactors didn't buy the food nearby—nor even from their wealthier neighbors in South Africa. Nor did they turn to the children's farmer parents to grow their own. Instead they followed a culinary tradition any American can relate to: They had it delivered.

On the surface, that type of giving makes sense. The U.S. is not only one of the richest countries on the planet, but also a preeminent food producer. Even as the U.S. has shipped scores of non-farm jobs overseas, it continues to enjoy a $32.4 billion agricultural trade surplus. A recent study in the journal *Food Policy* estimated that the amount of food Americans *throw away without eating* totals more than $165 billion every year—equal to one-seventh of the combined economies of all 48 countries in Sub-Saharan Africa.

So, for the past 60 years, we have followed that logic to its apparent conclusion: relying on transportation to get food from the bountiful U.S. to countries where hunger is

ILLUSTRATION BY PETER AND MARIA HOEY

widespread. Those food giveaway programs, organized primarily under the U.S. government's "Food for Peace" initiative, have developed into a $1.4 billion-a-year industry.

Yet something is clearly not working. Take Mozambique. Through 2012, the East African nation was one of the top ten recipients of American food aid. Three years ago, the U.S. spent $25.9 million shipping U.S. produced commodities across the Atlantic, around the Cape of Good Hope, and up the coast of the Indian Ocean, bound for Mozambican villages, towns, and schools. Yet for all that giving, Mozambique has not been better off. A quarter of its 24.1 million people face acute annual food shortages, according to the United Nations World Food Programme. More than 1.7 million of its children under 5 years of age suffer chronic malnutrition.

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How can so many millions of dollars fail to buy food security for people in need? The answer is in the journey itself.

In October 2012, the nongovernmental organization (NGO) World Vision U.S., based outside of Seattle, asked the U.S. government for a thousand metric tons of "corn-soy blend" to use in its school feeding programs in Mozambique's northern Nampula Province. Corn-soy blend is a vitamin-fortified cornmeal and soy flour mix that can be cooked into porridge, fritters, or pancakes. It's a favorite product of U.S. farmers because they can produce corn, in particular, more efficiently than their foreign competition—thanks in no small part to the billions of dollars in government subsidies they receive each year. Corn-soy blend has thus become a staple of food aid programs around the world.

When it received the order, the U.S. Department of Agriculture put out a call for bids. Anyone could apply, but large agribusinesses typically offer the most competitive rates. For the Mozambique order, the winning bid came from private, family-owned Didion Inc. of Wisconsin—the fifth-largest supplier of U.S. food aid, according to a 2012 investigation by *The Guardian*. Their asking price: around $850,000.

In January 2013, the order was loaded onto trucks and trains, bound for the international seaport in Houston, where another bid winner waited: a hulking single-engine diesel ship, with a dusky black hull, rust-covered cranes, and a towering white bridge, called the *Noble Star*.

The ship's owner, New York shipping firm Sealift Inc., asked for $431 per metric ton for the 8,500-mile journey to Africa, then another $300 for shipping overland to World Vision's warehouse in Mozambique. That brought the total cost of food and delivery to roughly $1.5 million. Just under half the cost was devoted to transportation alone.

But a ship like the *Noble Star* can't bring lunch very quickly, at any price. Traveling at roughly 14 knots, a ship such as the 16,000-ton freighter needs "at least a month in good weather for the trip from Houston to the east coast of Africa," said Judith Thimke, a shipping expert at the U.N. World Food Programme. If the seas are rough or traffic bad, it can take longer.

Once the *Noble Star* docked, its load of corn-soy blend needed 15 days to clear customs. Then the food was loaded onto trucks and driven to Nampula Province. The overland part of the trip can be hazardous: Bad roads, floods, communication breakdowns, or even hijackings by bandits have been known to thwart deliveries.

This shipment arrived unscathed. After its long journey, the food was unloaded at World Vision's warehouses in the villages of Muecate and Nacarôa in March. In May 2013—seven months after the order was placed—it was finally distributed to the schools, where it was used for meals for 56,000 children, according to World Vision.

That's not a number to sneeze at. Surely the children and their parents appreciated the meal. But once lunch was over, what was left? Most of the money spent on the shipment had never left the U.S. The children and their parents in Mozambique were as poor as ever, left to await the next shipment of food, or the next food crisis, whichever came first.

EXAMPLES LIKE THIS ONE have led experts and aid workers to conclude that transporting commodities halfway across the planet is not a solution to global hunger. The problem, says Christopher Barrett, an economist at Cornell University and one of the world's leading experts on food aid, is that the U.S. has an entirely different goal when it comes to sponsoring humanitarian assistance. Feeding the hungry has never been its sole purpose.

Rather, the historical goal of food aid has been to stimulate U.S. businesses—the agriculture and shipping industries above all. Modern food aid was devised in the early days of the Cold War as a way to dispose of government-held surpluses, in order to regulate crop prices at home and create markets abroad. The main programs in the early days of food aid didn't even give food away for free, but sold it to foreign governments at a discount. "It just happened that this could get advertised as and provide humanitarian relief on occasion," Barrett said.

Over time, things began to change. Surplus disposal became less important than other forms of domestic price control, and the cheaply sold food did not prove very effective in opening markets. When in the 1970s and 1980s, the food that was donated during famine emergencies in Asia and Africa proved effective, free-food distributions took over as the dominant programs.

Today, the major players in food aid are nongovernmental organizations such as World Vision. But, because of how American laws are structured, domestic corporations still reap the much of the profit. Major U.S. agribusinesses can count on hundreds of millions of dollars in annual sales to the government.

Shipping companies do even better. Federal law mandates that at least half of all U.S. food aid must be shipped aboard U.S.-flagged vessels. With shipping costs taking up nearly 40 percent of any food assistance funding, the law guarantees hundreds of millions of dollars in contracts for shipping companies. The winner of the Mozambique shipment was no exception: Sealift Inc. has grossed $203 million in government contracts since 2011, mostly from the Pentagon, according to data at USASpending.gov. This benefit is not lost on the shipping industry: The sector's leading coalition, USA Maritime, spent $250,000 lobbying Congress on food aid and cargo-preference laws in 2011 and 2012.

The NGOs profit as well. Some, including World Vision, monetize a portion of the aid they are given to local markets and use the proceeds to finance their programs. A 2011 Government Accountability Office report found that this process, known as "monetization," had squandered $219 million in aid money over three years.

Little of that benefits the people whom food aid is supposed to help. In fact, it can harm. That's because, contrary to popular belief, even in most countries where there are chronic food crises, there is usually enough food to eat, if only people could afford it. "The

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issue isn't availability. In most markets, the issue is affordability," explained Oxfam's Eric Muñoz. Dumped heedlessly, donated food can undercut local farmers or cause prices to swing wildly. In the end, poverty can get even worse.

The way to make aid programs more effective isn't to find a faster, cheaper ship, experts say. It's to change the way that aid works entirely.

ONE ANSWER THAT SOCIAL scientists have come up with is local procurement. Recent studies of a USDA pilot program found that buying food closer to the place where it is going to be distributed is generally cheaper than long-distance imports. The studies also found that recipients, perhaps unsurprisingly, tend to prefer the taste of local products as well. Supporters of food-aid reform say that allowing increased local procurement could feed an extra two to four million people a year while putting money directly into local markets and helping to develop economies.

Economists and social scientists don't think that reform efforts should stop there. A growing research consensus has shown that another effective form of aid includes giving people vouchers to buy food in their own markets, or even just handing out cash so they can decide how to use it themselves. A special June series in *The Lancet* journal focused on studies and articles on combating malnutrition in the developing world. Editors explained that such investments can "increase producer incomes while protecting consumers from high food prices."

When food aid is used, experts from a variety of backgrounds argue that it has to be targeted well. One of *The Lancet*'s articles argued that scaling up ten highly-targeted nutritional interventions for the neediest pregnant women, newborns, and young children in the world's poorest countries by about $9.6 billion annually could save nearly a million children's lives per year. Another study, from the Stanford Business School, advocated screening children by height and weight to determine which are the most vulnerable and then concentrating resources on those most at risk—a strategy the authors said could reduce current costs by 61 percent while providing the same amount of health benefits.

Nearly all the current research advocates following up with recipients of food aid to gauge efficacy and set quantifiable goals for the future. These data-based approaches show that delivering help demands flexibility in the face of changing information. And indeed, flexibility has become the byword for nearly all the major aid-giving countries in the world, including European powers and Canada. Local procurement, voucher programs, and investment in local agriculture have become increasingly larger pieces of the pie.

The lone holdout is the U.S.. The Obama administration announced in April 2013 a plan to overhaul the food aid program. Many experts felt the proposed changes were exceedingly modest: Obama asked to reallocate much of the $1.4 billion budget between programs administered by both the Agriculture and the State departments, where it could be used on vouchers, local procurement, or aboard U.S. ships as needed. In a nod to domestic interests, the administration proposal agreed to keep 55 percent of the current program unchanged, still funding American farmers and shippers. As the Brookings Institution's George Ingram asked, "How can Democrats and Republicans not be united on a proposal that saves lives and, at the same time, saves dollars?"

Very easily, it turned out. Although food aid makes up less than 1 percent of what American farmers export, their representatives in Congress guard these subsidies jealously. Even before the administration could officially announce its plan, *The New York Times* reported that 21 senators from farm states—under pressure from lobbyists—had signed a letter asking that the programs be left unchanged. Bills supporting the reform effort were defeated in both chambers of Congress in June, while legislators rejected a proposed farm bill that would include substantive cuts in subsidies in favor of program changes that some economists say could mean even larger payouts if crop prices fall in the future.

Yet even as supporters of the reform effort vow to fight on in Washington, peasant advocates in developing countries are trying to take the lead themselves. Citing the research pioneered by Nobel Prize winner Amartya Sen in the 1960s that showed smaller farms produce proportionally larger yields, they argue that the ultimate answer to hunger lies in supporting local smallholder agriculture. One such program is the Comprehensive Africa Agriculture Development Programme, which aims to increase investment in farms to 10 percent of African Union members' national budgets, with hopes of raising agricultural productivity by 6 percent in the next two years.

Organizers hope that a serious dose of investment will help break the cycles of poverty and hunger, and attract more investment from the outside. Because whether you live in Wisconsin or Nampula, the surest way to get food from the farm to your lunch table is to grow your own.

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Traffic Ghost Hunting

When the biggest problem with traffic is nothing at all

BY BENJAMIN SEIBOLD

FEW EXPERIENCES ON THE road are more perplexing than phantom traffic jams. Most of us have experienced one: The vehicle ahead of you suddenly brakes, forcing you to brake, and making the driver behind you brake. But, soon afterward, you and the cars around you accelerate back to the original speed—and it becomes clear that there were no obstacles on the road, and apparently no cause for the slowdown.

Because traffic quickly resumes its original speed, phantom traffic jams usually don't cause major delays. But neither are they just minor nuisances. They are hot spots for accidents because they force unexpected braking. And the unsteady driving they cause is not good for your car, causing wear and tear and poor gas mileage.

So what is going on, exactly? To answer this question mathematicians, physicists, and traffic engineers have devised many types of traffic models. For instance, microscopic models resolve the paths of the individual vehicles, and are good at describing vehicle–vehicle interactions. In contrast, macroscopic models describe traffic as a fluid, in which cars are interpreted as fluid particles. They are effective at capturing large-scale phenomena that involve many vehicles. Finally, cellular models divide the road into segments and prescribe rules by which cars move from cell to cell, providing a framework for capturing

PHOTO BY RAYMOND DEPARDON/MAGNUM PHOTOS

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the uncertainty that is inherent in real traffic.

In setting out to understand how a phantom traffic jam forms, we first have to be aware of the many effects present in real traffic that could conceivably contribute to a jam: different types of vehicles and drivers, unpredictable behavior, on- and off-ramps, and lane switching, to name just a few. We might expect that some combination of these effects is necessary to cause a phantom jam. One of the great advantages of studying mathematical models is that these various effects can be turned off in theoretical analysis or computer simulations. This creates a host of identical, predictable drivers on a single-lane highway without any ramps. In other words, your perfect commute home.

Surprisingly, when all these effects are turned off, phantom traffic jams still occur! This observation tells us that phantom jams are not the fault of individual drivers, but result instead from the collective behavior of all drivers on the road. It works like this. Envision a uniform traffic flow: All vehicles are evenly distributed along the highway, and all drive with the same velocity. Under perfect conditions, this ideal traffic flow could persist forever. However, in reality, the flow is constantly exposed to small perturbations: imperfections on the asphalt, tiny hiccups of the engines, half-seconds of driver inattention, and so on. To predict the evolution of this traffic flow, the big question is to decide whether these small perturbations decay, or are amplified.

If they decay, the traffic flow is stable and there are no jams. But if they are amplified, the uniform flow becomes unstable, with small perturbations growing into backwards-traveling waves called "jamitons." These jamitons can be observed in reality, are visible in various types of models and computer simulations, and have also been reproduced in tightly controlled experiments.

In macroscopic, or "fluid-dynamical," models, each driver—interpreted as a traffic-fluid particle—observes the local density of traffic around her at any instant in time and accordingly decides on a target velocity: fast, when few cars are nearby, or slow, when the congestion level is high. Then she accelerates or decelerates towards this target velocity. In addition, she anticipates what the traffic will do next. This predictive driving effect is modeled by a "traffic pressure," which acts in many ways like the pressure in a real fluid.

The mathematical analysis of traffic models reveals that these two are competing effects. The delay before drivers reach their target velocity causes the growth of perturbations, while traffic pressure makes perturbations decay. A uniform flow profile is stable if the anticipation effect dominates, which it does when traffic density is low. The delay effect dominates when traffic densities are high, causing instabilities and, ultimately, phantom jams.

The transition from uniform traffic flow to jamiton-dominated flow is similar to water turning from a liquid state into a gas state. In traffic, this phase transition occurs once traffic density reaches a particular,

critical threshold at which the drivers' anticipation exactly balances the delay effect in their velocity adjustment. The most fascinating aspect of this phase transition is that the character of the traffic changes dramatically while individual drivers do not change their driving behavior at all.

The occurrence of jamiton traffic waves, then, can be explained by phase transition behavior. To think about how to prevent phantom jams, though, we also need to understand the details of the structure of a fully established jamiton. In macroscopic traffic models, jamitons are the mathematical analog of detonation waves, which naturally occur in explosions. All jamitons have a localized region of high traffic density and low vehicle velocity. The transition from high to low speed is extremely abrupt—like a shock wave in a fluid. Vehicles that run into the shock front are forced to brake heavily. After the shock is a "reaction zone," in which drivers attempt to accelerate back to their original velocity. Finally, at the end of the phantom jam, from the drivers' perspective, is the "sonic point."

The name "sonic point" comes from the analogy with detonation waves. In an explosion, it is at this point that the flow turns from supersonic to subsonic. This has crucial implications for the information flow within a detonation wave, as well as in a jamiton. The sonic point provides an information boundary, similar to the event horizon in a black hole: no information from further downstream can affect the jamiton through the sonic point. This makes dispersing jamitons rather difficult—a vehicle can't affect the jamiton through its driving behavior after passing through.

Instead, the driving behavior of a vehicle must be affected before it runs into a jamiton. Wireless communication between vehicles provides one possibility to achieve this goal, and today's mathematical models allow us to develop appropriate ways to use tomorrow's technology. For example, once a vehicle detects a sudden braking event followed by an immediate acceleration, it can broadcast a "jamiton warning" to the vehicles following it within a mile distance. The drivers of those vehicles can then, at the least, prepare for unexpected braking; or, better still, increase their headway so that they can eventually contribute to the dissipation of the traffic wave.

The insights we glean from fluid-dynamical traffic models can help with many other real-world problems. For example, supply chains exhibit a queuing behavior reminiscent of traffic jams. Jamming, queuing, and wave phenomena can also be observed in gas pipelines, information webs, and flows in biological networks—all of which can be understood as fluid-like flows.

Besides being an important mathematical case study, the phantom traffic jam is, perhaps, also an interesting and instructive social system. Whenever jamitons arise, they are caused by the collective behavior of all drivers—not a few bad apples on the road. Those who drive preventively can dissipate jamitons, and benefit all of the drivers behind them. It is a classic example of the effectiveness of the Golden Rule.

So the next time you are caught in a warrantless, pointless, and spontaneous traffic jam, remember just how much more it is than it seems.

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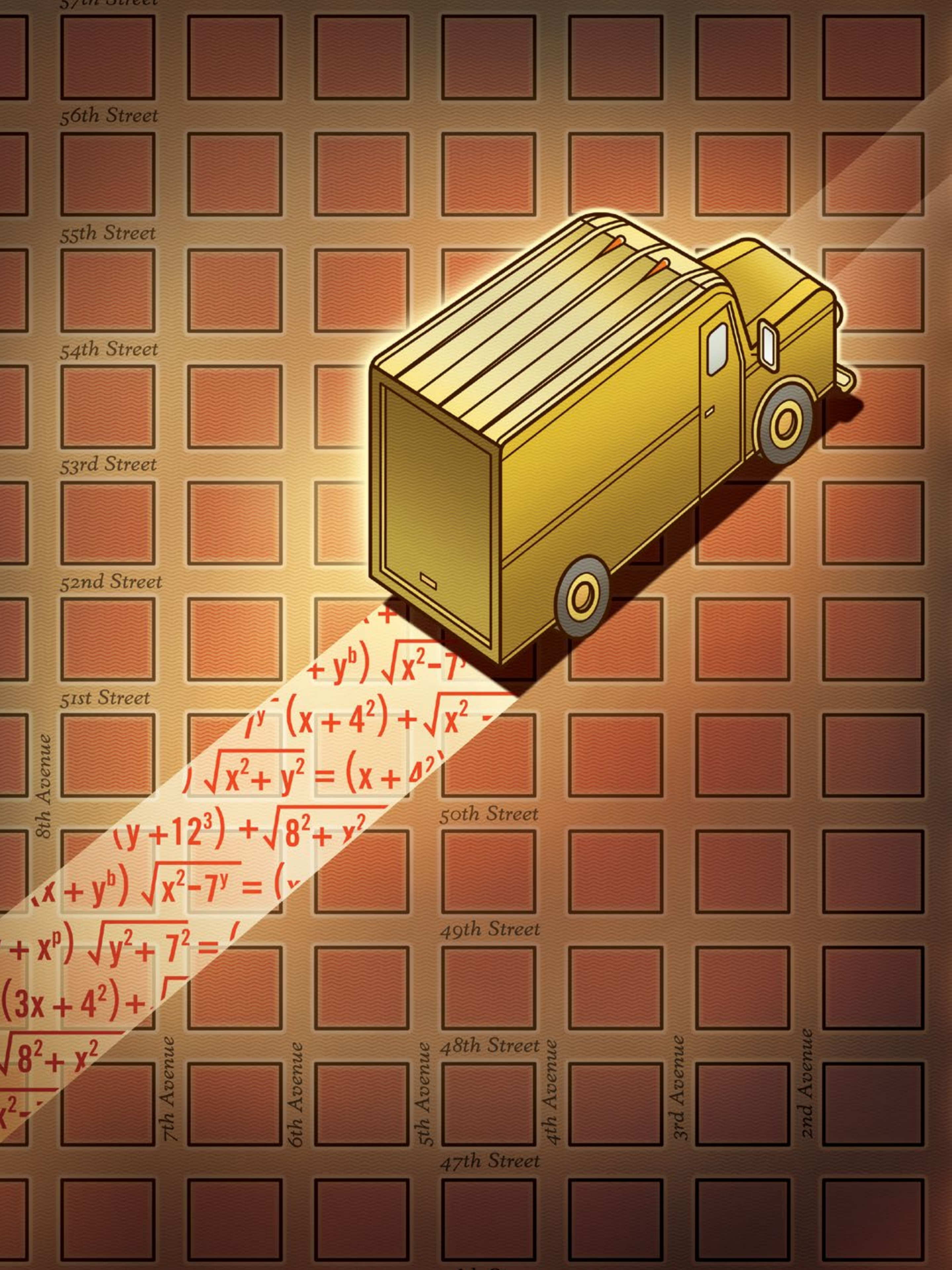
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Unhappy Truckers and Other Algorithmic Problems

Transportation optimization starts with math, but ends in understanding human behavior

BY TOM VANDERBILT

W**HEN BOB SANTILLI,** a senior project manager at UPS, was invited in 2009 to his daughter's fifth grade class on Career Day, he struggled with how to describe exactly what he did for a living. Eventually, he decided he would show the class a travel optimization problem of the kind he worked on, and impress them with how fun and complex it was. The challenge was to choose the most efficient route among six different stops, in a typical suburban-errands itinerary. The class devised their respective routes, then began picking them over. But one girl thought past the question of efficiency. "She says, my mom would never go to the store and buy perishable things—she didn't use the word perishable, I did—and leave it in the car the whole day at work," Santilli tells me.

Her comment reflects a basic truth about the math that runs underneath the surface of nearly every modern transportation system, from bike-share rebalancing to airline crew scheduling to grocery delivery services. Modeling a simplified version of a transportation problem presents one set of challenges (and they can be significant). But modeling the real world, with constraints like melting ice cream and idiosyncratic human behavior, is often where the real challenge lies. As mathematicians, operations research specialists, and

ILLUSTRATIONS BY PETER AND MARIA HOEY

corporate executives set out to mathematize and optimize the transportation networks that interconnect our modern world, they are re-discovering some of our most human quirks and capabilities. They are finding that their job is as much to discover the world, as it is to change it.

THE PROBLEM THAT SANTILLI posed to his daughter's class is known as a traveling salesman problem. Algorithms solving this problem are among the most important and most commonly implemented in the transportation industry. Generally speaking, the traveling salesman problem asks: Given a list of stops, what is the most time-efficient way for a salesman to make all those stops? In 1962, for example, a Procter and Gamble advertisement tasked readers with such a challenge: To help "Toody and Muldoon," co-stars of the Emmy-award-winning television show *Car 54, Where Are You?*, devise a 33-city trip across the continental United States. "You should plan a route for them from location to location," went the instructions, "which will result in the shortest total mileage from Chicago, Illinois, back to Chicago, Illinois."

A mathematician claimed the prize, and a regal $10,000. But the contest organizers could only verify that his solution was the shortest of those submitted, and not that it was the shortest possible route. That's because solving a 33-city problem by calculating every route individually would require *28 trillion years*—on the Department of Energy's 129,000-core supercomputer Roadrunner (which is among the world's fastest clusters). It's for this reason that William J. Cook, in his book *In Pursuit of the Traveling Salesman*, calls the traveling salesman problem "the focal point of a larger debate on the nature of complexity and possible limits to human knowledge." Its defining characteristic is how quickly the complexity scales. A six-city tour has only 720 possible paths, while a 20-city tour has—by Cook's quick calculations on his Mac—more than 100 quadrillion possible paths.

There are answers to some traveling salesman problems. Cook himself has produced an iPhone app that will crack 100 cities, using relaxed linear programming and other algorithmic techniques. And every few years or so, teams armed with sophisticated hardware and programming approaches set the bar higher. In 2006, for example, an optimal tour was produced by a team led by Cook for a 85,900-city tour. It did not, of course, given the computing constraints mentioned above, involve checking each route individually. "There is no

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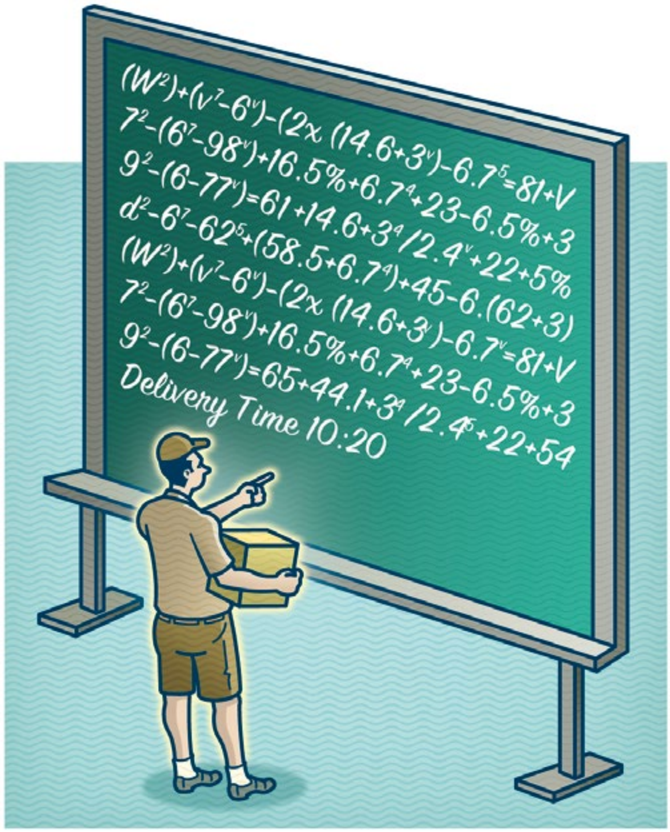
hope to actually list all the road trips between New York and Los Angeles," he says. Instead, almost all of the computation went into proving that there is no tour shorter than the one his team found. In essence, there is an answer, but there is not a solution. "By solution," writes Cook, "we mean an algorithm, that is a step-by-step recipe for producing an optimal tour for any example we may now throw at it."

And that solution may never come. The traveling salesman problem is at the heart of an ongoing question—the question—in computer science: whether or not *P* equals *NP*. As summarized with blunt elegance by MIT's news office, "roughly speaking, *P* is a set of relatively easy problems, *NP* is a set of incredibly hard problems, and if they're equal, then a large number of computer science problems that seem to be incredibly hard are actually relatively easy." The Clay Mathematics Institute offers a $1 million reward to a meta-problem hovering like a mothership over the *Car 54* challenge and its ilk: proving that *P* does or does not equal *NP*.

By now it should be clear that we are not talking just about the routing needs of salesmen, for even the most trenchant of regional reps does not think about hitting 90,000 far-flung burghs on a call. But the Traveling Salesman Problem, and its intellectual cousins, are far from theoretical; indeed, they are at the invisible heart of our transportation networks. Every time you want to go somewhere, or you want something to get to you, the chances are someone is thinking at that very moment how to make that process more efficient. We are all of us traveling salesmen.

A POSITION LIKE BOB Santilli's, performing optimization, didn't always exist at UPS. Times used to be simpler. Until the early 1980s, UPS drivers used to have one simple goal: to get all the packages in their truck delivered by the end of the day. Those were the "ground" days. "The only thing we had was time sensitivity for commercial drivers," notes Santilli. Jeff Winters, who heads operations research for UPS, says "everything was a human-scalable problem to solve." And it had to be. "We had individual carload diagrams for drivers every day," says Santilli (UPS calls its brown delivery vans "cars"). On paper. Routes were laid out via pushpins on a map. At the end of the day, everything was filed, and the process began again.

But then, in 1982, the world changed: Next-day air delivery was introduced. Suddenly, there was an increasing variety of time "commits"; packages had to be at one address by 10:30 a.m., another by 1:30 p.m., another



by noon. There were new time constraints for package pickups as well. It was no longer just an optimal routing problem, but an optimal scheduling problem. And the one thing UPS suspected was that it was not doing things optimally. One imagines that within these walls there is no greater sin. Even the insides of vans are subjected to a kind of routing algorithm; the next time you get a package, look for a three-letter letter code, like "RDL." That means "rear door left," and it is so the driver has to take as few steps as possible to locate the package. In one typical aside, Santilli told me that when a driver stops the van, he "has nine seconds to select a package and get out of there." His tone suggested he was talking about a member of a bomb disposal unit.

In 1986, UPS purchased Roadnet, a logistics company that created optimal routes for businesses like beer distributors. There was just one problem: the drivers that Roadnet worked with typically plied the same route every day or so, with few hard time constraints. And so UPS began what would become known as Project ORION (Onroad Integrated Optimization and Navigation), a project spanning many years and many millions of dollars, whose algorithmic efforts are just beginning to bear fruit in its fleet of nearly 58,000 trucks. At the core of ORION was the traveling salesman problem. Each UPS truck—which makes around 130 stops per day—is essentially a traveling salesman problem on wheels.

ORION's promise was and is clear: For each mile saved, per driver, per year, UPS saves $30 million. The mathematics required to arrive at some solution to the traveling salesman problem, even if approximate, is also clear. But in trying to apply this mathematics to the real world of deliveries and drivers, UPS managers needed to learn that transportation is as much about people and the unique constraints they impose, as it is about negotiating intersections and time zones. As Jeff Winters put it to me, "on the surface, it should be very easy to come up with an optimized route and give it to the driver, and you're done. We thought that would take a year." That was a decade ago.

For one thing, humans are irrational and prone to habit. When those habits are interrupted, interesting things happen. After the collapse of the I-35 bridge in Minnesota, for example, the number of travelers crossing the river, not surprisingly, dropped; but even after the bridge was restored, researcher David Levinson has noted, traffic levels never got near their previous levels again. Habits can be particularly troublesome for planning fixed travel routes for people, like public buses, as noted in a paper titled, "You Can Lead Travelers to the Bus Stop, But You Can't Make Them Ride," by Akshay Vij and Joan Walker of the University of California. "Traditional travel demand models assume that individuals are aware of the full range of alternatives at their disposal," the paper reads, "and that a conscious choice is made based on a tradeoff between perceived costs and benefits." But that is not necessarily so.

People are also emotional, and it turns out an unhappy truck driver can be trouble. Modern routing models incorporate whether a truck driver is happy or not—something he may not know about himself. For example, one major trucking company that declined to be named does "predictive analysis" on when drivers are at greater risk of being involved in a crash. Not only does the company have information on how the truck is being driven—speeding, hard-braking events, rapid lane changes—but on the life of the driver. "We actually have built into the model a number of indicators that could be surrogates for dissatisfaction," said one employee familiar with the program.

This could be a change in a driver's take-home pay, a life event like a death in the family or divorce, or something as subtle as a driver whose morning start time has been suddenly changed. The analysis takes into account everything the company's engineers can think of, and then teases out which factors seem correlated to accident risk. Drivers who appear to be at highest

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risk are flagged. Then there are programs in place to ensure the driver's manager will talk to a flagged driver.

In other words, the traveling salesman problem grows considerably more complex when you actually have to think about the happiness of the salesman. And, not only do you have to know when he's unhappy, you have to know if your model might make him unhappy. Warren Powell, director of the Castle Laboratory at Princeton University's Department of Operations Research and Financial Engineering, has optimized transportation companies from Netjets to Burlington Northern. He recalls how, at Yellow Freight company, "we were doing things with drivers—they said, you just can't do that." There were union rules, there was industry practice. Tractors can be stored anywhere, humans like to go home at night. "I said we're going to need a file with 2,000 rules. Trucks are simple; drivers are complicated."

At UPS, a program could come up with a great route, but if it violated, say, the Teamsters Union rules, it was worthless. For instance, time windows need to be built in for drivers' breaks and lunches. And while the filmed testimonials of drivers I saw at UPS were largely positive in their description of ORION, it is interesting to note that the latest contract between the company and the union included a provision that no driver would be "discharged based solely on information received from GPS or any successor system."

Powell's biggest revelation in considering the role of humans in algorithms, though, was that humans can do it better. "I would go down to Yellow, we were trying to solve these big deterministic problems. We weren't even close. I would sit and look at the dispatch center and think, how are they doing it?" That's when he noticed: *They are not trying to solve the whole week's schedule at once. They're doing it in pieces.* "We humans have funny ways of solving problems that no one's been able to articulate," he says. Operations research people just punt and call it a "heuristic approach."

This innate human ability was at work in Santilli's daughter's class, too. The fifth graders got it about right. As James MacGregor and Thomas Ormerod note, "the task of the traveling salesman problem may happen to parallel what it is natural for the perceptual system to do in any case when presented with an array of dots." Curiously, using this heuristic approach, they note, subjects in experiments were "exceptionally good at finding the optimum tours." In other experiments, when subjects were shown images of optimal tours, they were thought to be more aesthetically pleasing than sub-optimal tours.

Of course, even the human balks at understanding the behavior of other humans. Powell showed me a sample diagram he'll sometimes give to a roomful of trucking executives. "I've got a load that has to be picked up. I've got a driver 60 miles away. All I have to do is dispatch him and it's done. I've got another driver who, once he unloads, will be about 30 miles away—should be in around midafternoon." Do you take the sure thing, even if it consumes more miles? Or do you take the risk on the shorter trip, which might get in later? When he asks for a show of hands which choice is better, the response is typically mixed. "Driver B saves me miles. *But he hasn't arrived yet, and what if he doesn't?*" he says, his voice dropping to a conspiratorial whisper. "Different people will answer it differently. They'll say, 'I know that driver, he'll make it.' Welcome to real-world decision making."

In the end, the best approach turns out to be building on what people are already doing. When Powell consulted with Schneider trucking a decade ago, curiously, he did not model some über-efficient idealized vision of what Schneider could be. He essentially modeled Schneider as it was. "Our objective wasn't to get the best solution," says Ted Gifford, a longtime operations research specialist at Schneider. "Our objective was to try to simulate what the real world planners were really doing." When I suggest to Gifford that he's trying to understand the real world, mathematically, he concurs, but adds: "The word 'understand' is too strong—we are happy to get positive outcomes."

At UPS, too, allowing for human behavior in a quantitative way was key. "In the old business rule," says UPS's Winters, "we held the drivers accountable for how closely they follow the trace"—UPS speak for route. Even worse, he says, drivers, while not being given guidance, were being penalized—"coached and counseled"—for errors and delays, or "breaking trace." This, he says, was a "dumb rule," a hangover of legacy thinking inherited from the company's origins as a ground-only delivery service. "The right thing to do," Winters says, "is build your route with just your air work, and then look at expensive ground areas that you can do to eliminate the need to go back to that area. It turned a business problem on its head."

TRANSPORT OPTIMIZATION, THEN, IS hard, and understanding how to implement it can be harder still. "One of the hardest things to teach a math analytics group," Santilli tells me, "is the difference between a feasible solution and an implementable solution. Feasible just means it meets all the math constraints. But implementable is something the human can carry out."

But optimization has succeeded in coming a very long way. Modeling has become much more sophisticated, a development that Powell outlines in his life's work, a book called *Approximate Dynamic Programming: Solving the Curses of Dimensionality*. "You went to the

Powell's biggest revelation in considering the role of humans in algorithms, though, was that humans can do it better.

math literature, and it was all toy problems. It was literally about 20 years before I could go to a whiteboard and say, you know what, I can actually write down the problem." Mapping has improved dramatically. A few decades ago, the mapping service UPS bought literally had people calling businesses to ask them if they actually were where the data UPS had suggested they were. Early GPS maps were also flawed. "When we got some bad results early on," says Ranga Nuggehalli, UPS's principal scientist, "we didn't know whether it was because the algorithm was so bad, or our data was so bad." It was the latter.

The data acquisition needed for tracking has since been developed. UPS's "Delivery Information Acquisition Device," or DIAD, the brown handheld computer upon which you have no doubt signed your name, creates a data architecture that underpins their optimization strategy.

And the end result has been one of slow but steady improvement. Powell and Santilli point to their own success stories. Yellow Freight used to have some 700 "end of lines," Powell says, which are sorting terminals where cargo is transferred to its end customers. Powell developed a model that delivered a counterintuitive message: Trucks were traveling farther to get to the customer with so many terminals. Today, he says, Yellow Freight has 400 end of lines. "That was the right number," he says. As for UPS, Santilli notes that a driver in Gettysburg, Pa. is now driving nearly 25 miles less per day, from an original route of more than 150 miles down to 126 miles—with the same number of stops.

We are getting smarter at moving things around. But the less obvious story is that we are getting a grasp on how to model the human element in transportation. Just as we are getting to know algorithms, algorithms are getting to know us.

TOM VANDERBILT writes on design, technology, science, and culture, among other subjects. His most recent book is *Traffic: Why We Drive the Way We Do (and What It Says About Us)*.


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Jared Diamond

Celebrated author of Guns, Germs and Steel, Collapse, *and* The World Until Yesterday *reflects on the themes in* Nautilus

ON HUMAN UNIQUENESS

Only 20 years ago it would have been routine to say there were humans and animals. So it was astonishing when it came out in the '90s that humans share 99 percent of their DNA with chimpanzees. Where in that 1 percent is the explanation for why we keep chimpanzees in cages, rather than chimpanzees keeping us in cages? Of course, we evolved a unique anatomy. We have fingers and delicate hands. Dolphins are smart, not as smart as we are, but even if they were, they could never build tools, computers, and atomic bombs. Humans are inventive. And ultimately our capacity for language allowed us to do all the interesting stuff.

ON UNCERTAINTY

The most important lesson I learned in New Guinea was how to think clearly about uncertainties in life. I was once camping with New Guineans on a site near a ridge, where I could see parrots fly by. I told them, "Let's put up a tent under this beautiful big tree." They freaked out. "No! Look at the tree, it's dead." Yes, I told them, the tree was dead, but it was going to be standing for 70 years. But they would not sleep under the tree! Boy, I thought, they're really paranoid. But as I spent more time camping in New Guinea, I seemed to hear a tree falling every night. And nearly all the New Guineans I met seemed to know somebody killed or crippled by a tree fall. That taught me to think about uncertainty and risk. The number of Americans killed by terrorists or plane accidents is a fraction of those killed by slipping in the shower. I'm 75 years old now, and all you have to do is read the obituary page to see how many old people lose their life from a fall in the shower. So now I have rough strips on the shower floor and hold the shower bar.

ON TRANSPORTATION

What concerns me is the transportation of ideas. People outside the West see what's going on here. They want medical care for their children and don't want to die at age 45. They want a comfortable standard of living. It's a matter of self-preservation for the West to make sure people with third-world living standards are happy. If they're miserable, they can do things like build nuclear weapons. That's my worst-case scenario—the end of civilization. My happy scenario is where everybody around the world has similar living standards, or the prospect of good living standards, and aren't desperate to emigrate and commit terrorism.

ILLUSTRATION BY ANDY FRIEDMAN


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