

NAUTILUS

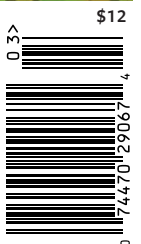
34 **ADAPTATION**
Fitting in

35 **BOUNDARIES**
Both sides of the story



Where I Belong

A HYMN TO SCIENCE p.24

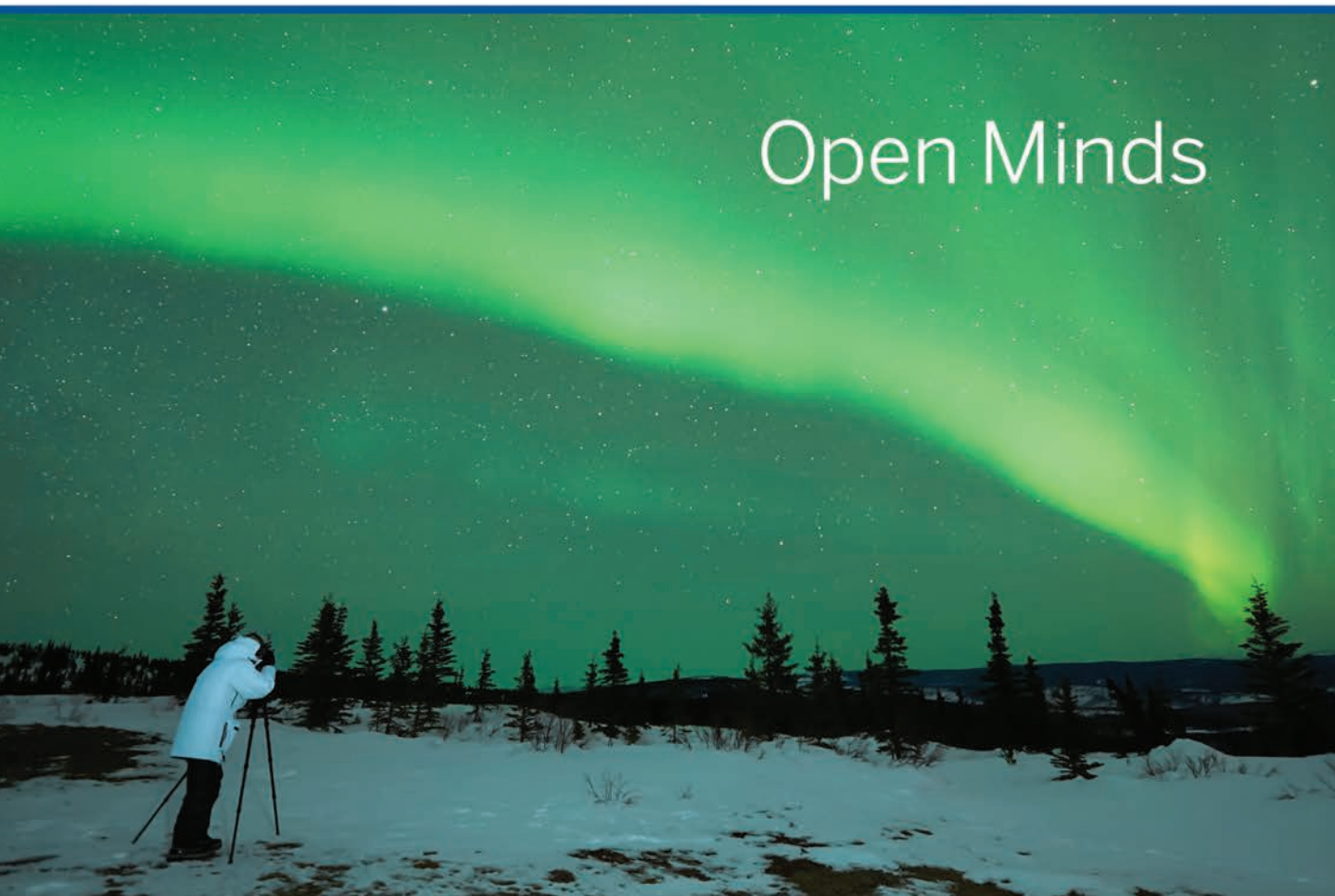


MAR/APR 2016

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NAUTILUS

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Childhood Sparks

FOR THE PAST TWO DECADES, Kirk Johnson, the director of the Smithsonian National Museum of Natural History, has been collecting stories of how people got into science. He has observed that the moment often involves a mentor, or being outdoors, or a book or TV show. His own story involves wandering around with a metal detector searching for buried artifacts.

There is one other thing—the stories almost always involve someone young. “It’s all pretty much in the can by the age of 20 or so,” says Johnson. The observation certainly holds for *Nautilus*’ own collection of stories about how a lifelong interest in science gets sparked (at spark.nautil.us), where nearly every story is about childhood.

There is launching model rockets behind school, beachcombing with dad, perusing a well-stocked home library—or, in the case of Hope Jahren, author of this issue’s cover story, spending wintry Minnesota nights at her dad’s lab playing with magnets and pH testing tape.

The wonder and human connection of these early sparks gives us a window into the motivation of the working scientist, one that stands in contrast to the dispassionate nature of the scientific method itself. Where the lay public might see machines and numbers, the scientist carries with herself a personal, secret interpretation—one that often stretches back to childhood.

The connection is even the subject of academic work. “Social studies of science have only recently turned attention to the importance of emotions in scientific work,” wrote Lesley Head, geography professor at the University of Melbourne, this year. A 2013 study by two sociologists examining the emotions of a working scientist catalogued grief, boredom, frustration, pride, joy, excitement, tribalism, ritual, and conflict. “It is unimaginable,” they concluded, “to think of scientific knowledge construction as devoid of emotions.”

And why should it, any more than the dispassionate act of building a home out of wood, nails, and engineering guidelines be devoid of emotion? For Jahren, there is precious little difference. When she is in her lab, she is in a place with her name on the door, her best friend around the corner, and the outside world kept at bay. “The machines drone a gathering hymn as I enter,” she writes, and “I can be the child that I still am.”

Welcome to the March/April 2016 *Nautilus* print edition.

—Michael Segal
Editor in Chief



Animated Life Film Series

A. R. Wallace

Seeing the Invisible

Pangea

Mary Leakey

The Living Fossil Fish

www.biointeractive.org/animatedlife



hhmi

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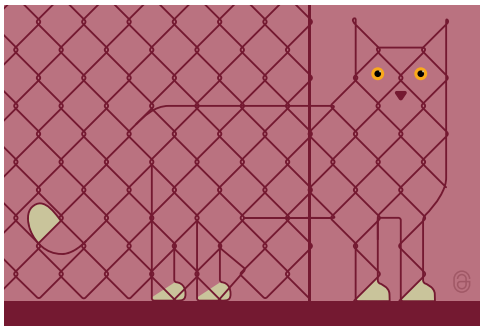
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“Individuals, not couples or clans or other social groups, are fast becoming the fundamental units of society.”

—Bella DePaulo, p. 58

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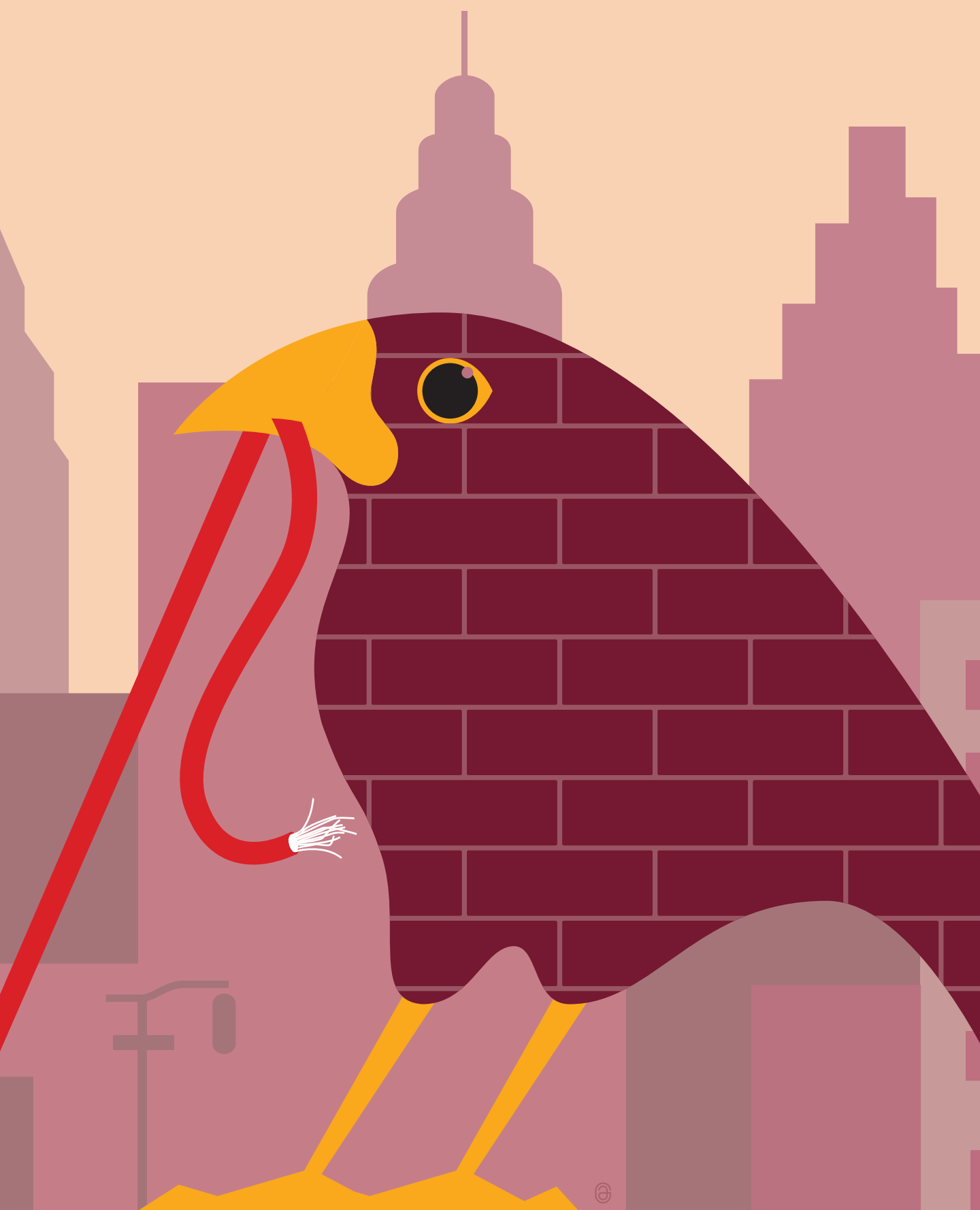
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“The immune system is our border patrol.”

—Robert Levine, p. 80

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Matter-antimatter asymmetry

Dark matter



illuminating science

PHYSICS

Explore the vast frontier of fundamental physics.

BIOLOGY

Learn how primitive comb jellies are forcing scientists to rethink the origin of neurons.



MATHEMATICS

Follow the ambitious effort to rewrite century-old rules underlying mathematics.



Bruno C. Vellutini



VIDEOS

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NAUTILUS *think*

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Letters

Reader responses to the January/February 2016 print edition.



“THE DEEP SPACE OF DIGITAL READING”

The problem with Internet reading is not that it causes the mind to wander off, but that it *prohibits* mental wandering. To wander is not to be passive or distracted but to actively blaze a trail, follow a lead, explore. Internet links do not link, they don’t connect and form a trail; they are more often an abandoned trail. The Internet is a forest of possible paths, and we’re hikers who started the first five steps of every last one, seeing none.

—C.K. Dexter

“2015 WAS THE BEST YEAR EVER IN SPACE”

A beautiful and romantic elegy to our very human impulse to explore. Yet human migration and exploration always begs the question—what are we leaving behind? As we press outward, it is easy to

ignore or deny the messes we have left behind. As Dwight Eisenhower (and others) have observed, we should leave our piece of earth better than we found it.

—George Gantz

“HOW TO SURVIVE SOLITARY CONFINEMENT”

It’s similar (on a much smaller temporal scale) to going into an MRI tube for a brain scan while being afraid of confined spaces. You close your eyes and imagine yourself on a tropical island ... sometimes it is difficult to maintain the fantasy, but with persistence and not wanting to be a pain in the arse to the MRI techs as well as the next patients ... it works pretty well.

—Drewinmass



“SHE’LL TEXT ME, SHE’LL TEXT ME NOT”

Here’s a little secret that’s worked for a long, long time. If you like her, tell her you like her. If she likes you, she’ll let you know. If she doesn’t, she’ll let you know that, too. Stop making the simple, complex.

—Rex Riley



CORRECTIONS

As originally published in the Jan/Feb 2016 print edition of *Nautilus*, “These Tricks Make Virtual Reality Feel Real” suggested that Evan Suma was an author of the “one for three” illusion paper. In fact, that research was led by Microsoft Research, and Suma was not an author.

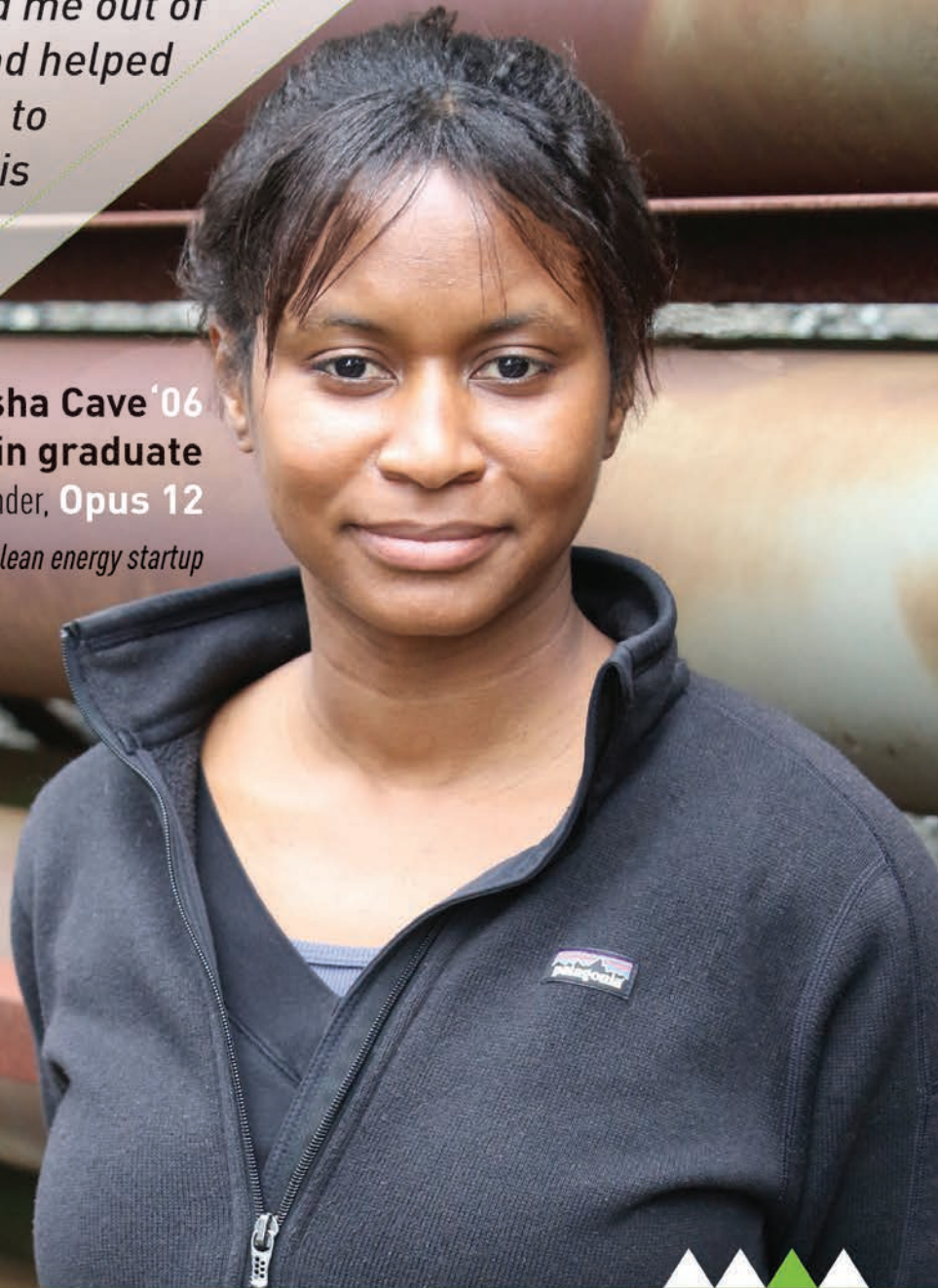
In the Jan/Feb 2016 print edition of *Nautilus*, “How to Survive Solitary Confinement” misstated that Johnny Perez spent 13 years at Rikers Island penitentiary. He spent some of that time at prisons in upstate New York.

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

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- Etosha Cave '06
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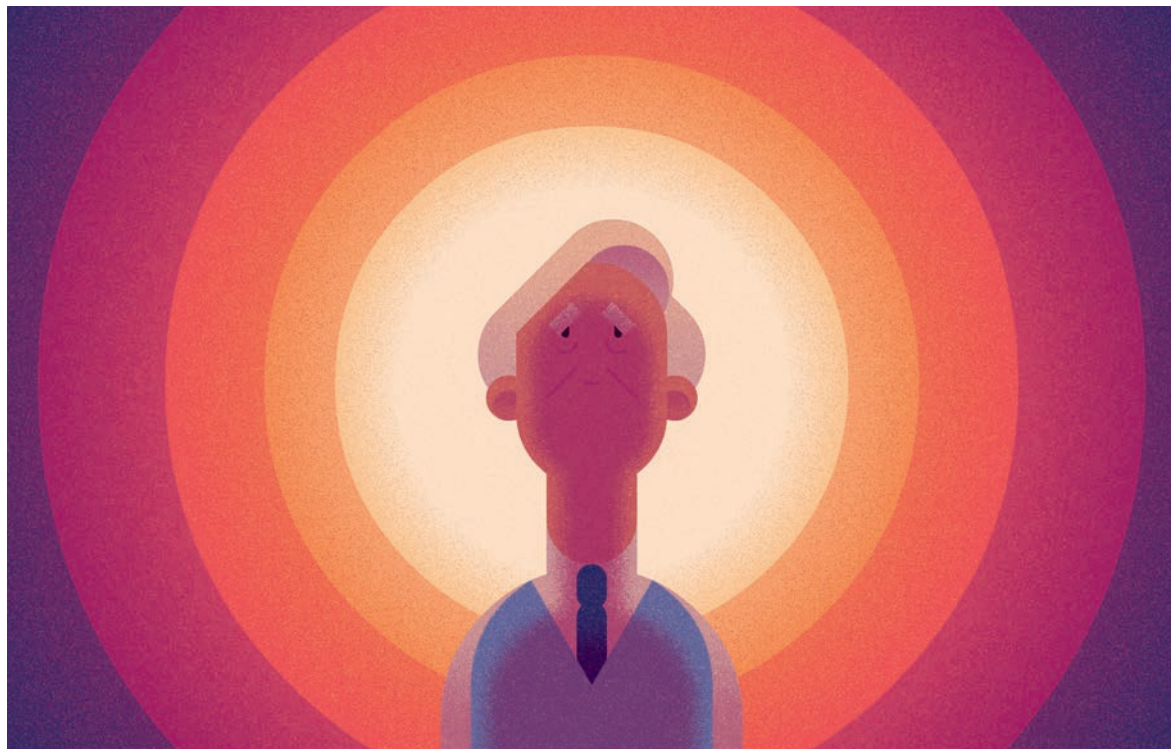
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Preludes



ASTRONOMY

New Data Boosts Forgotten Star Scientist

WHEN YOU OBSERVE a solar eclipse—with great care, of course—what you see is a thin, red crescent outlining the blocked-out sun and, extending beyond it, a stark white mane. This is the corona, an aura millions of miles thick of superheated plasma.

It's natural to assume the corona is cooler than the sun's blazing surface. But in fact it gets hotter as it ranges outward. The sun's surface temperature is

about 10,000 degrees Fahrenheit. The corona can get as hot as 5.4 million degrees Fahrenheit. This phenomenon, known as the “coronal heating problem,” “remains one of the great unsolved problems in space science,” says James A. Klimchuk, a research astrophysicist at the NASA Goddard Space Flight Center.

Scientists still don't quite understand why the corona is so toasty. But at least they accept that it is hotter. Which was not the case for

It's natural to assume the corona is cooler than the sun's blazing surface.

ILLUSTRATIONS BY ROBIN DAVEY

a long chapter in science history. It took a little-known Swede, Hannes Alfvén, an electrical engineer by training, to convince the world of the corona's hotness.

In the 1940s, there was no coronal heating problem. That's because scientists were certain the corona's temperature was much lower than the surface of the sun. One estimate, by Swedish astronomer Bengt Edlén in 1943, was 450,000 degrees Fahrenheit. If you look up the discovery of the corona's extraordinary heat, you'll generally come across only Edlén's name.

But two years before Edlén made his estimate, Alfvén published a paper in an obscure Swedish journal, where he theorized that the sun's magnetic field, interacting with charged particles, plays a crucial role in the corona's bewildering heat, overcoming presumed thermodynamic limits—that heat cannot be transported from a cool to a hot body. While his contemporaries didn't dare to draw such a conclusion, Alfvén boldly declared that the corona is “heated to an extremely high temperature.”

A year later, Alfvén showed the existence of a special wave associated with plasmas, pioneering the field of plasma astrophysics. The waves came to be known as Alfvén waves. When Alfvén's discovery of the waves won him the Nobel Prize, in 1970 (which he shared with a solid state physicist), an article was published in *Science* with the title, “Swedish Iconoclast Recognized after Many Years of Rejection and Obscurity.” The article's author, a solar physicist named Alex Dessler, wrote that Alfvén's “extraordinary



Hannes Alfvén

Scientists still don't quite understand why the corona is so toasty.

physical intuition,” concerning how a form of wave could move through any ionized gas, “was, for several years, condescendingly dismissed.”

Later, Alfvén postulated these waves caused the corona's immense heat. Excited by perturbations in the sun's magnetic field, the waves propagate upward carrying, Alfvén reasoned, 1 percent of the sun's radiated energy.

In 2015, in a study published in *The Astrophysical Journal*, a team of researchers wrote that observations from satellite telescopes provided “direct evidence” for Alfvén's idea, narrowing “down to unparalleled levels” the evidence for Alfvén wave heating of the corona.

Alfvén passed away in 1995, but perhaps the evidence that his waves cause the corona's wild heat will help the iconoclast stave off obscurity.

— Virat Markandeya

ANIMALS

Evolved Weaponry Isn't Just for Males

QUEEN ANTS FIGHT DIRTY. With their powerful jaws, they clamp down on each other, ripping through exoskeleton and vital flesh—a fight to the death.

When we think of animal weapons—antlers, tusks, horns, spurs—we usually think of fights between males. But females deploy lethal weaponry, too. Theirs just arose from different evolutionary pressures: Whereas males often battle for the right to reproduce, females commonly clash over ecological resources (food, breeding and nesting sites) and to protect offspring. Female weapons are “rarely due to sexual selection,” says Anders Berglund, a professor of ecology and genetics at Uppsala University in Sweden.

The spoils of victory from a queen ant (*Messor pergandei*) brawl, for example, include the



Female soay sheep evolved horns to compete for food.

WINNER TAKE ALL
Queen ants battling
for supremacy.



deceased's entire colony. As a result, fighting queens evolved heads that are 5 to 15 percent wider (and thus able to house stronger jaws) than those of non-fighting queens, says Ken Helms, an evolutionary ecologist at the University of Vermont. Similarly, female dung beetles evolved horns to win dung balls, an egg-carrying vessel; female soay sheep evolved horns to compete for food during lambing season; and female reindeer evolved antlers to secure prime foraging sites for calving.

Until the 1970s, most biologists accepted Charles Darwin's assertion that animal weaponry evolved primarily by sexual competition between males, thus ignoring competition between females over other resources, says Dustin Rubenstein, an evolutionary ecologist at Columbia University. Many scientists also just preferred studying male weapons because they're "really, really extravagant," says Douglas J. Emlen, author of *Animal Weapons*.

Females rarely evolve elaborate weapons because they have the burden of producing eggs, an energy intensive process, says Berglund. Weapons are costly: Besides requiring resources to develop, they're conspicuous to predators and provocative to same-species

rivals. Males can usually afford the expense because sperm are relatively cheap to make. Egg-bearing females, on the other hand, "have

to be more economic in producing weapons than males typically are," Berglund says.

—Ankur Paliwal

LINGUISTICS

Consonants Are from Mountains, Vowels from the Sea

TO HAWAIIAN SPEAKERS, VOWELS reign supreme. Its 8 to 5 consonant-to-vowel ratio is far smaller than that of other languages, so most of its meaning is derived from oohs, aahs, and eehs. One might say Hawaiian sounds like the sea that surrounds it; the bulk of its words are simple and spare, flowing smoothly from vowel to vowel. *Mahalo*.

On the opposite end of the spectrum, we have German. With its clipped consonants and "uvulars," sounds made by constricting the tongue against the



back wall of the throat, German is a notoriously harsh and guttural language. One might say the language is cold and craggy, just like the country.

Ian Maddieson, a linguist at the University of New Mexico, had a hunch that these differences were not purely coincidental. He and a colleague, Christophe Coupe, of France's *Laboratoire Dynamique du Langage*, analyzed more than 600 regional dialects by topography, weather, and climate. A study they published in late 2015 found the languages adhered to a phenomenon previously only seen in birdcalls and other animal noises—acoustic adaptation. Put simply, acoustic adaptation maintains that the land where a language is born is instrumental to how it evolves.

The scientists looked at how environments affect the lifespans of sounds. Acoustic signals degrade naturally as they travel. Factors that affect the rate of decay include temperature, humidity, and vegetation. But not all sounds are created equal. High-frequency sounds, such as consonants, have short wavelengths, and low-frequency sounds, such as vowels, have long ones.

Because consonants are higher in frequency, they confront more obstacles in their transmission. So in hot, forested areas, they degrade faster. Vowels, on the other hand, with their longer wavelengths, slip through trees and surf heat ripples without losing too much quality. In colder climates, consonants' higher frequencies rise above lower and more languorous sounds, and don't have the time and space to degrade. Just as birds in hotter,

The land where a language is born is vital to how it evolves.

lusher regions have evolved to communicate through low coos, so languages from those regions have fewer distinct consonants and rely more heavily on vowels.

Acoustic adaptation shapes not only the sound and structure of a language, but its meaning. To a Hawaiian, German might sound like a bunch of consonants chopping vowels into a mishmash, where the dulcet *Mahalo* sounds direct. To a German, meanwhile, a tender *Auf Wiedersehen* runs over the eardrums like honey, and means everything.

—Susie Neilson

TWO QUESTIONS

Why did belief in supernatural punishment arise?



Benjamin Grant Purzycki

Centre for Human Evolution, Cognition, and Culture,
The University of British Columbia

Supernatural punishment arose, in part, because of its impact on cooperation. The behavior of contemporary priests, politicians, and televangelists suggests that clever humans noticed our attraction to the supernatural and used it to manipulate others. By appealing to the concerns of powerful gods, religious and political leaders can trigger pan-human psychological systems, steer our attention, and guide our behavior. By outsourcing social maintenance costs to the gods, people, in turn, have more predictable and stable cooperative relations that contribute to the chances that one successfully reproduces.

If the universe is expanding, how can it have no boundary?



Eric Thrane

Monash University

Imagine a vast rubber sheet extending outward in every direction to infinity. The sheet can be stretched so that two marbles on it move farther apart. However, you could travel for an arbitrary amount of time and still never get to the edge of the sheet. The sheet is the fabric of spacetime, and the marbles are galaxies. So those gravitational waves LIGO detected, for example, emanating from the merger of the two black holes, will continue to propagate forever, never reaching a boundary to bounce off of.

ALIENS

It's Raining ET

MILTON WAINWRIGHT BELIEVES he's seen ET. In Earth's upper atmosphere, he claims to have found evidence of panspermia—the hypothesis that life travels through the cosmos via meteoroids and other objects. A microbiologist and astrophysicist at the University of Sheffield, Wainwright sends large balloons up to the stratosphere, as high as 25 miles above the planet's surface, to look for microorganisms drifting in from space.

"Nearly every time we go to the stratosphere, we find these unusual organisms," he says. "They're not coming up from Earth." If they were, he argues, his samples would contain earthly particles or look like earthly beings—which they don't. But he's had a hard time overcoming his critics' skepticism that the samples differ enough from Earth-bound life to count as aliens. "We cannot get away from the 'little green man syndrome,'" he says.

Nautilus sat down with Wainwright to discuss his controversial research.

How do you sample the upper atmosphere with balloons?

You go out into the stratosphere and you bump into the microbes. We use, essentially, a CD drawer on a computer. When it opens, it exposes to the stratosphere. When it closes, it's airtight—completely sealed and everything. Inside the drawer, you've got microscope stubs. They're little round carbon circles, which we can take out and put directly into the electron microscope. It looks at the surface of this stub, and if anything landed on it, we can study it. I was amazed, absolutely stunned, by what we saw.

What did the specimens look like?

They have what we call "bilateral symmetry." That is, if I put a line through you, you are bilaterally symmetrical. If I put a line through a piece of dust, it isn't. This is an important function of organisms. One specimen we found had this structure that looks like a backbone. I think it's probably part of an organism. They're too



There's nothing special about this planet.

big for bacteria. I don't want to call them algae, because they're not. I don't want to call them protozoa, because we can't. So the word "biological entity" seems reasonable.

Is it possible that your samples were contaminated with organic matter from Earth?

Why would they get contaminated with strange organisms? This is a major criticism, so we are very careful. On our samplers—and this is incredibly important—there's no pollen, no fungal spores, no grass. We do all our transfers in a clean room. But even if we weren't in a clean room, you wouldn't get these things. Why would you? They've never been seen before.

How does this discovery change our understanding of life in the cosmos?

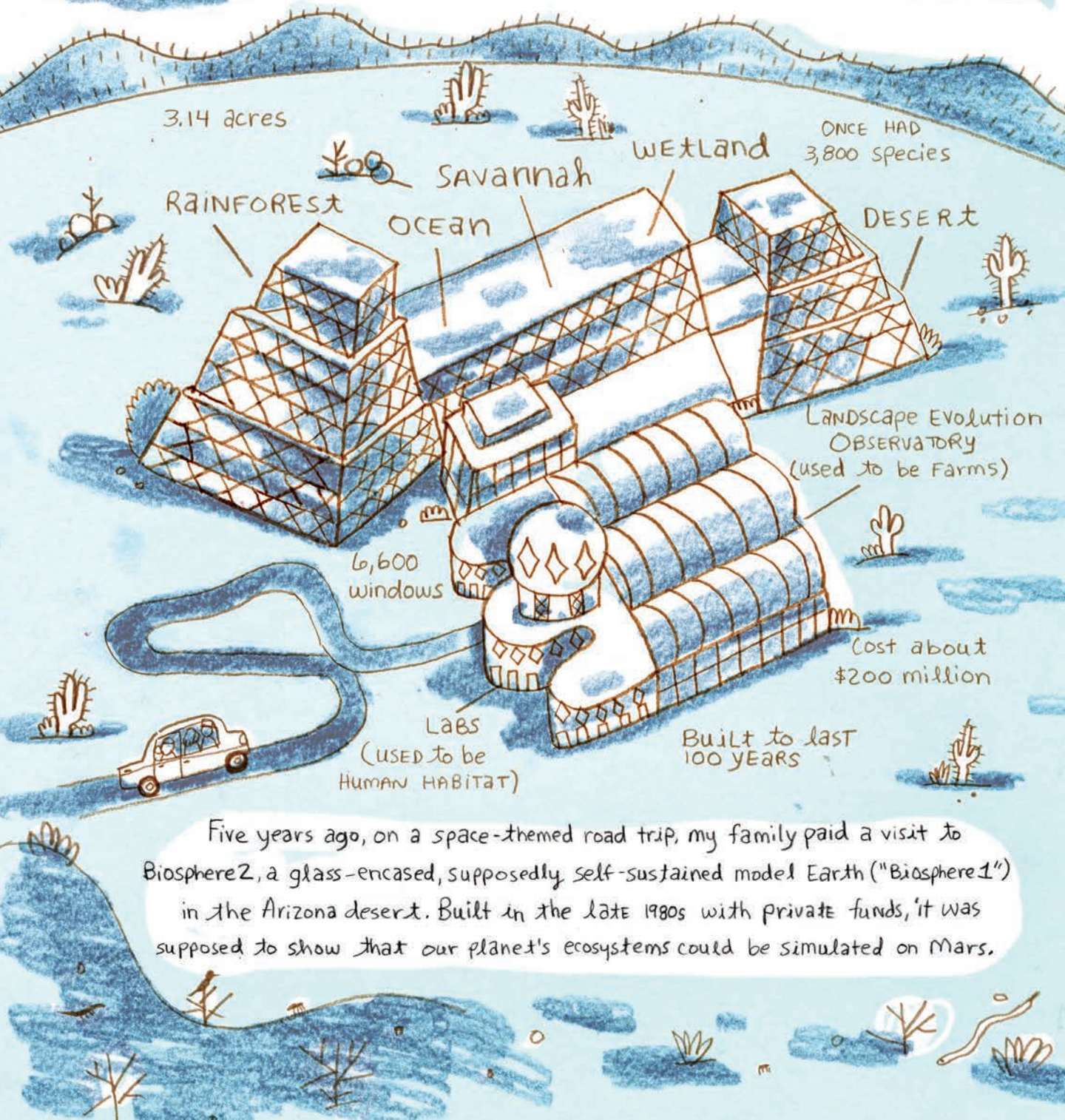
What you've got is a paradigm shift. You've got biologists being brought up with this theory of the chemical origin of life, and it's so inbred into their brain system, they can't break free of it. There's nothing special about this planet. The Earth is open to material going out; it's open to material coming in. Every other rocky planet in the cosmos is like this. The astronomer Fred Hoyle and my colleague, Chandra Wickramasinghe, suggested that life is what we call a "cosmic imperative"—it's going to be everywhere.

—Gayil Nalls

Biosphere — The Remake

This time the test is Earth's own ecological future.

By Esther Pearl Watson



Five years ago, on a space-themed road trip, my family paid a visit to Biosphere2, a glass-encased, supposedly self-sustained model Earth ("Biosphere1") in the Arizona desert. Built in the late 1980s with private funds, it was supposed to show that our planet's ecosystems could be simulated on Mars.



In 1991, eight "Biospherians" sealed themselves inside—a human experiment in a bottle.



Their story reminded me of my dad's ambition to build future transportation.



The irony was that he never could keep his own transportation running.



How could humans possibly build a utopian world if we can't take care of the one we have?

But Biosphere2 didn't die. When we visited in 2011, the University of Arizona had recently taken over, with plans to turn it into a research center—the largest earth science observatory on Earth.



The early Biospherians tried to piece together an iconic ocean from seas and coral reefs around the globe.
But there was a lot they didn't know.



If we try to mimic an entire ecosystem, we lose control.
It is too complex.



But we can recreate small pieces that we can control.



OCEAN BIOME

WE CAN TEST DIFFERENT ACIDITY LEVELS HERE.

YOU CAN'T DO THAT IN THE REAL OCEAN.

RAINFOREST BIOME

WE CAN DO CONTROLLED DROUGHTS.

WE left feeling as if we'd taken a time machine to a future in which global warming took over and we were woefully unprepared. Biosphere2 taught us we have to do everything we can to save Biosphere1...Because we won't get a second chance.



My Family, My Science

One girl's scientific awakening

BY HOPE JAHREN

ILLUSTRATIONS BY ANGIE WANG



THERE IS NOTHING IN the world more perfect than a slide rule. Its burnished aluminum feels cool against your lips, and if you hold it level to the light you can see God's most perfect right angle in each of its corners. When you tip it sideways, it gracefully transfigures into an extravagant rapier that is also retractable with great stealth. Even a very little girl can wield a slide rule, the cursor serving as a haft. My memory cannot separate this play from the earliest stories told to me, and so in my mind I will always picture an agonized Abraham just about to almost sacrifice helpless little Isaac with his raised and terrible slide rule.

I grew up in my father's laboratory and played beneath the chemical benches until I was tall enough to play on them. My father taught 42 consecutive years' worth of introductory physics and earth science in that laboratory, nestled within a community college deep in rural Minnesota; he loved his lab, and it was a place that my brothers and I loved also.

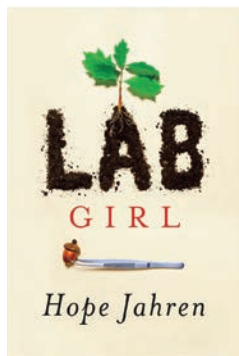
The walls were made of cinder blocks slathered in thick cream-colored semigloss paint, but you could feel the texture of the cement underneath if you closed your eyes and concentrated. I remember deciding that the black rubber wainscoting must have been attached with adhesive, because I couldn't find any nail holes anywhere when I measured its whole length with the yellow surveying tape that extended to a full 30 meters. There were long workbenches where five college boys were to sit side by side, all facing the same direction. These black countertops felt cool as a tombstone and

were made of something just as timeless, something that acid couldn't burn and a hammer couldn't smash (but don't try). The benches were strong enough for you to stand on the edge of and couldn't be scratched even with a rock (but don't try).

Evenly spaced across the benches were braces of impossibly shiny silver

nozzles with handles that took all your strength to turn 90 degrees, and when you did the one that said "gas" did nothing because it wasn't hooked up, but the one that said "air" blew with such an exhilarating rush that you kind of wanted to put your mouth on it (but don't try). The whole place was clean and open and empty, but each drawer contained a fascinating array of magnets, wire, glass, and metal that were all useful for something; you just had to figure out what it was. In the cupboard by the door there was pH testing tape, which was like a magic trick only better because instead of just showing a mystery it also solved one: You could see the difference in color and thus pH between a drop of spit and a drop of water or root beer or urine in the bathroom but not blood because you can't see through it (so don't try). These were not kids' toys; they were serious things for grown-ups, but you were a special kid because your dad had that huge ring of keys, so you could play with the equipment anytime you went there with him, because he never, ever said no when you asked him to take it all out.

In my memory of those dark winter nights, my father and I own the whole science building, and we walk about like a duke and his sovereign prince, too preoccupied in our castle to bother about our frozen duchy. As my father prepared for class the next day, I would work backward through each canned experiment and demonstration, making sure the college boys would have the easy success toward which they were predisposed. We pored over the equipment and fixed



what was broken, and my father taught me how to preemptively take things apart and study how they work, so that as they inevitably failed I'd be able to restore them. He taught me that there is no shame in breaking something, only in not being able to fix it.

At 8 o'clock we would start our walk home, so I could be in bed by 9. First we'd stop by my father's tiny, windowless office, which was bare of decoration except for the pencil holder that I had made for him out of clay. From there we'd collect our coats, hats, scarves, and the other things that my mother had knitted for me because she had never had decent ones when she was a little girl. As I wrestled my sturdy boots over an extra pair of socks, the smell of warm, wet wool mixed with that of wood shavings as my father sharpened each of the pencils that we had dulled. He would then briskly button up his big coat and don his deerskin mittens and tell me to check that my hat was fully covering both of my ears.

Always the last to leave the building for the day, he would walk the halls twice, first to confirm that all the doors to the outside were locked, and then to turn off the lights, one by one, as I trotted along behind him, fleeing the pursuing darkness. Finally, at the back entrance, my father would let me reach up and swipe off the last set of light switches, and we'd walk outside. He'd pull the door shut behind us and then check it twice to make sure that the lock had set.

Thus sealed out into the cold, we'd stand on the loading dock and look up at the frozen sky and into the terminal coldness of space and see light that had been emitted years ago from unimaginably hot fires that were still burning on the other side of the galaxy. I didn't know any of the constellations that people used to name the stars above me, and I never asked what they might be, though I am certain that my father knew each one and the story behind it. We had long since established the habit of not speaking as we walked the 2 miles home; silent togetherness is what Scandinavian families do naturally, and it may be what they do best.

The community college where my father worked was situated at the western end of our little hometown, the incorporated portion of which spanned 4 miles from truck stop to truck stop. My three older brothers and I lived with our parents in a big brick house located south of Main Street, four blocks west of where



BIRTHDAY GIRL Hope Jahren celebrates her birthday with her father.





A LAB OF ONE'S OWN Hope Jahren in her lab. “I still find reasons to work cross-legged on the floor,” she says. “Now in my own lab instead of my father’s.”

my father had grown up in the 1920s, eight blocks east of where my mother had grown up in the 1930s, 100 miles south of Minneapolis, and 5 miles north of the Iowa border.

Our path through town took us past the clinic where the same doctor who had delivered me occasionally swabbed my throat to test for strep infections, past the toothpaste-blue water tower that constituted the tallest structure in town, past the high school that was manned by teachers who had once been my father’s students. When we passed under the eavestroughs of the Presbyterian church where my father and mother had their first date at a Sunday School picnic in 1949, were married in 1953, had me baptized in 1969, and where our family spent every Sunday morning without exception, my father would lift me up so that I could break off a thick icicle. I would kick it along like

a hockey puck while we walked, and it would ring out every 10 steps or so as it ricocheted off the sides of the hard-packed snowbanks.

We made our way down hand-shoveled sidewalks, past thickly insulated houses that sheltered families who were no doubt partaking of silences similar to our own. In almost every one of these houses lived someone that we knew. From playpen to prom, I grew up with the sons and daughters of the girls and boys whom my mother and father had played with when they were children, and none of us could remember a time when we all hadn’t known each other, even if our deeply bred reticence kept us from knowing much about each other. It wasn’t until I was 17 and moved away to college that I discovered how the world is mostly populated by strangers.

When I heard a weary monster sighing on the other

My father and I walk about like a duke and his sovereign prince.

side of town, I understood that it was 23 minutes after 8 o'clock and the train was pulling out of the factory, as it did every night. I heard the great iron brakes wrench and then relax as a string of empty tank cars started to drag northward, toward Saint Paul, where they would each be filled with 30,000 gallons of brine. In the morning we would hear the train return, and the exhausted monster would again sigh as its burden was pumped into the bottomless reservoir of salt made necessary by the factory's continuous manufacture of bacon.

The train tracks ran north-south, isolating one corner of my little town, upon which still stands what is perhaps the most magnificent slaughterhouse of the Midwest. Starting at its killing chute, upward of 20,000 animals are processed for their meat every single day.

Mine was one of the few families I knew of that was not directly employed by the factory, but our extended

lineage had worked there plenty. My great-grandparents, like practically everybody else's in that town, had come to Minnesota as part of a mass emigration from Norway that began in about 1880. And like everybody else in my hometown, this is pretty much all that I knew about my ancestors. I suspected that they hadn't relocated to the coldest place on Earth and then taken up disemboweling pigs because things were going well in Europe, but it had never occurred to me to ask for the story.

By the time my father and I had crossed Fourth Street, we could see the front door of our big brick house. It was the house that my mother had dreamed of living in as a child, and after my parents were married they had saved for 18 years in order to buy it. Despite my having walked briskly—it was always an effort to keep up with my father—my fingers were chilled such

My strongest memory of our garden is not how it smelled, or even looked, but how it sounded.



that I knew it would be painful when they warmed up. Once it gets to a certain point below zero, the thickest mittens in the world won't keep your hands warm, and I was glad that the walk was almost over. My father turned the heavy iron handle, pushed with his shoulder, and opened our oaken front door. We went inside the house, into a different kind of cold.

In the foyer, I sat down and wrestled off my boots, then began to molt coats and sweaters. My father hung our clothes in the heated closet, and I knew that they would be waiting for me, warm and dry, when it was time to walk to school the following morning. I could hear my mother in the kitchen unloading the dishwasher, the butter knives clanging together as she dropped them into the silverware drawer and then slammed it shut.

I went upstairs, changed into my flannel pajamas, and put myself to bed. My bedroom faced south toward the frozen pond where I would spend all day Saturday ice-skating—if it had warmed up enough by then. The wool carpet was dusky-blue and the walls had been papered in complementary damask. The room had originally been designed for twin girls, with two built-in desks, two built-in vanities, and so on. On the nights when I couldn't sleep, I would sit at my window seat and trace the feathery ice crystals across the glass with my finger, trying not to look at the vacant seat in front of the other window where a sister should have been.

The fact that I remember so much cold and darkness from my childhood isn't surprising, given the fact that I grew up in a place where there was snow on the ground for nine months out of each year. Descending into and then surfacing from winter formed the driving rhythm of our lives, and as a child I assumed that people everywhere watched as their summer world died, confident in its eventual resurrection, having been tested so often within a crucible of ice.

Every year I saw the first stuttering flakes of September crescendo into the spilling white heaps of December, then petrify into the deep, icy emptiness of late February, eventually to be varnished as a grand, frictionless expanse by the stinging April sleet. Our Halloween costumes as well as our Easter dresses were sewn such that they could be worn inside our snowsuits, and Christmastime wrapped us in wool, velvet, and more wool. The one summertime activity

that I remember vividly is working in the garden with my mother.

In Minnesota, the spring thaw happens all at once when the frozen ground yields to the sun in one day, wetting the spongy soil from within. On the first day of spring, you can reach into the ground and easily pull up great, loose clumps of dirt as if they were handfuls of too-fresh devil's food cake and watch the fat pink earthworms come writhing out and fling themselves joyfully back into the hole. There is not even a hint of clay within the soils of southern Minnesota; they have lain like a rich black blanket over the limestone of the region for 100,000 years, periodically chased off by glaciers. They are richer than any pre-fertilized potting soil that you can buy at the hardware store; anything will grow in a Minnesota garden, and there's no need to water or fertilize—the rain and the worms will supply everything that is needed—but the growing season is short, so there's no time to be wasted.

My mother wanted two things from her garden: efficiency and productivity. She favored sturdy, independent vegetables like Swiss chard and rhubarb, the ones that could be relied upon to yield in abundance and seemed only to thrive in response to frequent harvesting. She had neither the time nor the sympathy required to nurse lettuce or prune tomatoes; instead she preferred the radishes and carrots that could tend to their own needs quietly underground. Even the flowers that she grew were selected for their toughness: the golf ball-sized buds of peonies that spilled out petals as they swelled into pink blossoms the size of cabbages, the leathery tiger lilies, and the fat, bearded irises that barged out of their bulbs without fail, spring after spring after spring.

Each May Day, my mother and I poked individual seeds into the ground, and then a week later we plucked out the ones that hadn't grown, replacing them and immediately starting over. By the end of June the whole crop was well on its way and the world around us was so green that it seemed impossible that it could ever have been otherwise. By July, the sweating leaves of all of these plants had pumped the air so full of moisture that the humidity caused the electrical lines to buzz and crackle overhead.

My strongest memory of our garden is not how it smelled, or even looked, but how it sounded. It might

strike you as fantastic, but you really can hear plants growing in the Midwest. At its peak, sweet corn grows a whole inch every single day and as the layers of husk shift slightly to accommodate this expansion, you can hear it as a low continuous rustle if you stand inside the rows of a corn field on a perfectly still August day. As we dug in our garden, I listened to the lazy buzzing of bees as they staggered drunkenly from flower to flower, the petty, sniping chirps of the cardinals remarking upon our bird feeder, the scraping of our trowels through the dirt, and the authoritative whistle of the factory, blown each day at noon.

My mother believed that there was a right way and a wrong way to do everything, and that doing it wrong meant doing it over, preferably a few times. She knew how to stitch a different tension into each of the buttons on a shirt, based on how often it would be called into use. She knew the best way to pick elderberries on a Monday such that their stems wouldn't clog the old tin colander on Wednesday, when we strained them after stewing them all day Tuesday. Thinking two steps ahead in every conceivable direction, she never doubted herself, and I figured that there was nothing in the world she didn't know how to do.

Whenever I looked at my mother, it was difficult for me to believe that the well-spoken and smartly dressed woman before me could ever have been a dirty, hungry, and scared child. Only her hands gave her away: They were far too durable for the life she now led, and I sensed that she could have grabbed the rabbit that plagued our garden and wrung its neck without thinking, had it been stupid enough to get too close to her.

When you grow up around people who don't speak very much, what they do say to you is indelible. As a child, my mother had been both the poorest and the smartest girl in Mower County. During her senior year of high school, she was awarded an honorable mention in the ninth annual nationwide Westinghouse Science Talent Search. This was an unusual recognition for a female growing up in a rural area, and although it counted only as a near miss for the real prize, it put her in good company. Other 1950 also-rans included Sheldon Glashow, who went on to win a Nobel Prize in Physics, and Paul Cohen, who won the Fields Medal in 1966—the highest honor given in the field of mathematics.

Unfortunately for my mother, scoring an honorable mention carried with it a one-year honorary junior membership to the Minnesota Academy of Science, not the college scholarship that she had been hoping for. Undeterred, she moved to Minneapolis anyway and tried to support herself while studying chemistry at the University of Minnesota, but soon came to the realization that she couldn't attend the long afternoon laboratory sections and still put in enough babysitting hours to pay her tuition. In 1951, the university experience was designed for men, usually men with money, or at the very least men who had job options outside of being some family's live-in nanny. She moved back to our hometown, married my father, gave birth to four children, and threw herself into 20 years of raising them. Determined to earn her bachelor's degree once the last of her children was at least in preschool, she re-enrolled in the University of Minnesota. Her options were limited to correspondence courses, so she chose English literature. Because I spent my days mostly in her care, it became natural for her to include me in her studies.

We plowed through Chaucer, and I learned to assist her using the Middle English dictionary. One year we spent the winter painstakingly noting each instance of symbolism within Pilgrim's Progress on separate recipe cards, and I was delighted to see our pile grow to be thicker than the book itself. She set her hair in curlers while listening to records of Carl Sandburg's poems over and over, and instructed me on how to hear the words differently each time. After discovering Susan Sontag, she explained to me that even meaning itself is a constructed concept, and I learned how to nod and pretend to understand.

My mother taught me that reading is a kind of work, and that every paragraph merits exertion, and in this way, I learned how to absorb difficult books. Soon after I went to kindergarten, however, I learned that reading difficult books also brings trouble. I was punished for reading ahead of the class, for being unwilling to speak and act "nicely." I didn't know why I simultaneously feared and adored my female teachers, but I did know that I needed their attention, positive or negative, at all times. Tiny but determined, I navigated the confusing and unstable path of being what you are while knowing that it's more than people want to see.

WHEN I WAS 5 I came to understand that I was not a boy. I still wasn't sure what I was, but it became clear that whatever I was, it was less than a boy. I saw that my brothers, who were five, 10, and 15 years older than me, could do all of our laboratory play in the outside world. In Cub Scouts they raced model cars and built and set off rockets. In shop class they used tools big and powerful enough to be mounted on the wall or suspended from the ceiling. When we watched Carl Sagan and Mr. Spock and Doctor Who and the Professor, we never even commented on Nurse Chapel or Mary Ann in the background. I retreated further into my father's laboratory, as the place where I could most freely explore the mechanical world.

It made sense, in a way. I was the one who was like our father, or at least I thought so. The differences between us were purely cosmetic: My father looked just like a scientist was supposed to. He was tall and pale and clean-shaven, thin-almost-gaunt in his khakis and white shirt and horn-rimmed glasses, complete with a pronounced Adam's apple. When I was 5 I also decided that the real me looked exactly like that, even though on the outside I was disguised as a girl.

While pretending to be a girl I spent my time deftly grooming myself and gossiping with my girlfriends about who liked whom and what if they didn't. I could jump rope for hours and sew my own clothes and make anything anybody wanted to eat from scratch in three different ways. But in the late evenings I would accompany my dad to his laboratory, when the building was empty but well lit. There I transformed from a girl into a scientist, just like Peter Parker becoming Spider-Man, only kind of backward.

As much as I desperately wanted to be like my father, I knew that I was meant to be an extension of my indestructible mother: a do-over to make real the life that she deserved and should have had. I left high school a year early to take a scholarship at the University of Minnesota—the same school that my mother, my father, and all of my brothers had attended.

I started out studying literature, but soon discovered that science was where I actually belonged. The contrast made it all the clearer: In science classes we did things instead of just sitting around talking about things. We worked with our hands and there were concrete and almost daily payoffs. Our laboratory

experiments were predesigned to work perfectly and elegantly every time, and the more of them that you did, the bigger the machines and the more exotic were the chemicals that they let you use.

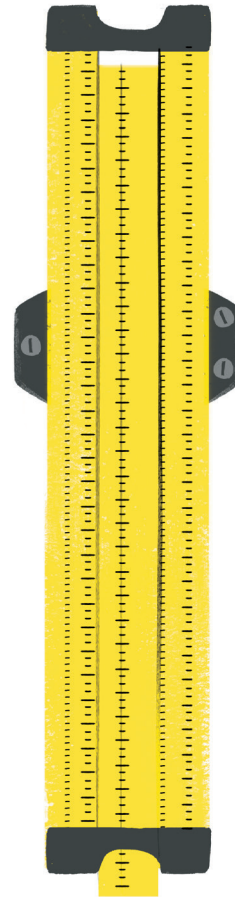
Science lectures dealt with social problems that still could be solved, not defunct political systems for which both the proponents and the opponents had died before my birth. Science didn't talk about books that had been written to analyze other books that had originally been written as retellings of ancient books; it talked about what was happening now and of a future that might yet be. The very attributes that rendered me a nuisance to all of my previous teachers—my inability to let things go coupled with my tendency to overdo everything—were exactly what my science professors liked to see. They accepted me despite the fact that I was just a girl, and assured me of what I already suspected: that my true potential had more to do with my willingness to struggle than with my past and present circumstances. Once again I was safe in my father's laboratory, allowed to play with all of the toys for as long as I wanted.

People are like plants: They grow toward the light. I chose science because science gave me what I needed—a home as defined in the most literal sense: a safe place to be.

Growing up is a long and painful process for everyone, and the only thing I ever knew for certain was that someday I would have my own laboratory because my father had one. In our tiny town, my father wasn't a scientist, he was the scientist, and being a scientist wasn't his job, it was his identity. My desire to become a scientist was founded upon a deep instinct and nothing more; I never heard a single story about a living female scientist, never met one or even saw one on television.

As a female scientist I am still unusual, but in my heart I was never anything else. Over the years I have built three laboratories from scratch, given warmth and life to three empty rooms, each one bigger and better than the last. My current laboratory is almost perfect—located in balmy Honolulu and housed within a magnificent building that is frequently crowned by rainbows and surrounded by hibiscus flowers in constant bloom—but somehow I know that I will never stop building and wanting more. My laboratory is not “room T309,” as stated on my university's blueprints;

When I was 5 I came to understand that I was not a boy.



it is “the Jahren Laboratory” and it always will be, no matter where it is located. It bears my name because it is my home.

My laboratory is a place where the lights are always on. My laboratory has no windows, but it needs none. It is self-contained. It is its own world. My lab is both private and familiar, populated by a small number of people who know one another well. My lab is the place where I put my brain out on my fingers and I do things. My lab is a place where I move. I stand, walk, sit, fetch, carry, climb, and crawl. My lab is a place where it’s just as well that I can’t sleep, because there are so many things to do in the world besides that. My lab is a place where it matters if I get hurt. There are warnings and rules designed to protect me. I wear gloves, glasses, and closed-toed shoes to shield myself against disastrous mistakes. In my lab, whatever I need is greatly outbalanced by what I have. The drawers are packed full with items that might come in handy. Every object in my lab—no matter how small or misshapen—exists for a reason, even if its purpose has not yet been found.

My lab is a place where my guilt over what I haven’t done is supplanted by all of the things that I am getting done. My uncalled parents, unpaid credit cards, unwashed dishes, and unshaved legs pale in comparison to the noble breakthrough under pursuit. My lab is a place where I can be the child that I still am. It is the place where I play with my best friend. I can laugh in my lab and be ridiculous. I can work all night to analyze a rock that’s 100 million years old, because I need to know what it’s made of before morning. All the baffling things that arrived unwelcome with adulthood—tax returns and car insurance and Pap smears—none of them matter when I am in the lab. There is no phone and so it doesn’t hurt when someone doesn’t call me. The door is locked and I know everyone who has a key. Because the outside world cannot come into the lab, the lab has become the place where I can be the real me.

My laboratory is like a church because it is where I figure out what I believe. The machines drone a gathering hymn as I enter. I know whom I’ll probably see, and I know how they’ll probably act. I know there’ll be silence; I know there’ll be music, a time to greet my friends, and a time to leave others to their contemplation. There are rituals that I follow, some I understand

My laboratory is like a church because it is where I figure out what I believe.



and some I don't. Elevated to my best self, I strive to do each task correctly. My lab is a place to go on sacred days, as is a church. On holidays, when the rest of the world is closed, my lab is open. My lab is a refuge and an asylum. It is my retreat from the professional battlefield; it is the place where I coolly examine my wounds and repair my armor. And, just like church, because I grew up in it, it is not something from which I can ever really walk away.

My laboratory is a place where I write. I have become proficient at producing a rare species of prose capable of distilling 10 years of work by five people into six published pages, written in a language that very few people can read and that no one ever speaks. This writing relates the details of my work with the precision of a laser scalpel, but its streamlined beauty is a type of artifice, a size-zero mannequin designed to showcase the glory of a dress that would be much less perfect on any real person. My papers do not display the footnotes that they have earned, the table of data that required painstaking months to redo when a graduate student quit, sneering on her way out that she didn't want a life like mine. The paragraph that took five hours to write while riding on a plane, stunned with grief, flying to a funeral that I couldn't believe was happening. The early draft that my toddler covered in crayon and applesauce while it was still warm from the printer.

Although my publications contain meticulous details of the plants that did grow, the runs that went smoothly, and the data that materialized, they perpetrate a disrespectful amnesia against the entire gardens that rotted in fungus and dismay, the electrical signals that refused to stabilize, and the printer ink cartridges that we secured late at night through nefarious means. I know damn well that if there had been a way to get to success without traveling through disaster someone would have already done it and thus rendered the experiments unnecessary, but there's still no journal where I can tell the story of how my science is done with both the heart and the hands.

Eventually 8 a.m. rolls around, the chemicals need to be restocked, the paychecks need to be cut, the plane tickets need to be bought, and so I've lowered my head and written yet another scientific report while the pain, pride, regret, fear, love, and longing have built

up deep in my throat unspoken. Working in a lab for 20 years has left me with two stories: the one that I have to write, and the one that I want to.

Science is an institution so singularly convinced of its own value that it cannot bear to throw anything away. This is true even of my father and his slide rules, carefully boxed in the basement of my childhood home and labeled "Standard Linear Slide Rule [25 cm] 30 ct." There are 30 of them, because it is important that each student has his own—scientists do many things, but they do not share equipment. These old slide rules will never be useful again; they've been thoroughly and terminally outmoded, first by calculators, then by desktop computers, and recently by phones. Nobody's name is written on the box, just a label itemizing what's inside. I used to look at it and wish, with an inexplicable yearning, that my father would write my name on the box. But no one owns those slide rules; they just are. And they certainly never belonged to me. ☺

HOPE JAHREN has received three Fulbright Awards in geobiology and is one of four scientists, and the only woman, to have been awarded both of the Young Investigator Medals given in the earth sciences. Named by *Popular Science* in 2005 as one of the "Brilliant 10" young scientists, she has taught and pursued independent research at universities around the country, most recently as a tenured professor at the University of Hawai'i at Mānoa in Honolulu.

From the Book:

Lab Girl by Hope Jahren

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LATE LAST YEAR, the Michelson interferometer finished what it had started 129 years earlier.

It was in 1887 that Albert Michelson and Edward Morley split and recombined a light beam to prove that light was not a vibration in an invisible aether. What became known as the world's most famous failed experiment set the stage for special relativity, then general relativity and the prediction of gravitational waves.

How appropriate, then, that an outrageously sophisticated version of the same interferometer be the instrument that finally, directly detected gravitational waves last year. It's a classic story of adaptation in science: a single tool, used to probe vastly different regimes, producing disparate data points that are unified theoretically.

And it's just one story of many like it. From its tools to its subjects to its practitioners, science does nothing if not adapt.

Welcome to "Adaptation."

—MS

"Mustering all of the leverage he could, he pried loose every purple or orange starfish and hurled them as far as he could."

SEAN B. CARROLL

"The Ecologist Who Threw Starfish" p.64

Adaptation

FITTING IN

How Do You Say “Life” in Physics?

A new theory sheds light on the emergence of life’s complexity

BY ALLISON ECK

*“To imagine a language is to imagine a form of life.”
—Ludwig Wittgenstein, Philosophical Investigations (1921)*

JEREMY ENGLAND IS CONCERNED about words—about what they mean, about the universes they contain. He avoids ones like “consciousness” and “information”; too loaded, he says. Too treacherous. When he’s searching for the right thing to say, his voice breaks a little, scattering across an octave or two before resuming a fluid sonority.

His caution is understandable. The 34-year-old assistant professor of physics at the Massachusetts Institute of Technology is the architect of a new theory called “dissipative adaptation,” which has helped to explain how complex, life-like function can self-organize and emerge from simpler things, including inanimate matter. This proposition has earned England a somewhat unwelcome nickname: the next Charles Darwin. But England’s story is just as much about language as it is about biology.

There are some 6,800 unique languages in use today. Not every word translates perfectly, and meaning

sometimes falls through the cracks. For instance, there is no English translation for the Japanese *wabi-sabi*—the idea of finding beauty in imperfection—or for the German *waldeinsamkeit*, the feeling of being alone in the woods.

Different fields of science, too, are languages unto themselves, and scientific explanations are sometimes just translations. “Red,” for instance, is a translation of the phrase “620–750 nanometer wavelength.” “Temperature” is a translation of “the average speed of a group of particles.” The more complex a translation, the more meaning it imparts. “Gravity” means “the geometry of spacetime.”

What about life? We think we know life when we see it. Darwin’s theory even explains how one form of life evolves into another. But what is the difference between a robin and a rock, when both obey the same physical laws? In other words, how do you say “life” in physics? Some have argued that the word is untranslatable. But maybe it simply needed the right translator.

ILLUSTRATION BY JON HAN



WHILE OTHER 12-YEAR-OLD BOYS were reading Marvel comics, England was reading *The Cartoon Guide to Genetics*. The cover depicts a scuba diver encountering a life-sized strand of underwater DNA. Inside is a tour of biology basics, from ribosomes to plant sex. England was immediately intrigued.

“I thought it was really marvelous to behold how functions are accomplished by molecules,” he tells me. England speaks ebulliently, and with his hands, and wears a kippah atop his head.

Take DNA polymerase, he says. In biological terms, its job is to create new DNA molecules by assembling nucleotides, which consist of a chemical base, a sugar, and a phosphoric acid. “When you see that story laid out before you, it all makes sense—it just looks to us like it’s working to accomplish a goal,” England says. “And yet, these things are barely distinguishable from inanimate matter. You break them into slightly smaller pieces, and all they can do is spin and vibrate.”

England saw more of the same as an undergraduate at Harvard University, where he studied protein folding with the biophysicist Eugene Shakhnovich. Protein data banks held files detailing “beautifully delineated ribbons and sheets,” color-coded by property. Unraveled, each protein is made up of the same 20 amino acids. Yet somehow, once they are folded into shape, each carries out a specific and vital process required for life. “Amino acids are not going to write you a sonnet,” England says. “But when you string a few hundred of them together, suddenly you get this machine that looks like it is made for a particular purpose.”

Somehow, from the churning of blind gears, something like purpose emerges. The pieces, individually obeying nothing more than the basic laws of physics, collectively accrue function. Function seems absent from the world of physics: Time and space don’t exist for any express reason, but just are. In biology, systems are fine-tuned to act. To move, catalyze, and construct. The word “function” trapezes between life and not-life. Is it a word we bestow on things that merely seem life-like, or is it something more inherent? As England would tell an audience at Sweden’s Karolinska Institutet in 2014, physics doesn’t make a distinction between life and not-life. But biology does.

After his Ph.D., when he was a research fellow at Princeton, England would sometimes drive up to New



DEFINING LIFE Jeremy England was compelled to combine physics and biology in his research.

York City to visit his oldest friend from childhood, a philosophy major. His friend took England to some of his favorite Lower East Side haunts and engaged him in long conversations about the Austrian-British philosopher Ludwig Wittgenstein.

Wittgenstein lived in solitude for a portion of his life in the forests of Norway—*waldeinsamkeit*—and wrote of so-called “language games,” or shared sets of conventions about communication. Some philosophers had maintained that a word’s meaning inheres in the physical object out there in the world. Wittgenstein, however, argued that a word’s meaning depends on its context, a context determined by the people who are using it. Playing a language game is sort of like speaking in code—if two people are participating in an activity that’s well understood by both parties, they can use fewer and simpler words to make themselves heard. Different groups of people—musicians, politicians, scientists, and so on—employ language games that suit their separate needs. New language games are constantly bursting into being. Meaning changes shape. Words adapt.

“In making that kind of a point, he’s channeling the same kind of idea that I also locate in, among other places,

The word “function” trapezes between life and not-life.

the opening passages of the Hebrew Bible,” says England.

“In the beginning, God created the heavens and the earth ...” Here, the Hebrew word for “create” is *bara*, the word for “heavens” is *shamayim*, and the word for “earth” is *aretz*; but their true meanings, England says, only come into view through their context in the following verses. For instance, it becomes clear that *bara*, creation, entails a process of giving names to things; the creation of the world is the creation of a language game. “God said, ‘Let there be light,’ and there was light.” God created light by speaking its name. “We have heard this phrase so many times that by the time we are old enough to ponder it, we easily miss its simplest point,” England says. “The light by which we see the world comes from the way we talk about it.” That might be important, thought England, if you’re trying to use the language of physics to describe biology.

Which he was compelled to do. As a young faculty member at MIT, he neither wanted to stop doing biology, nor thinking about theoretical physics. “When you refuse to let go of two things that are divergent in the way they cause you to talk,” he says, “it forces you in the direction of translation.”

IN THE JEWISH TRADITION, “miracles” don’t necessarily defy the laws of nature. They’re a bit less grandiose than that—instead, a miracle is a phenomenon that was previously considered unimaginable. Witnesses to that miracle are called upon to reframe their assumptions and resolve contradictions. In short, they must start to think about their world in a new light.

To the physicist steeped in statistical mechanics, life can, in this sense, appear miraculous. The second law of thermodynamics demands that for a closed system—like a gas in a box, or the universe as a whole—disorder must increase over time. Snow melts into a puddle, but a puddle does not (on its own) spontaneously take the shape of a snowflake. Were you to see a puddle do this, you’d assume you were watching a movie in reverse, as if time were moving backward. The second law imposes an irreversibility on the behavior of large groups of particles, allowing us to play with words like “past,” “present,” and “future.”

The arrow of time points in the direction of disorder. The arrow of life, however, points the opposite way. From a simple, dull seed grows an intricately structured flower, and from the lifeless Earth, forests and jungles. How is it that the rules governing those atoms we call “life” could be so drastically different from those that govern the rest of the atoms in the universe?

In 1944, physicist Erwin Schrödinger tackled this question in a little book called *What is Life?* He recognized that living organisms, unlike a gas in a box, are open systems. That is, they admit the transfer of energy between themselves and a larger environment. Even as life maintains its internal order, its loss of heat to the environment allows the universe to experience an overall increase in entropy (or disorder) in accordance with the second law.

At the same time, Schrödinger pointed to a second mystery. The mechanism that gives rise to the arrow of time, he said, cannot be the same mechanism that gives rise to the arrow of life. Time’s arrow arises from the statistics of large numbers—when you have enough atoms milling about, there are simply so many more disordered configurations than ordered ones that the chance of their stumbling into a more ordered state is nil. But when it comes to life, order and irreversibility must reign even at the microscopic scale, with far fewer atoms in play. At this scale, atoms don’t come in large

enough numbers for their statistics to yield regularities like the second law. A nucleotide—the building block of RNA and DNA, the basic components of life—is, for example, made of just 30 atoms. And yet, Schrödinger noted, genetic codes hold up impossibly well, sometimes over millions of generations, “with a durability or permanence that borders upon the miraculous.”

So how does a gene resist decay? How does it not collapse under the weight of its fragility? Something deeper than statistics had to be at play, something that could allow small groups of atoms to irreversibly pull themselves up by their bootstraps and become something “alive.”

A clue came half a century later, when an English chemist named Gavin Crooks mathematically described microscopic irreversibility for the first time. In a single equation, published in 1999, Crooks showed that a small open system driven by an external source of energy could change in an irreversible way, as long as it dissipates its energy as it changes.

Imagine you’re standing in front of a fence. You want to get to the other side, but the fence is too tall to jump. Then a friend hands you a pogo stick, which you can use to hop to the other side. But once you’re there, you can use the same pogo stick to hop the fence again and end up back where you started. The external source of energy (the pogo stick) allows you to make a change, but a reversible one.

Now imagine that instead of a pogo stick, your friend hands you a jet pack. You fire up the jet pack and it launches you over the fence. As you clear the fence, the jet pack dissipates its fuel out into the surrounding air, so that by the time you land, there’s not enough energy left in your pack to get you back over the fence again. You’re stuck on the far side. Your change is irreversible.

Crooks showed that a group of atoms could similarly take a burst of external energy and use it to transform itself into a new configuration—jumping the fence, so to speak. If the atoms dissipate the energy while they transform, the change could be irreversible. They could always use the next burst of energy that comes along to transition back, and often they will. But sometimes they won’t. Sometimes they’ll use that next burst to transition into yet another new state, dissipating their energy once again, transforming themselves

It could be easier for things like proteins and enzymes to emerge than he’d thought.

step by step. In this way, dissipation doesn’t ensure irreversibility, but irreversibility requires dissipation.

Crooks’ result was very general, applying to any transformation of a system out of equilibrium—including, potentially, life. But, says England, “there was maybe caution about the question of what could be said about a big messy many-body system with huge amounts of dissipation in it. It seemed like these results were true but maybe difficult to operationalize for calculation.” In 2013, while England was in California to give a talk at Caltech, he kept playing with the variables of Crooks’ equation in his hotel room. It was clear from the Crooks equation that in order to achieve the kind of irreversibility that is a hallmark of life, a system would need to be particularly good at absorbing and dissipating heat. But he knew that wasn’t the whole picture.

“It’s like wandering around the vicinity of the same basic point,” he says. “Then you put it down, and you sleep, and you think about different things. When you come back to it, sometimes there’s an opening in the wall. You receive things differently, time passes.”

Finally, something clicked. Given a particular energy source, some arrangements of atoms will be better at



TWO SOLAR MACHINES Both a tree and a solar panel absorb and transform solar energy, and dump heat into their environment. How would a physicist explain why only the tree is alive?

absorbing and spending it than others. These arrangements are more likely to undergo an irreversible transformation. What if some systems get better at doing this than others over time? Then the series of irreversible transformations become an effect that compounds, pulling itself up by its bootstraps. England put pencil to paper and wrote a generalization of the second law of thermodynamics that takes into account a system's dissipative history, and which, he says, sheds light on the emergence of the structures and functions of life. In a paper late last year, he put it this way:

While any given change in shape for the system is mostly random, the most durable and irreversible of these shifts in configuration occur when the system happens to be momentarily better at absorbing and dissipating work. With the passage of time, the “memory” of these less erasable changes accumulates preferentially, and the system increasingly adopts shapes that resemble those in its history where dissipation occurred. Looking backward at the likely history of a product of this non-equilibrium process, the structure will appear to us like it has self-organized into a state that is “well adapted” to the environmental conditions. This is the phenomenon of dissipative adaptation.¹

Of course, a system of atoms isn't trying to do anything—it's just blindly, randomly, shuffling itself around. And yet, through its journey from one shape to another, a constellation of chemical stories, it self-organizes into something that looks to us like it has adapted. “Language is a labyrinth of paths,” said Wittgenstein. To England, the translation felt right. *How do you say “life” in physics?* He called it “dissipative adaptation.”

IT MAY SOUND AS though dissipative adaptation reduces us to mere cooling towers for the sun. But the theory means much more than that. Darwinian natural selection could be recast as a special case of the more generalized phenomenon of dissipative adaptation, a dialect of a more fundamental language. Whereas dissipative adaptation occurs on the micro-scale, natural selection takes place in the world of macroscopic self-replicators. And self-replication is an excellent way to consume and dissipate energy. In the language of dissipative adaptation, words like “fitness” take on new meaning. “Fitness is defined here not in terms of a set of optimal functionalities, but rather as its ‘give

and take' relationship with available energy from the environment," says Meni Wanunu, assistant professor of physics at Northeastern University. As systems dissipate energy, they drift in an irreversible direction and by doing so become "exceptional," as England puts it, not perfect or ideal. "A bird is not a global optimum for flying," England says, "It's just much better at flying than rocks or worms."

The theory challenges us to rethink the remarkable functions that make life special: "We have more flexibility in the places we look for function," says England. The emergence of complex function from a collection of weakly interacting particles, without any strong coordination, is now a process that can be broken down into many small irreversible transformations driven by an external drive. It could be easier for things like proteins and enzymes to emerge than we'd thought. "It might not be an issue of exquisitely selecting the amino acid sequences over eons of self-replication," says England. "There may be faster time scales on which you can self-organize things. If we can convince ourselves that the very beginning of life looks a bit more like a ramp or stairway with lots of smaller incremental changes that point in the right direction, then that may at least reset our notion of what kinds of scenarios we should be imagining."

The theory doesn't just help us peer into the past—it also suggests new design and engineering approaches. "If I want to mimic something that living things do, maybe it doesn't have to mimic living things as much as I thought it did." One example may be something called "emergent computation," which England and members of his lab are currently studying. The goal is to get systems of particles to evolve an ability to predict changes in their environment, without receiving any design instructions on how to do so. Getting good at absorbing and dissipating energy in a fluctuating environment requires some degree of anticipation, after all. "If we succeed in doing this, the argument will be that somehow the particles in the system are interacting in such a way as to effectively implement a calculation about the future based on the statistics of the past," England says. That could impact technologies that are based on predictive power, from neural networks to bots that tell us when to buy a plane ticket.

This is the surprising power of translation. If it

works, it could be the proof in the pudding that dissipative adaptation needs. For now, Wanunu is reserving judgment. "England proposes a new set of ingredients. Just how the pudding turns out will be exciting and interesting to see." Jeremy Gunawardena, associate professor of systems biology at Harvard University, isn't entirely sold on the approach either. "Jeremy is hoping that he can avoid thinking about the chemistry and see the abstract essentials of life emerging as a physical necessity," he says. "I am not convinced. However, I think it is great that he is working on the problem and I am sure we will learn something interesting from it."

Which is fair enough. After all, in the words of the late Umberto Eco, "translation is the art of failure." The failures and trade-offs in this brand-new translation remain to be discovered. There may not, at the end of the day, be just one language to express the complexities of life. But England wants us to try a new one. He put it this way in *Commentary* magazine last year: "There is more than one viable language for describing the world, and God wants man to speak all of them." ☺

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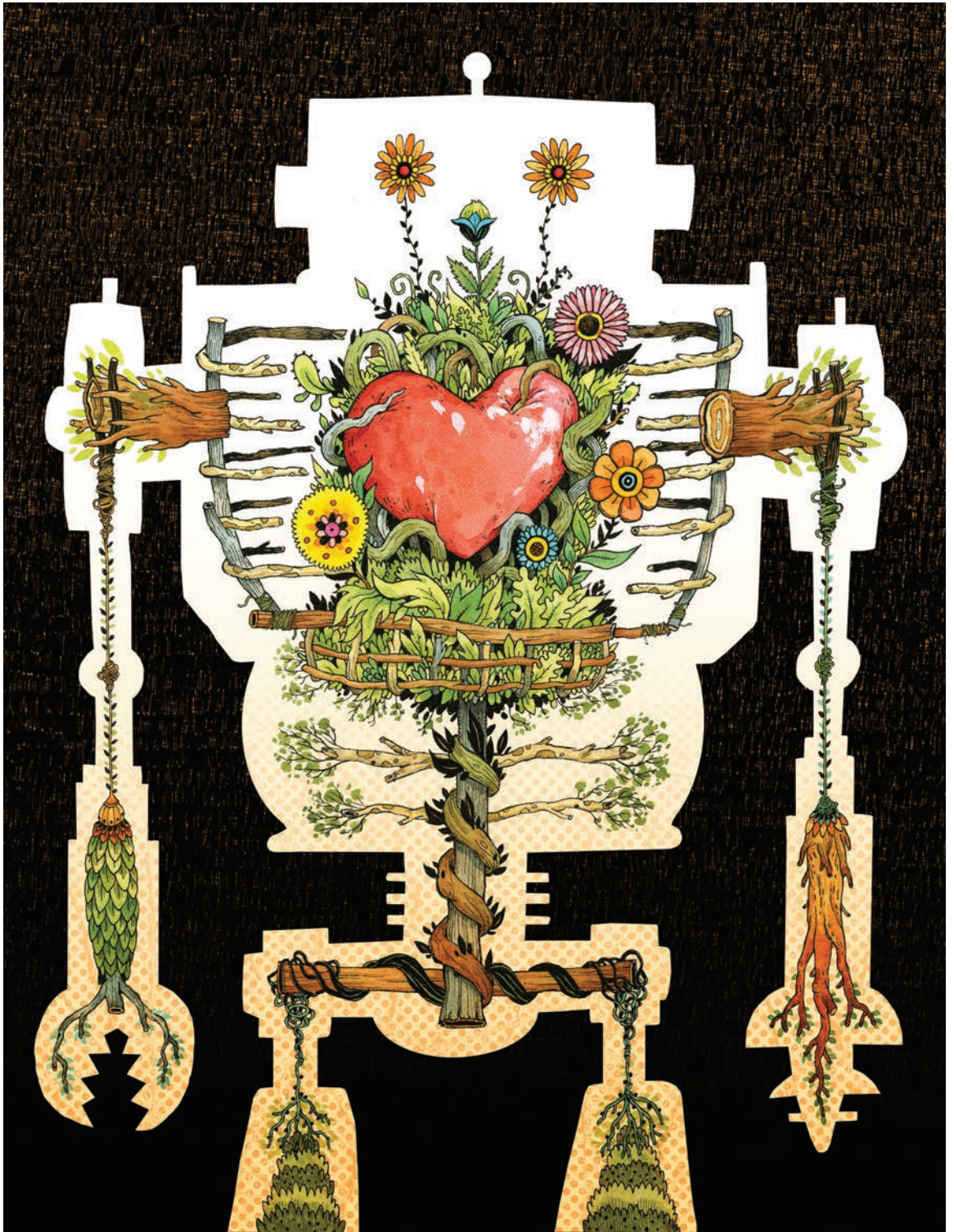


ILLUSTRATION BY **JOHN HENDRIX**

Strange Worms Are Taking Their Place on Your Family Tree

The Cambrian explosion of animal life now seems more like a whimper

BY AMY MAXMEN

JUST BEFORE THE ATOMIC BOMB drops on Hiroshima, the land below appears smooth as glass. The bomb falls on a grid of streets aligned between lazy rivers. In footage from 1945, the city's exceptional stillness seems to give the explosion oxygen.

The calm before the storm is a standard trope for movie directors. Composers too. Without a prior silence, there is no “KaBoom!” Although they’d never admit it, scientists fall into the same storytelling trap. There’s no better way to emphasize a phenomenon than to clear the space around it.

Science is rife with dramatic entrances: the Big Bang, the origin of life, the origin of animals. Biology students learn that animal lineages blossomed in the Cambrian explosion, about 530 million years ago. Shrimp-like monsters named anomalocaris swooped through the seas, stuffing prey into voracious, donut-shaped mouths. Large worms that resembled penises—named priapulids after the Greek god

of fertility—sifted nutritious snacks out of the water. Other animals hobbled along on spiky legs; their fossils look so strange that the paleontologist who discovered them named them *Hallucingenia* for their “bizarre and dream-like appearance.”

Most of the animal groups alive today evolved within the Cambrian explosion, a relatively short time frame—a span of several million years. At least that’s what the scientists say. What prompted scientists to call this chunk of the Cambrian period, which stretches from 541 to 485 million years ago, an explosion, was the near absence of life in the tens of millions years preceding it, and the lack of new animal groups after it.

However, it now appears that squishy creatures were eating, mating, and struggling for survival long before the so-called explosion. According to a host of bold scientists, recent findings suggest life evolved gradually long before explosion. Suddenly, the dogma about the origin of most animal groups seems artificial.

“If you look at the Cambrian fossil record, it is



amazingly unexplosive,” says Graham Budd, a paleontologist at Uppsala University in Sweden. “It is really quite a stately process,” he adds. “It’s not true that everything suddenly appears.”

Harvard paleontologist Stephen Jay Gould waxed poetic on the Cambrian explosion in his 1989 book *A Wonderful Life*. A graceful writer as well as a scientist, he muffled the period preceding the burst, and had the explosion in major animal groups, called phyla, fill a vacuum. Fits and starts are a hallmark in Gould’s evolutionary thinking. The fossil record, he wrote, “is punctuated by brief, sometimes geologically instantaneous, episodes of mass extinction and subsequent diversification.” The fossilized remains of a bizarre assortment of animals dating back 508 million years to the heart of the Cambrian period inspired Gould’s vision, along with the relative absence of fossils 40 million years prior. But what seems silent so long ago may not have been.

This February, more than a decade after Gould’s passing, evolutionary biologists published findings in *Nature* that hint at dramas occurring in oceanic dirt long before the Cambrian burst. Andreas Hejnol, an evolutionary biologist at Sars International Center for Marine Molecular Biology in Norway, led the project. He places a group of flat worms that resemble tiny flecks of paint, called acoels, and an enigmatic group of marine worms, *Xenoturbella* (the Latin name means strange worm), near the root of the animal life tree. Unfortunately, traces of tiny, squishy worms don’t tend to stick around. “It means we might never find the fossils that gave rise to all this diversity,” Hejnol says.

Hejnol and his team, though, did not study fossils. They created an animal tree of life using gene sequencing. They compared about 800 genes from 76 animals ranging from worms, to chickens, to people. With this data, they built a tree of life based on the genetic differences between species. They discovered that the wee worms branch off near the tree’s root. If our earliest ancestors were soft and slight, like these simple worms, they might have lived long before the Cambrian explosion.

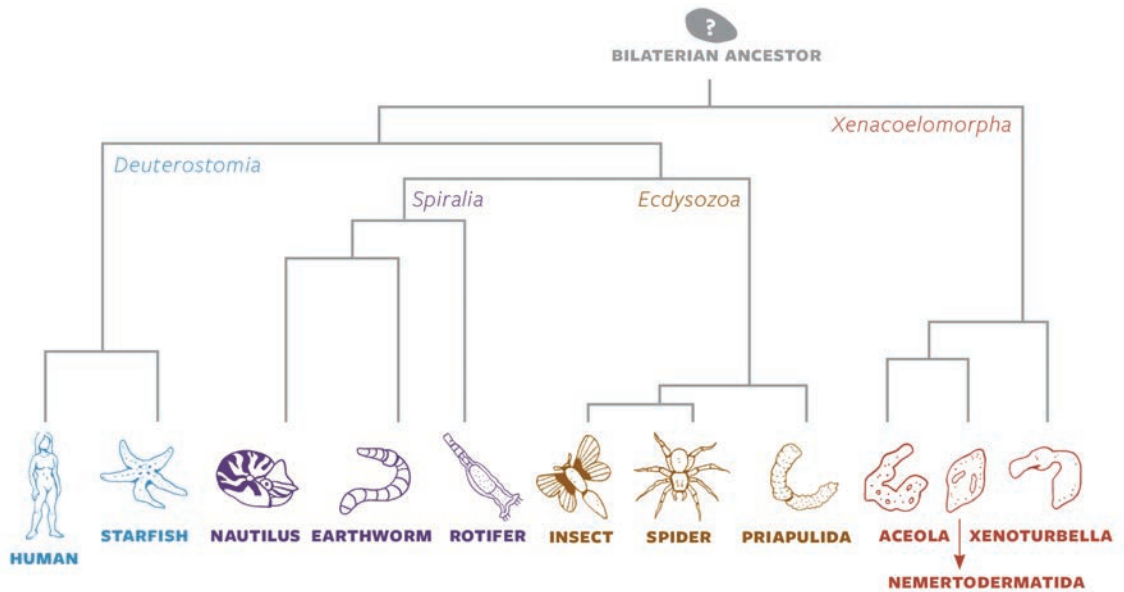
What has been discovered in fossil beds preceding the Cambrian explosion are remnants of mysterious organisms shaped like puffy ferns, segmented balloons, and spirals. Named the Ediacarans, these creatures

There’s no better way to emphasize a phenomenon than to clear the space around it.

bear no resemblance to anything alive today. A popular theory suggests the Ediacarans were an animal-like kingdom that went extinct before ours blossomed in the Cambrian explosion. This story suits Gould’s ideas about cycles of extinction and explosion. However, it’s backed up by a lack of fossils, and as any logistician will tell you, the absence of evidence is not evidence of absence.

Budd, a paleontologist who specializes in animal evolution, questions the moat that scientists place between Ediacarans and animals. “We can’t say Ediacarans don’t look like animals since there’s no way to know what early animals looked like then,” he says. Budd adds there’s no reason to assume the connection between Ediacarans and animals is anything but fluid.

When Budd imagines the 50-million year period preceding the Cambrian explosion, he envisions ocean floors populated by Ediacarans, as well as creatures that share a key characteristic of animals including humans, worms, and flies—namely, bilateral symmetry. Bilaterally symmetrical animals have heads, rears, and distinct left and right sides. They tend to move



TREE OF LIFE This chart of animal relationships suggests the roots of bilaterally symmetrical animals run deeper than previously imagined. Each creature, including humans, descended from a bilaterian ancestor that evolved prior to the Cambrian explosion.

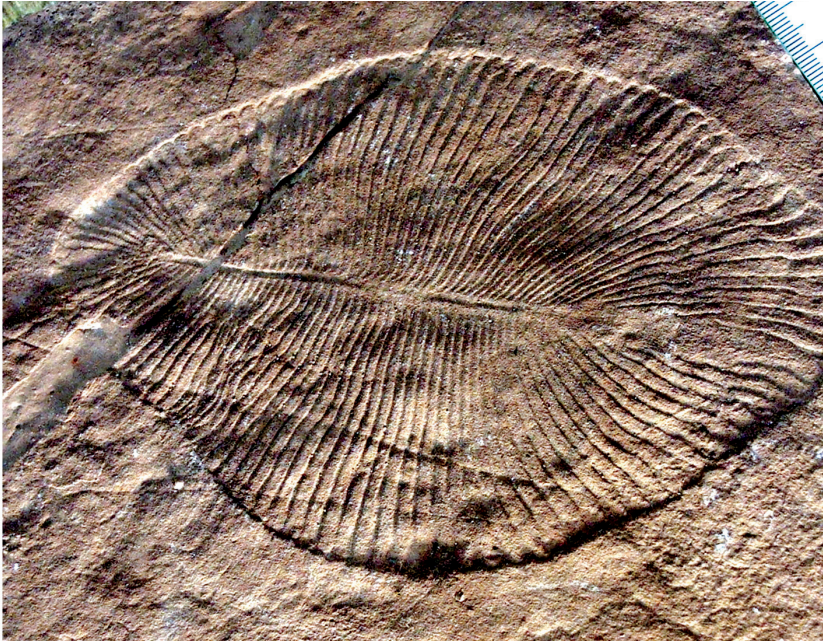
with their head facing forward. According to trees of life constructed with DNA evidence, all bilaterally symmetrical animals share a common ancestor from whom they inherited symmetry. The tiny acoel and *Xenoturbella* worms are, indeed, bilaterally symmetrical.

Budd believes in a dynamic interaction between Ediacarans and ancient, wormy bilaterians that drove diversification. He speculates that in spots where the Ediacarans lived and died, their bodies left splotches of nutrients on the barren ocean floor. Because resources were scarce, worms might have adapted novel methods to obtain what they could before their brethren did. Some developed innovative ways to scavenge and digest; some learned to burrow. It was survival of the fittest. Budd calls this his Savannah Hypothesis. He likens it to a theory on how our human ancestors began to walk upright when they needed to move quickly across African grasslands to find spottily distributed food. In this vision of early animal life, evolution gradually occurred over tens of millions of years prior to the Cambrian explosion.

Although there is scant evidence in the fossil

record to show that worms interacted with Ediacarans, molecular biologists have argued for earlier animal origins for over a decade. These biologists calibrate “molecular clocks” by counting the number of changes in DNA between a pair of living animals, and placing that numerator over the number of years that passed between them and a fossil ancestor they indisputably share. With this rate on hand, the researchers then infer the time passed between more disparate living animals, who shared an ancestor a very long time ago. Most of these reports conclude that the first animals arose more than 700 million years ago. But there’s hardly any fossil evidence to back up the claim, and that has led to controversy. “It’s always been hard for paleontologists to accept that theory,” says Blair Hedges, an evolutionary biologist at Temple University in Philadelphia.

Hedges speculates that a low level of atmospheric oxygen before the Cambrian explosion would have made early animal life possible for tens of millions of years prior. Indeed, geologists have found traces of this gas in rocks, along with a surge in oxygen by the



mid-Cambrian. Hedges says that uprising accounts for why animals grew larger and developed hard skeletons that are abruptly so apparent in the fossil record during the explosion.

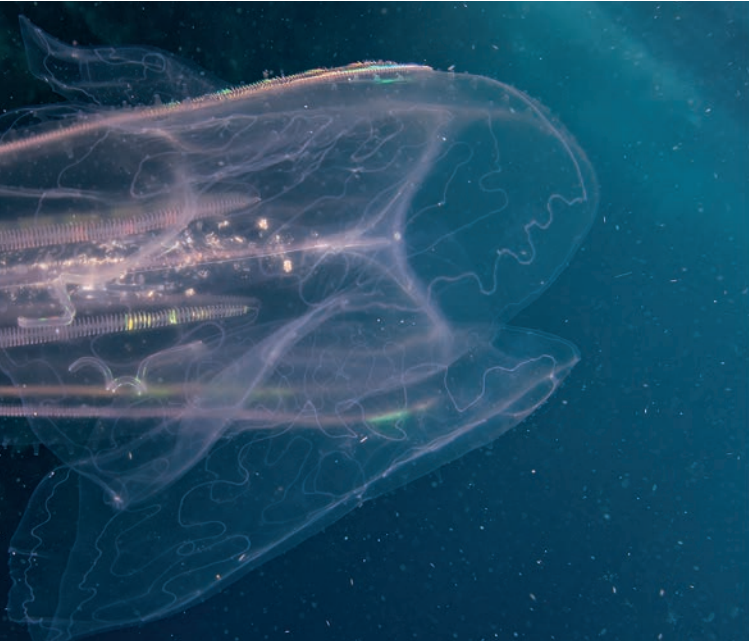
As for the line about how most major groups of animals—some 36 phyla—appeared in the Cambrian explosion, this too has a flaw rooted in humankind’s desire to arrange the world around them. Phylum and other ranks, such as class, order and family, are arbitrary constructs. “They were a way to slice up all the diversity in nature because it was too much to take it all in at once,” explains Casey Dunn, an evolutionary biologist at Brown University.

Dunn’s perspective has been shaped by observing mysterious animals he scoops from the ocean, such as shimmering, colonial, gelatinous siphonophores. Creatures that defy expectation. The problem with rankings like phylum, class, and order, Dunn says, is that they are biased by scientists who arbitrarily decide what features are relevant and which are not. Dunn sees no reason for why there should be 36 phyla (or, as some argue, 32, or 34, or 37). He says there could be as many phyla

as the number of ancestors that any two species share. And since there are about 2 million known species, that number could be 2 million minus one. If this were the case, the Cambrian would not nearly contain them all.

Dunn, skilled in computer science and field biology, has a mop of dirty blond hair and speaks with a hippie twang. Referring to the arbitrariness of terms like phylum, he says, “It’s as if someone declares that one country has more music than another because they count more genres being played there. Well, one person might care a lot about melody and classify genres according to that scheme, while another person wouldn’t get the same result because they put emphasis on rhythm instead.”

In 2013, Dunn and his colleagues caused an uproar with another tree-of-life study. In a DNA analysis, they found that complex sea creatures, called comb jellies, or ctenophores, have roots that go deeper than those leading to acol worms and even headless, gutless sponges, long considered to resemble the prototype of a primitive animal. The study implies that animals had time to evolve a tremendous amount before bilaterally



If you look at the Cambrian fossil record, it is amazingly unexplosive. It's not true that suddenly everything appears.

BEFORE THE EXPLOSION

Mysterious organisms shaped like puffy ferns, Ediacarans (left), have been discovered in fossil beds preceding the Cambrian explosion. Shimmery comb jellies (right) may have an evolutionary lineage that also predates the time period long thought to represent the first flowering of animal life.

symmetrical animals arose—and left a plethora of fossils—in the Cambrian explosion. This pre-explosion period must have lasted long enough that ancient lineages diversified enough to give rise to modern comb jellies—with bioluminescent beads, little brains, and feathery teeth—on one hand, and passive sponges on the other.

Dunn's finding on comb jellies was contested last December. Scientists challenged his view that comb jellies evolved before gutless sponges. Hejnol's recent suggestion of oceans rich in life prior to the Cambrian explosion will no doubt be contested as well. Indeed, the origin of animals half a billion years ago is one of the hardest evolutionary problems to solve, despite dramatic advances in DNA analysis. For his part, Hejnol is content to let the disruptive findings sit. "I like the provocation of evolutionary thinking," he says. "When we find something that makes us think, 'This cannot be,' it means we need to stop and ask ourselves why we think it cannot be."

Charles Darwin would have understood Hejnol's position. Uncertainty laces *On the Origin of Species*.

Chief among the difficulties he enumerated in his theory of evolution by natural selection was the lack of fossils to prove that species transform over evolutionary time. When he published the book in 1859, the dogma was the sudden appearance of animals in the fossil record was proof of the immutability of species. Yet Darwin felt strongly that these fossilized creatures could not have appeared from the ether. If his theory on evolution was true, the world prior to those known fossils must have been "swarmed with living creatures." In humility, Darwin acknowledged the geologists before him, and wrote, "I feel how rash it is to differ from these great authorities." He continued, "For my part ... I look at the natural geological record as a history of the world imperfectly kept, and written in a changing dialect; of this history we possess the last volume alone, relating only to two or three countries."

A silence before a storm requires closer listening. 🌀

AMY MAXMEN is a journalist who writes for *Nautilus*, *Wired*, *Newsweek*, *Nature*, and other magazines. She has a Ph.D. in evolution from Harvard.



When You Listen to Music, You're Never Alone

Technology hasn't diminished the social quality of listening to music

BY DANIEL A. GROSS

ON A LATE SPRING evening in 2015, at South Street Seaport, a square on the southern tip of Manhattan, hundreds of people slipped on headphones and slipped into their own worlds. It was a clear night, perfect for a stroll, but attendees weren't interested in local shops and restaurants. They were too busy dancing silently to the music, tuning in—or tuning out—to a “silent disco.”

The silent disco is a concert that passersby can barely hear, and that attendees can customize with a flip of the switch. At this event, a wireless signal allowed dancers to choose their favorite of three playlists. Each pair of headphones covered the ears and gave off a robotic glow. “This is what we’ve been reduced to: dancing with ourselves,” one dancer told a reporter from *The New York Times*.

To some observers, the silent disco represents a peculiar form of shared isolation—a way to turn up the volume of modern alienation, to look social but remain solitary. “Headphones have been creeping into

musical activities that once were social,” the writer and jazz musician Eric Felten lamented in the *Wall Street Journal*.

Silent disco, Felten added, is just one of many activities that are “atomizing” our society. “What a shame to turn the concert hall or dance club into another such lonely crowd,” he wrote. “These venues should be super—not anti—social.” Headphones may silence our city streets, runs the argument, but they also silence our social connections. To paraphrase those seminal pop philosophers from Athens, Georgia, the B-52s, we’re all living in our own private Idahos.

That, anyway, has been a refrain in sociological circles since Thomas Edison invented the phonograph in the 19th century. Critics complained that the social fabric was being shredded when, rather than gathering in ballrooms to dance to Johann Strauss, we listened to recordings in our living rooms.

But recent looks at the evolution and neurology of music suggest we are not waltzing by ourselves.



Private listening started long before Sony or Apple. Wax cylinder recordings were installed in rows in penny arcades.

Musical experiences are inherently social, scientists tell us, even when they happen in private. When we listen alone, we feel together.

Istvan Molnar-Szakacs, Ph.D., a research neuroscientist at the Semel Institute for Neuroscience at the University of California, Los Angeles, has explored how music “creates the sense of social belonging,” as he writes in a 2015 paper, “Please Don’t Stop the Music.”

“When you’re home alone in your house, it feels empty,” he says. “And then you put on music and all of a sudden you feel better because you’re not alone. It’s not that literally you’re not alone. But you feel like you have company.”

As science is altering the picture of the lonely crowd of iPod listeners, it is giving us a new appreciation of technology. Peter Alhadeff, a professor of music business at the Berklee College of Music, suggests that our recent technologies—from Facebook to Spotify to Fitbit—shed light on a shift in our social lives. “Maybe

our way of being social and being private is changing,” he says. In a way, “the world was more private before. There is a different way of socializing today.”

“MUSIC IS A FUNDAMENTAL PART of our evolution; we probably sang before we spoke in syntactically guided sentences,” write Jay Schulkin and Greta Raglan in a 2014 article in *Frontiers in Neuroscience*. Long before there were dance clubs or concert halls, there was the musical bond formed by a mother singing to her child. There was the melody that guided a tribe in worship, or the beat that led warriors into battle.

Music is as much a part of human evolution as language, tool-making, and cognitive development, Schulkin and Raglan tell us. It’s a bridge. “Music is typically something shared, something social; we may sing in the shower or on a solitary walk, but music is most of the time social, communicative, expressive, and oriented toward others,” Schulkin and Raglan write.



HOUSE MUSIC Gustav Klimt's 1899 painting, *Schubert at the Piano* (left), evokes a romantic era when music formed a social bond in intimate, personal settings. A silent disco (right), where everybody wears headphones, has the same effect in our technology era.

Molnar-Szakacs explains the brain's mirror-neuron system provides the neural basis of music's social powers. The properties of the human mirror-neuron system are based on research showing that the same regions in our brain are active when we perform, see, or hear an action. The "mirror" regions of our brains fire whether we're playing the guitar or listening to Pete Townshend play it.

The mirror-neuron system, Molnar-Szakacs says, "allows someone to identify with another by providing an automatic, pre-cognitive mechanism by which to understand their actions by mapping them onto our own neural representations of those actions. In addition, it represents the intention behind those actions."

The moment you hear a sequence of hierarchically organized abstract sounds we call music, a multitude of associations are activated in your brain. These can include memories, emotions, and even motor programs for playing music. Together they can imply a sense of

human agency. That sensation is what sets music apart from other types of sounds. "The brain interprets the structure of the music as intentionality that is coming from a human agent," Molnar-Szakacs says. "This, combined with all the associations evoked by the music, is what makes the experience social."

Not all scientists agree certain neurons have properties that connote intentionality or agency, as those are complex subconscious processes, not easily reduced to specific neurons. Molnar-Szakacs, for his part, sees the mirror-neuron system "as a node or hub within a larger network, integrating cross-modal information" in the brain. Another important node within this network is the limbic system, the region involved with emotions, reward, motivation, and pleasure.

Our sense of others as represented by the mirror-neuron system, charged with emotion from the limbic system, can give rise to empathy. To Molnar-Szakacs, it is emotional empathy that can explain "why music

To paraphrase those seminal pop philosophers from Athens, Georgia, the B-52s, we're all living in our own private Idahos.

can be experienced as a social phenomenon even when someone is listening alone on their earphones.”

Solitary listening seems, at first glance, like a striking break from the social roots of music. But a stroll through the history of listening technologies challenges that narrative. It reveals technologies for private listening can be seen as ways to amplify the social nature of music.

To begin with, private music started long before Sony or Apple; in fact, it dates back to the origins of recorded music. “The very first commercial phonographs, later called jukeboxes, used headphones,” points out Q. David Bowers, author of *Encyclopedia of Automatic Musical Instruments*. Edison’s wax cylinder recordings were often installed as rows of separate machines in penny arcades. “They had to be individual, like a private booth.”

“Earbuds are new, headphones are not,” says Jonathan Sterne, the James McGill Chair in Culture and Technology at McGill University. “Almost everything that was said about the iPod in 2001, and the iPhone in 2007, you can find said about the Walkman in the 1980s.”

In light of the history of listening, it’s possible to reevaluate the first impression that music listening has become, as Stanford music professor and composer Jonathan Berger puts it, “a more isolated or even isolating experience.”

Schulkin, a research professor in neuroscience at Georgetown University, points out that activities we now view as social, like reading, were once viewed as anti-social. “Your neighbor might have been reading Charles Dickens, and you’re reading something else,” he says. Maybe listening in private isn’t so different from reading in private. “I don’t see why this is necessarily more isolating,” Schulkin says.

Meanwhile, says Berger, performances of Western music that we normally see as social can easily be reinterpreted as isolating—like classical music concerts. “You have to shut up and sit straight, and you can’t move, and everything is a disturbance,” says Berger, whose own compositions are often performed in this manner. “From one point of view, that’s at least as isolating as people in their own zone with their earbuds on.”

What’s more, Berger believes earbuds can play a role in stitching society together. “I see kids walking with their earbuds and I’m trying to infer what they’re listening to. In a way that’s social bonding,” he says. “I’m aware of how they’re tapping their feet, how they’re mouthing the music.” Music that’s experienced alone can still communicate with others.

Schulkin agrees. “You put the headphones on, you’re listening to music, but the music’s still part of the larger social world.” Headphone listeners might block out the world around them, but Schulkin says they’re “plugged in” to the social experience of listening.

The Internet, and music streaming, can clearly be social too. Spotify and Pandora playlists are very often consumed through mobile phones and earbuds. But even when taste algorithms help us discover music in private, that process is a social experience of sharing.

Likewise, services like Last.fm have turned individual music tastes into a source of new social bonds. These new bonds start in our imagination, in that they help us perceive a community of like-minded listeners. But they also help existing friends better understand each other’s habits and tastes.

Sterne portrays listeners as experts at finding new uses for existing technologies. “They get in the hands of users, and they’re transformed,” he says. That’s what

happened when DJs started spinning records backward. DJs and fans took a potentially private listening technology, the phonograph record, and turned it into an improvised and unique group experience.

None of this is to say that music listening isn't individualistic. It's just that individualistic listening can be social and communicative—like the waltz, the jam session, or the drumbeat that sends soldiers into war. "It's incorporating the technology into a particular vision of being together," Sterne says.

Critics who lament private listening cuts us off from one another and tear the social fabric don't have the full picture. Evolution has stitched the intersubjective powers of music into our brains. Technology hasn't diminished the social bonds of music. On the contrary, we've created and adapted technology to enhance them.

"If you talk about social-media listening, or silent raves, where people are listening to the same music but they've got earbuds in—those kinds of activities are completely consistent with the history of music as a collective practice," says Sterne. "But it's being remediated and re-performed through the technologies of the moment."

A FEW YEARS AGO, LJ Berube traveled to the Bonnaroo Music Festival on a farm in Tennessee. Over the course of four days, dozens of bands took the stage, blasting music to tens of thousands of fans. One day Berube was wandering the festival grounds when he came across a long line. It led to a crowded tent, but strangely, he couldn't hear any music inside. "I figured it must be something fun," Berube says. The wait was almost an hour.

The line inched along. The occasional cheer emanated from the tent. "All of a sudden, I figured out what was going on," Berube recalls. He looked inside and saw hundreds of people dancing—but each person had a pair of headphones on.

It was a bizarre sight: hundreds of people busting moves to music only they could hear. Some of the dancers were synchronized, but others were not. "I was like, uh, I don't know if this is for me," Berube says. "But at that point I'd already waited 45 minutes." He put on a pair of headphones and joined the dance floor. "It was weird at first," he says. "But that faded quickly." He danced for an hour.

"I completely get it now," Berube says. Silent disco turns a private experience into a public one. "You get in your own world and at the same time experience what you're doing with a group. You're in tune with yourself, and with everybody else."

For Berube, that first silent disco was a conversion. Today he works as a "Customer Excitement Manager" for Party Headphones, a silent disco business in New Hampshire. He estimates that tens of thousands of people attend American silent discos each weekend, with even more going to events in Europe. Every week, his company ships crates of headphones all across the United States, so teenagers and young adults can silently get their groove on.

"I actually brought some headphones home for Thanksgiving," Berube says. "My grandparents were dancing around to Sinatra wearing them." 🎧

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Families of Choice Are Remaking America

Through their networks of friends, singles are strengthening society's social bonds

BY BELLA DEPAULO

WHEN DAN SCHEFFEY TURNED 50, he threw himself a party. About 100 people packed into his Manhattan apartment, which occupies the third floor of a brick townhouse in the island's vibrant East Village. His parents, siblings, and an in-law were there, and friends from all times and walks of his life. He told them how much they meant to him and how happy he was to see them all in one place. "My most important family," says Dan, who has been single his entire life, "is the family that I've selected and brought together."

Dan has never been married. He doesn't have kids. Not long ago, his choice of lifestyle would have been highly unusual, even pitied. In 1950, 78 percent of households in the United States had a married couple at its helm; more than half of those included children. "The accepted wisdom was that the post-World War II nuclear family style was the culmination of a long journey—the end point of changes in families that had been occurring for several hundred years," sociologist

John Scanlon wrote in 2001.

But that wisdom was wrong: The meaning of family is morphing once again. Fueled by a convergence of historical currents—including birth control and the rising status of women, increased wealth and social security, LGBTQ activism, and the spread of personal communication technologies and social media—more people are choosing to live alone than ever before.

Pick a random American household today, and it's more likely to look like Dan's than like Ozzie and Harriet's. Nearly half of adults ages 18 and older are single. About 1 in 7 live alone. Americans are marrying later, divorcing in larger numbers, and becoming less interested in remarrying. According to the Pew Research Center, by the time today's young adults reach age 50, a quarter of them will have never married at all.

The surge of singlehood is not just an American phenomenon. Between 1980 and 2011, the number of one-person households worldwide more than doubled, from about 118 million to 277 million, and will rise to



334 million by 2020, according to Euromonitor International. More than a dozen countries, including Japan and several European nations, now have even larger proportions of solo-dwellers than the U.S. (Sweden ranks highest at almost 50 percent.) Individuals, not couples or clans or other social groups, are fast becoming the fundamental units of society.

And yet, in the stories we tell each other about the workings of community, it is often the married couples and the traditional families who are holding us together. In the U.S. Supreme Court's 2015 opinion legalizing same-sex marriage, for instance, Justice Anthony Kennedy discounted the country's 107 million singletons when he declared marriage "a keystone of the Nation's social order." We tend to view single people—especially those who live alone—as isolates, holed up in their apartment, lonely and loveless, more social repellent than social glue.

Research by social scientists paints a very different picture. Most singles, studies show, are more like Dan Scheffey than their miserable or narcissistic caricatures. They host salons, take classes, go to rallies, organize unions, care for aging friends and relatives, help raise kids, and cultivate large, diverse social networks—often with more zeal and commitment than the married demographic they're displacing.

Rather than tear us apart, the rising tide of solo dwellers is creating, sustaining, and perhaps even strengthening, the ties that bind us.

THE BELIEF THAT NUCLEAR families are essential to the social operating system has long infused our collective psyche. In late 19th-century France, Emile Durkheim, an eminent figure in sociology, proclaimed that marriage integrates people into society while single life alienates them. Because they lack social support and a sense of belonging, Durkheim argued, single people were more likely to kill themselves.

More than a century of statistical scrutiny tells us that any link between singlehood and asocial behavior, including suicide, has been vastly overstated, if one exists at all. And yet the stereotype persists. In our own research on the perceptions of single people, my colleagues and I presented study participants with pairs of near-identical biographical profiles, differing only in marital status. Participants routinely judged the

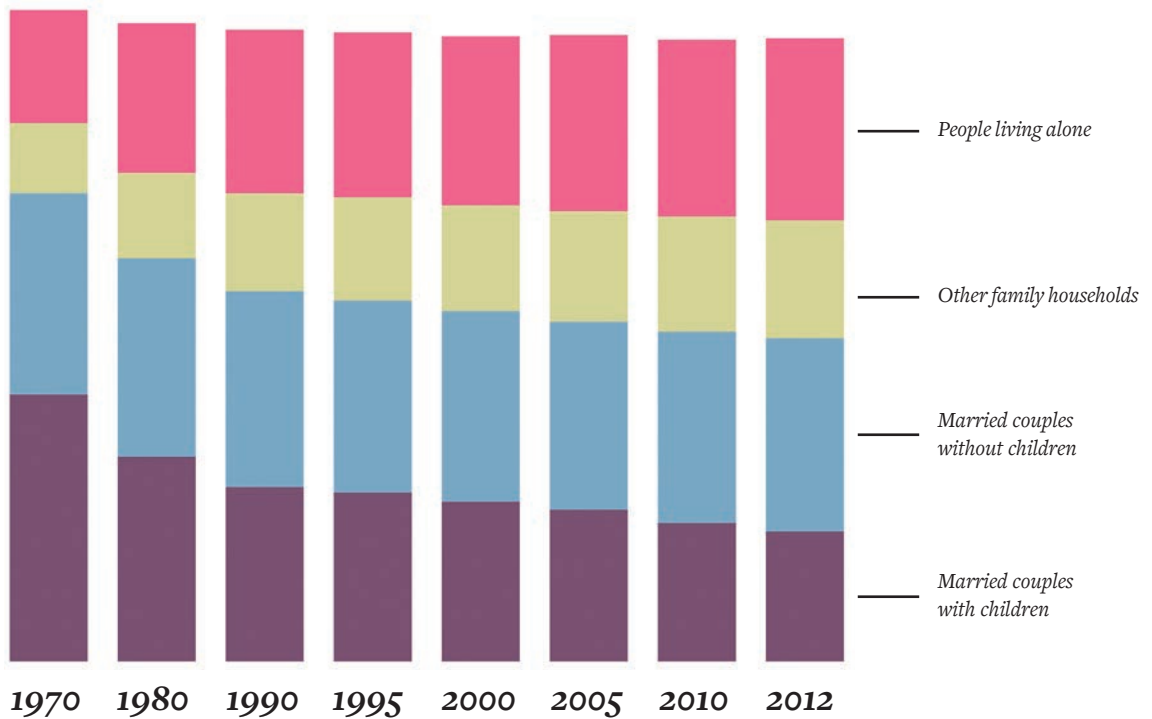
Single people as a group spend more time connecting with and helping others than their married counterparts.

married people as kinder, more loyal, and more caring. They tended to view the singles as shyer, lonelier, and more selfish.

Not only are these biases false—they may be backward. In multiple national surveys involving representative samples of thousands of citizens, participants answered questions about their social life. How often did they socialize with friends, neighbors, or coworkers? How often did they give rides, help with errands, or pitch in with housework or repairs? Did they also offer advice, encouragement, or emotional support? Did they receive similar support in return?

In every measure, single people as a group spend more time connecting with and helping others than their married counterparts. Singles are more likely to do the same for their parents and siblings. They also devote more time and resources to caring for aging relatives or friends who are sick, disabled, or elderly. These differences hold for people who have young children and those who don't. They're true for men and women, whites and non-whites, the rich and the poor, and the employed and the jobless.

In cities and towns, single people are cultivators of urban culture. Compared to married folk, they participate in more civic groups and public events. They go out to dinner more often and take more music and art classes. In studies that surveyed only men, bachelors were more likely than husbands to take part in professional societies, unions, and farm organizations. Single



ON THEIR OWN As traditional family living declines, single-person households and non-traditional families are on the rise.

men also tend to be more generous with their money.

Longitudinal studies, which follow people over many years, show these dynamics unfolding over time. One such study, published in the *Journal of Marriage and Family* in 2012, enlisted more than 2,700 representative Americans under age 50 who were not married or living with a partner (cohabitation), and then tracked them for six years. Those who stayed single kept in touch with friends and relatives. Those who wedded or entered into a cohabiting relationship, meanwhile, became more insular. They had less contact with their parents and siblings, and spent less time with friends than when they were single.

The shrinkage of partnered people's social networks wasn't just a honeymoon effect. After more than three years of marriage or cohabitation, with or without kids, couples were still less connected. Other research shows that when married people get divorced,

their social networks expand again.

There is some evidence that romantic coupling also comes at the expense of other core relationships. In a recent study, the British anthropologist Robin Dunbar (who famously estimated that 150 is about the number of meaningful relationships a person can have at any one time) surveyed 540 people ranging in age from 18 to 69. He asked them to list all the people they felt they could turn to in times of "severe emotional or financial crisis." Including their partner, coupled participants named, on average, one fewer than singles. The results, though far from definitive, suggest that when a single-ton couples up, his or her lover replaces two former confidants.

Many single people maintain their diverse social ties even as they age, bucking the stereotype that singlehood dooms you to die alone. Consider Lucy Whitworth, a retired teacher and single mother-of-none



ALONE TOGETHER Studies suggest that single people spend more time participating in communal activities and civic events than coupled people.

living amongst gardens and fruit trees in an intentional community in California. When she was diagnosed with cancer at age 68, her friends mobilized. One person helped her make a list of everything she would need to do in the months ahead. Forty-eight others—square dance partners, bridge players, fellow volunteers—divvied up the tasks. They called themselves “Lucy’s Angels.” Because they spread the work over so many hands, no one felt overburdened or resentful.

Lucy’s case may be extreme, but it’s not unusual. In five of six countries for which data were available (Finland, the Netherlands, Spain, the United Kingdom, and the U.S.), researchers found that elderly women (but not men) who never married and have no children are especially likely to have expansive support networks. In that study, Australia was the exception. But in another study of 73- to 78-year-old Australians, never-married childless women regularly participated

in social groups and were more likely to volunteer than those who were or had previously been married.

Perhaps because the experience is often anything but isolating, many elderly singles choose to stay single. As sociologist Eric Klinenberg points out in his book *Going Solo*, in the U.S., only 2 percent of widows and 20 percent of widowers ages 65 and older remarry. Sure, they may have fewer available partners. But many of them aren’t keen to find a new one. Eighteen months after a spouse’s death, only 1 in 6 elderly women say they want to marry again, according to research by Rutgers University sociologist Deborah Carr. For elderly men, the rate is 1 in 4, but if they have a lot of friends, they’re just as unlikely to want to remarry as women. “Their friendships may provide at least some of the desired aspects of a romantic relationship,” Carr writes.

Friends, in other words, can be family too.

IN RESEARCHING MY BOOK *How We Live Now*, I traveled the country talking to people like Dan and Lucy about the people and domestic spaces most important to them. I met single mothers who live together and share the burdens and joys of child rearing. I met elderly friends who share a home as well as meals, chores, and stories—*Golden Girls* style. I met committed couples who choose to live apart; parents who partnered to raise kids but keep their own relationship platonic; and a single mom whose daughter has 12 Godparents.

Family has become a do-it-yourself kit. Or, as the late German sociologist Ulrich Beck put it: “Marriage can be subtracted from sexuality, and that in turn from parenthood; parenthood can be multiplied by divorce; and the whole thing can be divided by living together or apart, and raised to a higher power by the possibility of multiple residences and the ever-present potentiality of taking back decisions.”

Americans are freer than they’ve ever been to choose the life path that suits them—a change that is reflected in our language. When Patricia Greenfield, a scholar at the University of California Los Angeles, analyzed more than 1 million books published in the past two centuries, she found that over time, use of the word “obliged” fell while use of the word “choose” rose. Similarly, instances of “authority,” “obedience,” and “belonging” decreased while mentions of “individual,” “self,” and “unique” became more commonplace.

It’s not just singles who are leading the charge. Even traditionally coupled people are living more independently than they once did. A study comparing marriages in 2000 with those in 1980 found that millennial spouses were less likely to eat together, do chores together, go out for fun together, and have as many mutual friends as did spouses 20 years earlier. Today’s couples often have separate phones, computers, and online accounts. Although their social networks may overlap, they are unique.

This setup may seem unromantic. But as with singlehood, there may be benefits to pursuing a wider-ranging social life.

In their book *Rethinking Friendship*, British sociologists Liz Spencer and Ray Pahl describe an especially intense form of traditional family living they call the “partner-based personal community.” A coupled person’s partner, they write, “is the focal point of the

person’s social world, acting as confidant, provider of emotional and practical support, and constant companion.” Spencer and Pahl have found that, when compared with those who let more people into their inner circles, partner-based couplers have poorer mental health. Other research suggests that people who rely on multiple friends and family members for emotional support (cheering up, celebrating, commiserating) are more satisfied with their lives than people who lean on just one person.

Not everyone I met during my travels had as many enduring relationships or was as happy as Dan and Lucy. Just as there were miserable and lonely and self-absorbed people who lived in 20th-century marriages and nuclear families, there will be miserable and lonely and self-absorbed people who live in 21st-century “families of choice.” What’s compelling about this new model, however, is that it is yielding a society that is arguably more fluid, more interconnected, and more adaptable.

As networked individuals, we have the freedom to design the community we want to live in. And if what we choose isn’t working for us, we can always try something else. ☺

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The Ecologist Who Threw Starfish

Robert Paine showed us the surprising importance of predators

BY SEAN B. CARROLL

EVEN IN 1963, one had to go pretty far to find places in the United States that were not disturbed by people. After a good deal of searching, Robert Paine, a newly appointed assistant professor of zoology at the University of Washington in Seattle, found a great prospect at the far northwestern corner of the lower 48 states.

On a field trip with students to the Pacific Coast, Paine wound up at Mukkaw Bay, at the tip of the Olympic Peninsula. The curved bay's sand and gravel beach faced west into the open ocean, and was dotted with large outcrops. Among the rocks, Paine discovered a thriving community. The tide pools were full of colorful creatures—green anemones, purple sea urchins, pink seaweed, bright red Pacific blood starfish, as well as sponges, limpets, and chitons. Along the rock faces, the low tide exposed bands of small acorn barnacles, and large, stalked goose barnacles, beds of black California mussels, and some very large, purple and orange starfish, called *Pisaster ochraceus*.

“Wow, this is what I have been looking for,” he thought.

The next month, June 1963, he made the four-hour journey back to Mukkaw from Seattle, first crossing Puget Sound by ferry, then driving along the coastline of the Straits of Juan de Fuca, then onto the lands of the Makah Nation, and out to the cove of Mukkaw Bay. At low tide, he scampered onto a rocky outcrop.

With a crowbar in hand and mustering all of the leverage he could with his 6-foot, 6-inch frame, he pried loose every purple or orange starfish on the slab, grabbed them, and hurled them as far as he could out into the bay.

So began one of the most important experiments in the history of ecology.

The 1960s were a time of revolution, but it was not all just sex, drugs, and rock and roll. Inside laboratories across the world, scientists were plumbing the depths of the gene to decipher the genetic code and the molecular rules of life, sparking a revolution that

would gather dozens of Nobel Prizes and ultimately transform medicine.

But largely outside of this spotlight, a few other biologists had started asking some simple, seemingly naïve questions about the wider world: Why is the planet green? Why don't the animals eat all of the food? And what happens when certain animals are removed from a place? These questions led to the discovery that, just as there are molecular rules that regulate the numbers of different kinds of molecules and cells in the body, there are ecological rules that regulate the numbers and kinds of animals and plants in a given place. And these rules may have as much or more to do with our future welfare than all the molecular rules we may ever discover.

Why Is the Planet Green?

Paine's journey to Mukkaw Bay and its starfish was a circuitous one. Born and raised in Cambridge, Massachusetts, Paine's interests in nature were fueled by exploring the New England woods. His first love was bird-watching, with butterflies and salamanders close seconds. Paine was inspired by the writings of prominent naturalists, who opened his eyes to the drama of wildlife. He was as enthralled by intimate accounts of spider behavior as by Jim Corbett's hair-raising tales of tracking down tigers and leopards in rural India, in *Man-Eaters of Kumaon*.

After enrolling at Harvard, and inspired by several famous paleontologists on the faculty, Paine developed an intense new interest in animal fossils. He was so fascinated by the marine animals that lived in the seas more than 400 million years ago that he decided to study geology and paleontology in graduate school at the University of Michigan.

The course requirements entailed rather dry surveys of various animal "ologies"—ichthyology (fishes), herpetology (reptiles and amphibians), and so forth that Paine found very boring. One exception was a course on the natural history of freshwater invertebrates taught by ecologist Fred Smith. Paine appreciated how the professor provoked his students to think.

One memorable spring day, the sort of day when professors don't feel like teaching and students don't want to be inside, Smith told the class, "We are going to stay in this room." He looked outside at a tree that

was just getting its leaves.

"Why is that tree green?" Smith asked, looking out the window.

"Chlorophyll," a student replied, correctly naming the leaf pigment, but Smith was heading down a different path.

"Why isn't all of its greenery eaten?" Smith continued. It was such a simple question, but Smith showed how even such basic things were not known. "There is a host of insects out there. Maybe something is controlling them?" he mused.

At the end of his first year, Smith sensed Paine's unhappiness with geology, and suggested that he consider ecology instead. "Why don't you be my student?" he asked.

It was a major change in direction, and there was a catch. Paine proposed to study some fossil animals from the Devonian period in nearby rocks. Smith said, "No way." Paine had to study living, not extinct creatures. Paine agreed, and Smith became his adviser.

Smith had long been interested in brachiopods or "lamp shells," marine animals with an upper and lower shell, joined at a hinge. Paine knew about the animals because they were abundant in the fossil record, but their present-day ecology was not well known. Paine's first task was to find living forms. Lacking a nearby ocean, Paine made scouting trips to Florida in 1957 and 1958, and found some promising locations. With Smith's approval, he began what he called his "graduate-student sabbatical." In June 1959, he drove back to Florida and began living out of his Volkswagen van. For 11 months he studied the range, habitat, and behavior of one species.

It was the sort of work that provided a solid foundation to a naturalist-in-training, and it would earn Paine his Ph.D. But the filter-feeding brachiopods were not the most dynamic animals. And sifting large amounts of sand for the less than quarter-inch-long creatures was, well, just not very exciting.

As Paine shoveled his way along the Gulf Coast, it was not Florida's brachiopods that captured his imagination. On the Florida panhandle, Paine discovered the Alligator Harbor Marine Laboratory, and was given permission to stay there. At the tip of nearby Alligator Point, he noticed that for a few days each month, the low tide exposed an enormous gathering of large



STAR HURLER

Robert Paine at Mukkaw Bay, on the Olympic Peninsula in Washington, in 1974, and again recently. To understand the role of predatory starfish he hurled them from an area and later returned to assess the sea life without them.

predatory snails, such as the horse conch, some more than a foot long. The mud and sawgrass of Alligator Point was not at all boring, quite the contrary—it was a battlefield.

On top of his thesis work on brachiopods, Paine made a careful study of the snails. He counted eight abundant snail species, and took detailed notes on who ate whom. In this “gastropod eats gastropod” arena, Paine saw that without exception it was always a larger snail devouring a smaller one, but not everything that was smaller. The 11-pound horse conch, for example, dined almost exclusively on other snails, and paid little attention to smaller prey such as the clams that were the main fare for the smaller snails.

While Paine was in Florida watching predators up close, his advisor Smith had kept thinking about those green trees and the roles of predators in nature. Smith was keenly interested in not just the structure of communities, but in the processes that shaped them. He often had bag lunches with two colleagues, Nelson Hairston Sr. and Lawrence Slobodkin, during which they had friendly arguments about major ideas in ecology. All three scientists were interested in the processes that control animal populations, and they debated explanations circulating at the time. One major school of thought was that population size was

controlled by physical conditions such as the weather. Smith, Hairston, and Slobodkin (hereafter dubbed “HSS”) all doubted this idea because, if true, it meant that population sizes fluctuated randomly with the weather. Instead, the trio was convinced that biological processes must control the abundance of species in nature, at least to some degree.

HSS pictured the food chain as subdivided into different levels according to the food each consumed (known as trophic levels). At the bottom were the decomposers that degrade organic debris; above them were the producers, the plants that relied on sunlight, rain, and soil nutrients; the next level were the consumers, the herbivores that ate plants; and above them the predators that ate the herbivores.

The ecological community generally accepted that each level limited the next higher level; that is, populations were positively regulated from the “bottom up.” But Smith and his lunch buddies pondered the observation that seemed at odds with this view: The terrestrial world is green. They knew that herbivores generally do not completely consume all of the vegetation available. Indeed, most plant leaves only show signs of being partially eaten. To HSS, that meant that herbivores were not food-limited, and that something else was limiting herbivore populations. That something, they believed,



RULER OF THE TIDAL ZONE Starfish are opportunistic gourmands that eat barnacles, limpets, snails, and mussels. In this rocky intertidal zone on the Pacific coast, the starfish prey on mussels, which enables other species such as kelp and small animals to occupy the community.

were predators, negatively regulating herbivore populations from the “top-down” in the food chain. While predator-prey relationships had long been studied by ecologists, it was generally thought that the availability of prey regulated predator numbers and not vice-versa. The proposal that predators as a whole acted to regulate prey populations was a radical twist.

To bolster their case, HSS noted instances where herbivore populations had exploded after the removal of predators, such as the Kaibab deer population in Northern Arizona that increased after decimation of local wolf and coyote populations. They assembled their observations and arguments in a paper entitled “Community Structure, Population Control, and Competition” and submitted it to the journal *Ecology* in May 1959.

It was rejected. The article did not see the light of day until the year-end issue of the *American Naturalist* in 1960.

The proposal that predators regulate herbivore populations is now widely known as the “HSS hypothesis” or “Green World Hypothesis.” While HSS declared,

“The logic used is not easily refuted,” their ideas, like most that challenge the status quo, drew a lot of criticism. One legitimate critique was their claims needed testing and more evidence. And that was just what Smith’s former student set out to do on Mukkaw Bay in 1963.

Kick It and See

The HSS hypothesis was essentially a description of the natural world based on observation. Indeed, virtually all of ecology up to the 1960s had been based upon observation. The limitation of such observational biology was that it left itself open to alternative explanations and hypotheses. Paine realized that if he wanted to understand how nature worked—the rules that regulated animal populations—he would have to find situations where he could intervene and break them. In the specific case of the roles of predators, he needed a setting where he could remove predators and see what happened—what would later be described as “kick it and see” ecology. Hence, the starfish-hurling.

Paine coined a new term, “trophic cascade,” to describe the strong ecological effects of a predator like the sea otter.

Twice a month every spring and summer, and once a month in the winter, Paine kept returning to Mukkaw to repeat his starfish-throwing ritual. On a 25-foot long, 6-foot tall stretch of rock, he removed all of the starfish. On an adjacent stretch, he let nature take her course. On each plot, he counted the number and calculated the density of the inhabitants, tracking 15 species in all.

To understand the structure of the Mukkaw food web, Paine paid close attention to what the predators were eating. The starfish has the neat trick of everting its stomach to consume prey. To see what they were feasting upon, Paine turned more than 1,000 starfish over and examined the animals held against their stomachs. He discovered that the starfish was an opportunistic gourmand that ate barnacles, chitons, limpets, snails, and mussels. While the small barnacles were the most numerous prey—the starfish was able to scarf up dozens of the little crustaceans at a time—they were not its primary source of calories. Mussels and chitons were the most important contributors to the starfish diet.

By September, just three months after he began

removing the starfish, Paine could already see that the community was changing. The acorn barnacles had spread out to occupy 60 to 80 percent of the available space. But by June of 1964, a year into the experiment, the acorn barnacles were in turn being crowded out by small, but rapidly growing goose barnacles and mussels. Moreover, four species of algae had largely disappeared, and the two limpet and two chiton species had abandoned the plot. While not preyed upon by the starfish, the anemone and sponges populations had also decreased. However, the population of one small predatory snail, *Thais emarginata*, increased 10- to 20-fold.

Altogether, the removal of the predatory starfish had quickly reduced the diversity of the intertidal community from the original 15 species to eight.

The results of this simple experiment were astonishing. They showed that one predator could control the composition of species in a community through its prey—affecting both animals it ate as well as animals and plants that it did not eat.

As Paine continued the experiment over the next five years, the line of mussels advanced down the rock face by an average of almost 3 feet toward the low tide mark, monopolizing most of the available space and pushing all other species out completely. Paine realized that the starfish exerted their strong effects primarily by keeping the mussels in check. For the animals and algae of the intertidal zone, the important resource was real estate—space on the rocks. The mussels were very strong competitors for that space, and without the starfish, they took over and forced other species out. The predator stabilized the community by *negatively regulating* the population of the competitively dominant species.

Paine's starfish-tossing was strong confirmation of the HSS hypothesis that predators exerted control from the top down. But this was just one experiment with one predator in one spot on the Pacific Coast. If Paine was going to draw any generalities, it was important to test other sites and other predators. The dramatic results of the Mukkaw Bay experiments inspired a flurry of kick-it-and-see experiments.

Paine discovered uninhabited Tatoosh Island when he was out on a salmon-fishing trip. On this small, storm-battered island, several miles up the coast from Mukkaw Bay and about half a mile offshore, Paine found many of the same species clinging to the rocks, including large *Pisaster* starfish. With the permission of the Makah tribe, Paine started tossing them back in the water. Within a few months, the mussels started spreading across the predator-free rocks.

While on sabbatical in New Zealand, Paine investigated another intertidal community at the north end of a beach near Auckland. There, he found a different starfish species called *Stichaster australis* that preyed on the New Zealand green-lipped mussel, the same species exported to restaurants around the world. Over a period of nine months Paine removed all of the starfish from one 400-square-foot area, and left an adjacent, similar plot alone. He saw immediate and striking effects. The treated area quickly began to be dominated by mussels. Six of 20 other species initially present vanished in just eight months; within 15 months the majority of space was occupied solely by the mussels.

To Paine, the predatory starfish of Washington and New Zealand were “keystones” in the structure of

intertidal communities. Just as the stone at the apex of an arch is necessary for the stability of the structure, these apex predators at the top of the food web are critical to the diversity of an ecosystem. Dislodge them, and as Paine showed, the community falls apart. Paine's pioneering experiments, and his coining of the term “keystone species” prompted the search for keystones in other communities, and would lead him to another seminal idea.

Sea Otters and the Cascading Effect

Paine's kick-it-and-see experiments were not limited to manipulating predators. He was interested in understanding the rules that determined the overall make-up of coastal communities. Other prominent inhabitants of the tide pools and shallow waters included a great variety of algae, such as the large brown seaweed known as kelp. But their distribution was patchy—abundant and diverse in some places, nearly absent from others. One of the most prevalent grazers on the algae were sea urchins. Paine and zoologist Robert Vadas set out to find out what affect the urchins had on algal diversity.

To do so, they removed all of the urchins by hand from some pools around Mukkaw Bay, or barred them from areas within Friday Harbor (near Bellingham) with wire cages. They left nearby pools and areas untouched as controls for their experiment. They observed dramatic effects of removing the sea urchins—several species of algae burst forth in the urchin-free zones. The control areas with large urchin populations contained very few algae.

Paine also noticed that such urchin-dominated “barrens” were common in pools around Tatoosh Island. At first glance, the urchin barrens seemed to violate a key assertion of the HSS hypothesis that herbivores tended not to consume all of the vegetation available. But the explanation for why there were such barrens in Pacific waters would soon become clear—in the surprising discovery of another keystone species, an animal that had been removed from Washington's coast long before Paine started tinkering with nature.

Sea otters once ranged from Northern Japan to the Aleutian Islands and along the North American Pacific Coast as far south as Baja California. Coveted for their luxurious fur, the densest of all marine mammals, the

Today, one predator has more influence than any other. And humans will be the ultimate losers if the rules are not understood.

animals were hunted so intensively in the 18th and 19th centuries that by the early 1900s only 2,000 or so animals remained of an original population of 150,000 to 300,000, and the species had disappeared from most of its range, including Washington state. The species gained protected status in 1911 under the terms of an international treaty. After their near-extirmination from the Aleutian Islands, the animals rebounded to high densities in some locations.

In 1971, Paine was offered a trip to one of those places—Amchitka Island, a treeless island in the western part of the Aleutians. Some students were working on the kelp communities there and Paine flew out to offer his advice. Jim Estes, a student from the University of Arizona, met with Paine and described his research plans. Estes was interested in sea otters, but he was not an ecologist. He explained to Paine that he was thinking about studying how the kelp forests supported the thriving sea otter populations.

“Jim, you are asking the wrong questions,” Paine told him. “You want to look at the three trophic levels:

sea otters eat urchins, sea urchins eat kelp.”

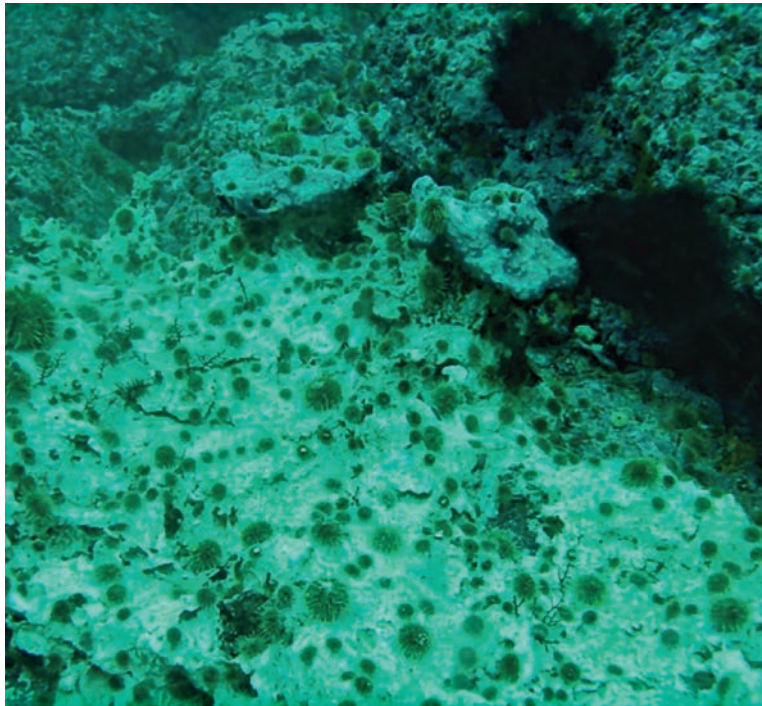
Estes had only seen Amchitka with its abundant otters and kelp forests. He quickly realized the opportunity to compare islands with and without otters. With fellow student John Palmisano, Estes traveled to Shemya Island, a 6-square-mile chunk of rock 200 miles to the west without otters. Their first hint that something was very different was when they walked down to the beach and saw huge sea urchin carcasses. But the real shock came when Estes dove under the water for the first time.

“The most dramatic moment of learning in my life happened in less than a second. And that was sticking my head in the water at Shemya Island,” Estes recalled. “We were in this sea of just sea urchins. And there was no kelp anywhere. Any fool would have been able to figure out what was going on.”

Estes and Palmisano saw other striking differences between the two communities around each island: Colorful rockfish, harbor seals, and bald eagles were abundant around Amchitka, but not around

THE IMPORTANCE OF BEING A SEA OTTER

(Top) In the presence of sea otters, sea urchin populations are controlled, which allows for kelp forests to grow. (Bottom) In the absence of sea otters, urchins proliferate, forming “barrens” that lack kelp.



otter-less Shemya. They proposed that the vast differences between the two communities were driven by sea otters, which were voracious predators of sea urchins. They suggested that sea otters were keystone species whose negative regulation of sea urchin populations was key to the structure and diversity of the coastal marine community.

Estes' and Palmisano's observations suggested that the reintroduction of sea otters would lead to a dramatic restructuring of coastal ecosystems. Shortly after their pioneering study, the opportunity arose to test the impact of sea otters as they spread along the Alaskan coast and re-colonized various communities. In 1975, sea otters were absent from Deer Harbor in southeast Alaska. But by 1978, the animals had established themselves there, sea urchins were small and scarce, the sea bottom was littered with their remains, and tall, dense stands of kelp had sprung up.

The presence of the otters had suppressed the urchins, which had otherwise suppressed the growth of kelp. This kind of double negative logic is widespread in biology. In this instance, otters "induce" the growth of kelp by repressing the population of sea urchins. The discovery of the regulation of kelp forest by sea otter predation on herbivorous urchins was very strong support for the HSS hypothesis and for Paine's keystone species concept.

In ecological terms, the predatory sea otters have a cascading effect on multiple trophic levels below them. Paine coined a new term to describe the strong, top-down effects that he and others had discovered upon the removal or reintroduction of species: He called them trophic cascades.

The discovery of trophic cascades was exciting. The many indirect effects caused by the presence or absence of predators (starfish, sea otters) were surprising because they revealed previously unsuspected, indeed unimagined, connections among creatures. Who would have thought that the growth of kelp forests depended on the presence of sea otters? These dramatic and unexpected effects raised the possibility that, unbeknownst to biologists, trophic cascades were operating elsewhere to shape other kinds of communities. And if they were, then keystone species and trophic cascades might be general features of ecosystems—rules of regulation that governed the numbers

and kinds of creatures in a community.

Indeed, trophic cascades have been discovered across the globe, where keystone predators such as wolves, lions, sharks, coyotes, starfish, and spiders shape communities. And because of their newly appreciated regulatory roles, the loss of large predators over the past century has Estes, Paine, and many other biologists deeply concerned.

Today, of course, one predator has more influence than any other. We have created the extraordinary ecological situation where we are the top predator and the top consumer in all habitats. "Humans are certainly the overdominant keystones and will be the ultimate losers if the rules are not understood and global ecosystems continue to deteriorate," Paine says. The only species that can regulate us is us. ☺

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Excerpted from *The Serengeti Rules: The Quest to Discover How Life Works And Why It Matters* by Sean B. Carroll. Copyright © 2016 by Princeton University Press. Reprinted by permission.

Why Are Wheelchairs More Stigmatized Than Glasses?

A design professor argues that improving the lives of disabled people is more than an engineering project

BY ANKUR PALIWAL

IN 2010, SARA HENDREN began a guerilla street art campaign. The assistant professor of design teamed with philosophy professor Brian Glenney to change the commonly accepted symbol for disability, called the International Symbol of Access. It shows a figure sitting in a wheelchair, on a blue background.

Hendren and Glenney thought the symbol made the chair look more important and visible than the person sitting on it. So they came up with their own version, in which the figure was leaning forward, elbows out, as if about to push off in some direction. The pair went around pasting a transparent sticker featuring their redesign over the old symbol in public places, so that people could see both old and new. Although the new symbol has not been formally adopted, it is being used by several educational institutions, private companies, and hospitals, and is part of the permanent collection at the Museum of Modern Art in New York City.

Hendren studied at Harvard's Graduate School of Design, and, together with her students at Olin College in Massachusetts, makes assistive and adaptive technology for the disabled. But she is also interested in changing the cultural understanding of disability, pointing out that we are all on a spectrum of varying ability. "My projects awaken hidden or suppressed politics about ability, health, interdependence, and bodily normativity," Hendren explains.

Nautilus caught up with Hendren this January.

How did you get interested in disability?

In my formative years, I thought of myself as somebody who was exclusively about books and words, and images and color, and metaphor and poetry, and all those kinds of things. I went to college in a little religious school outside of Chicago. I studied visual arts, painting, and drawing in Boston, and worked in



ACTION FIGURE Sara Hendren and Brian Glenney designed a more active version of the standard International Symbol of Access, then pasted it over the usual sign in public places.

education research. Then I started a Ph.D. in intellectual and cultural history at UCLA in 1999, got dissatisfied with history writing and history scholarship as it was performed then, and left it in 2003-04. Then, I did a bunch of freelance, stitched together a bunch of jobs, went back to painting, then figured out that public design language could also be critical and expressive. Then about 10 years ago, my son, my oldest of three children was born. He has Down syndrome. The politics of disability coupled with making things in design, and my training in cultural and intellectual history, all kind of came together in the decade following his birth. I went back to design school at Harvard in 2011, and joined Olin College in 2014.

Did your son's condition change your views on the subject?

People who had been invisible to me were suddenly

visible. My understanding of autism really morphed and changed. Really it's about being a parent of somebody who is vulnerable in the existing culture and whose genetic mutation stands in for his entire identity. Once people know that about him, that's kind of all they can see. So, now my life is full of people who are blind, who are deaf, autistic, and use wheelchairs, in ways I could never have imagined 10 years ago. His birth also woke me up to the material culture of artifacts and prosthetics and technologies. From the little braces he wore, to the glasses he got before he was a year old, to the therapeutic toys. I started to think about crutches and wheelchairs and hearing aids. What is the language of these things? What is their history and genealogy? A lot of those artifacts are medical, and from that association we get that patients are deformed. We see them as kind of medically broken. So, we have these tools to fix them and make them better.

People act like engineering is going to rescue these bodies. *Then what?*



What is disability for you?

I think disability is partly a medical identity, and partly a political identity. What our culture needs to hear, though, is how disability is a political identity, because we live in a time where disability exclusively exists on the body. Your legs don't work, so therefore you are disabled. Actually, you are not disabled by your legs not walking, you are disabled by infrastructure and cities and towns that are built with stairs and without ramps. We are all aggregates of things that we do really well and things that we do really poorly. Peaks and valleys in our abilities and capacities. Maybe the things that we do well are the things that culture wants, and what we don't do well are the things that culture doesn't want us to do.

Do we misunderstand technology that assists the disabled?

When we talk about design technology in the context of disability, we call it assistive technology. But all technology is assistive. Curb cuts were thought to be an extreme user case for wheelchairs. But it turns out that they also make passage through a city easy for a lot of people, like children who are learning to walk, and people who are pushing strollers. Look at the use of elevators. People who are with young children, people who are injured, people who are with older adults who have trouble walking all use them. The Oxo brand of kitchen tools was designed by a man whose wife had arthritis in her hands. He made a fortune by figuring out that a lot of people need some of the same tools that she did. Disabilities occupy the continuum of normal human variation, and technology can do something similar. It's not that there is technology for normal people, and there is assistive technology for not-normal people.

How can the stigma surrounding technology for the disabled be addressed?

There is no stigma attached to your eyes having less than 20-20 vision. People who wear eyeglasses do not feel any shame in walking out of the door. But studies show there is plenty of stigma attached to hearing aids. I want people to see technologies doing lots of things for lots of people. There are plenty of design speculations, like a hearing aid could not only control the volume of what you are hearing but also how much you are hearing of one thing in particular. How much you are hearing what is in front of you, while tuning out the rest. That can be quite useful in a noisy restaurant. I think there are lots of other opportunities like this to de-stigmatize.

What do you make of the wide publicity given to high-end gear for disabled people, like exoskeletons?

I love these exoskeletons. I am astonished at them as a feat of engineering and think we should celebrate them and support them. I also think that they monopolize the headlines about disability, about prosthetics, and about the promise of technology. We have 100 other kinds of stories about the ways people are living their lives. Lives that are worth living with artifacts and gears but also with systems, jobs, and supports that comes from lots of places. Some of them are low-tech, some of them are systems-scale, and some of them are architectural. A lot of them are hidden from you. The director of the Adaptive Design Association in New York City just won a MacArthur “Genius” award. They have been building adaptive furniture out of triple-walled cardboard for pennies, for decades, and they do it for free. Jaipur Foot in India is producing recycled rubber limbs. There is daily living advice on websites targeted for people living with muscular dystrophy. Ways to button a shirt on your own, ways to hold a fork in a steady manner. There are white canes. White canes are a smart technology. They have resisted many new market entrants. People who are blind find them incredibly elegant and useful tools. But they do not make newsworthy headlines.

Is cheap, scalable technology a necessity?

History shows that the availability of technology doesn't actually make a more equitable world. In this

country, after 25 years of working for rights for people with disabilities, we are still seeing high unemployment rates for the disabled. Look at what happens even in the best inclusive schooling situations. Disabled students who age out of the public school system, their prospects just tank. And this is the richest country in the world, with all kinds of assistive and adaptive technology products available. So you will never convince me that just the sheer production of products that can be scaled cheaply is going to change the way people think about people who have disabilities. You need people to change their minds. So, I am an unabashed culture producer. I think, does democracy come when the next five great products come to the market? History shows that is not the case. History shows that people change their minds based on a lot of things. Look at the way gay rights have been transformed in this country. Sitcoms starting in the '90s had openly gay characters that went out on national networks, like *Ellen*. It would have been unheard of more than 25 years ago. So, I think there is a lot of tech-saviorism in the world around disability. People act like engineering is going to rescue these bodies. *Then* what? Are they going to get better jobs, or suddenly get the respect or the dignity that they are asking for? I strongly feel that engineering does some good things—and cultural forms and stories, objects and artifacts, symbols and metaphors also do things to change the world. 🌀

ANKUR PALIWAL is a journalist who writes on science, health, and the environment. He is currently based in New York.

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IF RULES ONLY EXIST to be broken, then so do boundaries. After all, a boundary is just a rule in space. And there are no absolute boundaries. Why would there be? The cell membrane needs to keep out biological riffraff, for sure, but also to ingest and excrete. Academic disciplines stultify when their borders become hermetic. Human empathy is strengthened, not weakened, by strong personal boundaries.

Boundaries end up facilitating exchanges as much as blocking them, and some of the most productive activities happen in their vicinity. A concept as relevant to us today as ever.

Welcome to “Boundaries.”

—MS

“Eating spicy food has come to be regarded as an indication of such personal characteristics as courage, valor, and endurance, all essential for a potential revolutionary.”

ANDREW LEONARD

“Why Revolutionaries Love Spicy Food” p.112

Boundaries

BOTH SIDES OF THE STORY

Parasites Are Us

How biological invaders challenge our idea of self and other

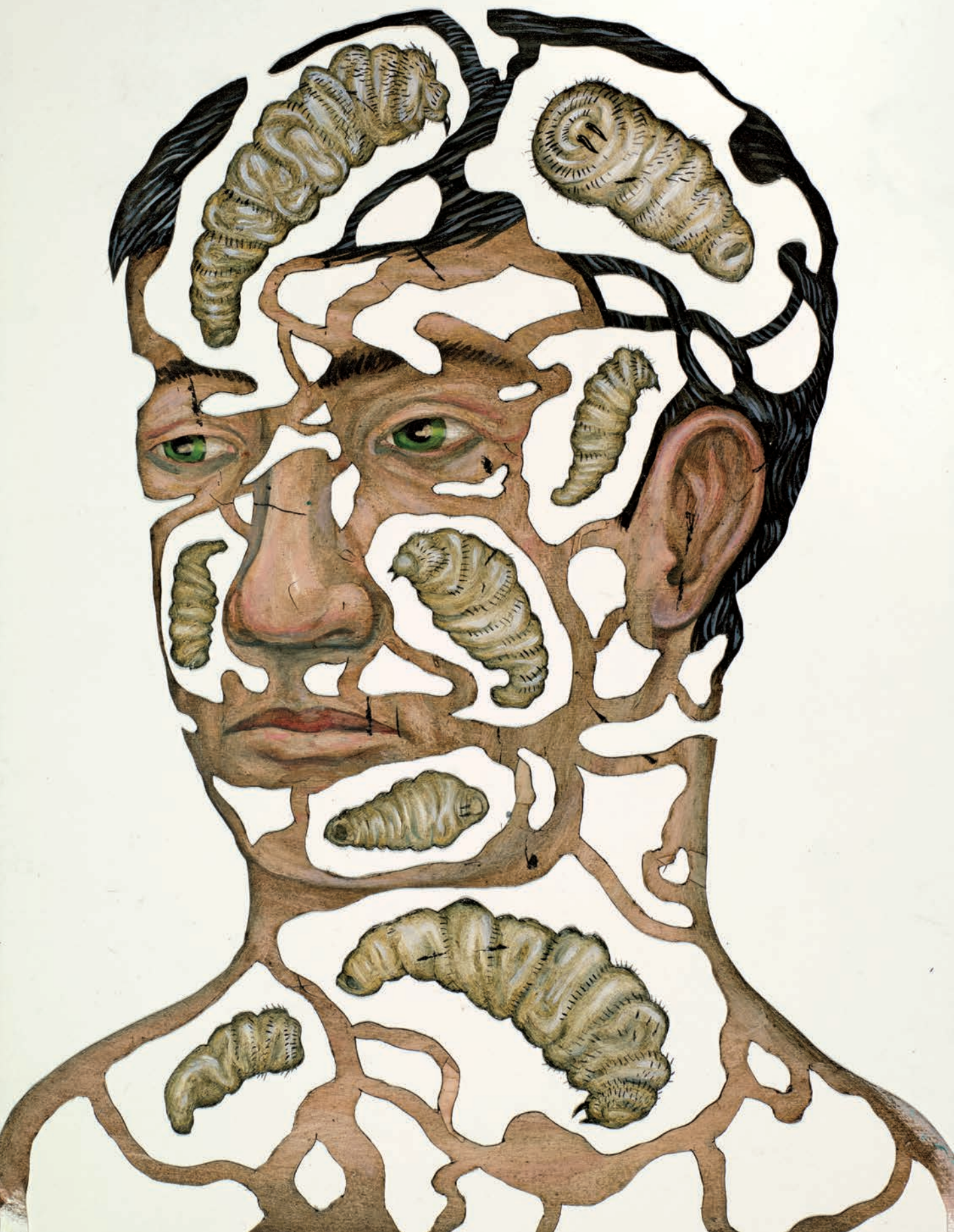
BY ROBERT V. LEVINE

JERRY COYNE IS AN EVOLUTIONARY BIOLOGIST at the University of Chicago. His research on population and evolutionary genetics has been widely published in professional and trade journals and his 2009 book, *Why Evolution Is True*, established him as a leading force in the study of evolution. Jerry is also an internationally famous defender of evolution against proponents of creationism and intelligent design. He is a highly respected scientist.

This, however, is a more personal story about Coyne. It goes back to 1973, when he was a mere 24-year-old graduate student at Harvard. As he moved through the program, Coyne was becoming well versed in the intellectual tools of his trade—genetics, evolutionary logic, research methods, and the like. But when it came to real-life contact with nature, his experience was pretty much “limited to unexciting fruit flies crawling feebly around food-filled glass tubes.” He was even more frustrated working at Harvard’s Museum of Comparative Zoology. This was the same museum that was founded

by the great Swiss naturalist Louis Agassiz, under the guiding philosophy to “study nature, not books.” But, aside from fruit flies in a sterile lab, the only nature Coyne was seeing were stuffed mammals in a display case on his way to the Pepsi machine. When given the opportunity to take a summer field course in tropical ecology in Costa Rica, Coyne didn’t hesitate. He never imagined how close to nature he would get.

Toward the end of his stay in Costa Rica, Coyne was walking through the forest when he heard a mosquito getting closer and closer, and finally, it bit him on the head. “Not too far from the crown and I scratched it,” he recalled. But, unlike a usual mosquito bite, this one didn’t want to go away. When, after a few days, the bump had grown to the size of a pea, Coyne consulted with a fellow student who was an entomologist. His friend got up on a bunk bed. “She looked at my head and pulled the hairs back, and she said, ‘Oh my God, there is something moving in there,’” Coyne said. She spotted what appeared to be a tiny hose protruding



from the mosquito bite. Then she realized the hose was wiggling. It was a breathing tube, like a little straw. That meant there was something live on the other side of the tube. The two biologists knew right away it had to be a maggot.

The maggot turned out to be a botfly, a hairy insect that lives in tropical regions in Central and South America. It has a biologically ingenious and, most humans would think, rather disgusting strategy for ensuring the survival of its young. The process works something like this: After a pregnant female lays her eggs, she flies in the air and grabs on to a mosquito. Then, in midflight, she glues her eggs to the mosquito's



UNWELCOME GUEST On top, the bot fly. On the bottom, the human infestation.

wings. The mother leaves. The mosquito, who probably has no idea anything has happened, continues doing what it always does, which is to fly around until it finds a warm mammal and sucks its blood. When the mosquito finds its prey, the mammal's heat triggers the eggs to hatch. One of the newly hatched larva—a tiny maggot—burrows its way inside the mammal through the mosquito bite, sets up a little home, and sticks its breathing tube out the opening. Botflies feed on the mammal's tissue until, after about six weeks, they've grown big enough to survive on their own, and then they exit through the hole in their host's skin. Coyne happened to be the host this time around.

He soon learned removing the botfly wouldn't be easy. The best solution would have been to cut it out with a sterile scalpel. But finding a good surgeon was a problem in a remote tropical forest. "There was a woman in the course who had botflies in her butt," Coyne recalled to me. She found someone to surgically remove them, but it wasn't a pretty scene. "This guy took her in a back room and started cutting them out with a Swiss army knife. I remember we could all hear her screaming when this was happening. I found myself thinking, 'Do I really want to go through this?'"

He was tempted to try yanking the maggot out by pulling on its protruding spiracle. But Coyne knew that was probably the worst thing he could do. "Like all marvels of evolution, the botfly maggot has devices to keep you from pulling it out because it makes its living in your body," he explained. "So it has a pair of hooks on the anal end, the other end, that are dug into your flesh so if you try to pull the thing out it just digs in and you'll break it in two. That's the thing you want to avoid because it can cause a serious infection."

The most common treatment where Coyne was living was known as the "meat cure." He was told to strap a slab of meat—a steak, maybe—to his head. This cuts off the maggot's air supply, and the maggot, thinking the steak is part of Coyne's flesh, burrows into it searching for air. Once the maggot gets far enough, he would just have to pull off the steak with the worm in it. It made sense, but Coyne respectfully declined. "The idea of toiling in the tropical heat every day with a T-bone strapped to my head was not something that I wanted to do."

Meanwhile, the symptoms were getting worse. "It's

The maggot raises difficult questions about the division between self and non-self.

a terrible itch and from time to time it would like move or twitch and you would feel this sort of sharp pain in your skull or you could feel it grinding up against it,” Coyne recalled. “And when I went swimming or took a shower, it would sort of freak out because its airhole would be cut off, then it would really go nuts. You know, make a lot of pain. So I tried to avoid getting my head under water.”

The lump was also getting noticeably bigger, and Coyne was all too aware why. “It was eating my muscles and tissues and scalp,” he said. “It’s turning human flesh into fly flesh.” Like any normal person, Coyne was initially disgusted. “I freaked out completely,” he said. But then the scientist in him took over. This was biology in its elegance. “You know, when you really think about it, it’s amazing how an animal can take human flesh and turn it, using its own genes, into a fly.” How astonishing, he thought, that “something was transforming my molecules into their own. The idea that a fly could convert you into a fly. That really amazed me.” And the fact that this fly, by eating him, was in a very literal sense becoming him? “That’s the part that made me like it,” he says.

COYNE RETURNED TO BOSTON a few weeks later and went straight to the Harvard health clinic. “Nobody had

ever seen anything like this at Harvard,” Coyne recalled. Within minutes he was surrounded by about 20 doctors. “I had to explain it to them. They were all poking and prodding but none of them seemed to know what to do with this. So I figured it wasn’t worth it to put myself in the hands of people who’d never treated anything like this before and were more likely to screw it up. The botfly wasn’t that painful and I knew it was going to come out on its own after a while,” Coyne told me. He decided to just try to enjoy and marvel at what was happening inside him as much as he could.

“This behavior might seem weird to a lay person,” he said, but “I make my living on flies. I work with fruit flies. I’m a geneticist, and here is a fly making its living on me.” Coyne was intrigued to find himself inside a food chain instead of on his usual perch as a consumer at its end. The botfly was fattening up on Coyne, and Coyne was becoming increasingly fond of the botfly. “I was getting more and more curious when it would come out. I didn’t want to kill it.”

The botfly kept growing. Within a couple of weeks it had become the size of an egg, then a quail egg. Coyne started wearing a baseball cap. One night he was at a Red Sox game at Fenway Park with his friend Sarah Rogerson. “Every once in a while I would rub my head, throughout the whole gestation of this thing, just to

check on it. During the game, when I rubbed my head I felt something coming out of the lump. “Jerry kept saying, ‘Oh my gosh. Oh my gosh. It’s coming out. I can feel it,’ ” said Sarah. “A foul ball came up where were sitting and it hit one of those wooden seats in Fenway and we narrowly escaped getting hit because we really weren’t paying much attention to the game at all.”

It didn’t come out right away. Sarah and Coyne went back to his apartment. He kept checking to feel the lump. Sometime later in the evening, he reached up and said, “It’s gone. It’s out.” He told Sarah they had to find it. “I turned on the light and there it was on the pillow and it was horrifying,” Coyne said. It was a fat, white worm, about an inch and a half long. It was bulbous on one end and tapered to a little tail on the other. And it had little black teeth. Forever the evolutionary biologist, Coyne was struck by the painlessness of the exit. “You know, it’s painful when it’s in there but when it comes out it does so very painlessly.” This, he realized, was another evolutionary invention. “If the worm did it painfully, then the horse or the monkey or whoever it is infecting would just slap it and kill it.”

But mostly he wanted to save the fly. He looked at his baby on the pillow and decided to try to rear it into an adult fly. “I’d prepared a jar of sterile sand and I took the worm and dropped it in the sand and put on a top with an airhole,” Coyne said. “But unfortunately it died.” Looking back, he said that he was sorry he “didn’t just put it into a jar of alcohol to preserve it.” Coyne felt extremely sad afterward. “You know in the temperate zone in Boston the botfly is not going to make it. It just can’t live and so it was doomed from the start. I wanted to see it complete its life cycle but unfortunately it didn’t quite make it. I did the best I could with what I knew.” He felt the loss. “It added richness into my life, it really did. People still get completely horrified when I tell them the story even though to me it’s sort of a nice story.” And, he told me, “It was my botfly.”

JERRY COYNE’S MAGGOT was clearly an intruder—a hit-and-run thief who conned its way into Coyne’s body, stole what it needed, and, when Coyne was no longer useful, went off to live an independent life. It was a parasite. But the maggot also raises difficult questions about the division between self and non-self.

The maggot was never invited into Coyne’s head. For those weeks it lived there, however, wasn’t the maggot in many ways literally Coyne? After all, other than the tip of its breathing tube, the maggot existed completely inside his body. Besides, the maggot was flesh-and-blood Coyne in the most literal sense: Almost the entirety of its physical bulk consisted of Coyne’s tissue. And then there was the boundary. To protect itself from infection, Coyne’s body had encapsulated the maggot in a little pocket under the surface of the skin. The pocket became the maggot’s home. The same physical boundary separating Coyne from the “lifeless” air outside himself—his epidermis—was now also separating the maggot from its own outside. So was the pocket more Jerry Coyne or maggot?

The psychologist in me loves watching the quirky ways people draw their personal boundaries. It’s interesting how emotional we get when we believe somebody or something has crossed into our personal territory. But, the fact is, psychological feelings are trivial in cases like this. It didn’t make much difference whether Coyne thought of his botfly as himself or his guest. Their relationship was a matter of life or death—certainly for the botfly and potentially for Coyne. Biologically speaking, all that mattered was that Coyne let the botfly survive.

And biologically is where the line between self and other is most critical. It is so important that we have, over the course of evolution, developed what is arguably the most complex biological system (other than perhaps our nervous system) in any living vertebrate to do the job: our immune system. The immune system is our border patrol. It consists of a roving bag of cells that patrol our body 24/7. Its job is to identify trespassers, assess their danger, and eliminate them if necessary. These watchguards are exquisitely tuned to distinguishing the fingerprints of intruders from their own body’s cells and molecules. One of their specialties is spotting parasites.

Coyne’s immune system had tracked the invader, labeled it as non-self, probably assessed that it was a temporary visitor who posed a limited danger, and decided it would be safer to contain rather than kill or remove it. Antibodies were dispatched to seal the maggot securely in a little pocket. All Coyne did was decide to let biology run its course.

THE ANATOMY OF THE SELF sounds simple. There is my body and then there is everything foreign to my body. Not so, it turns out. When it comes to the self-other boundary, the anatomical lines can be as messy and confusing as the ones we draw in our minds. Perhaps even more so.

Consider, for example, what are known as “molecular mimics,” a type of parasite whose very specialty is confusing self and other. “These parasites are really crafty,” says parasitologist Paul Crosbie. “They get inside the host’s body and stick some of the host’s protein on the outside of their own cells.” It’s how they survive. Some mimics even raid the macrophages, our combat troops, the very antibody cells whose job is to kill and devour parasites. The parasites then pull off pieces of the macrophages and stick them on their own surface as camouflage. Other parasites have learned to mutate their appearance to match that of the host’s cells. As Crosbie says, these molecular mimics fool the host’s immune system into thinking, “It’s okay, that’s one of my cells.” These sneaks, these miniature secret agents, are the biological world’s masters of disguise.

Don’t go looking for the serenity of Mother Nature

in the world of microbiology. This is a savage little jungle full of con men and killers. When Darwin argued that nature was a bad place to prove that God had a benevolent design, he pointed to parasites as primary evidence. “It is derogatory that the Creator of countless systems of worlds should have created each of the myriads of creeping parasites,” he wrote.

If you’re looking for a lesson in con artistry, may I recommend a group of mimics that operate as intracellular invaders? These trespassers don’t just disguise themselves as host cells. They sneak right inside the actual cells and wear the host’s membrane as their disguise. The immune system, which is a network of cells itself, only interacts with the surface of other cells. Antibodies, which are part of the immune system, don’t cross cell membranes. So once an assailant manages to get inside a cell, it’s home free. It enters a safe haven where it can grow, reproduce, and, in some cases, plan its next attack.

Species of *Plasmodium*, the protozoa that cause malaria, are a good example of these parasites. They enter the host’s body through a mosquito bite and immediately look for a liver cell to get into. Penetrating



Parasites in Paradise

“The sweller”

What: Thread-like nematode called the filarial worm

Where: Tropical and subtropical areas of Southeast Asia, South America, Africa.

How: Larvae inside mosquitos are transmitted via bite to human flesh, where they hatch in lymphatic and subcutaneous tissues.

Outcome: Elephantiasis, or gross enlargement, of the limbs and genitals. Affects 170 million people worldwide.

“The eye worm”

What: Loa loa, a filarial nematode, or roundworm

Where: Native to Ethiopia, inhabits rainforests in West Africa and equatorial Sudan. Loa loa have also been found in India.

How: Infected flies bite humans, transferring larvae onto our skin, which then travel into our bloodstream and subcutaneous tissue via the bite wound. They have been found in spinal fluid, urine, peripheral blood, and lungs.

Outcome: Most infected people don't show symptoms. Some may have itchy, non-painful swellings across the body, muscle and joint pain, and fatigue. Occasionally the loa loa enters the eyeball—when this happens, it can cause severe pain, inflammation, and blindness.

“The pee climber”

What: *Vandellia cirrhosa*, a small, thin, translucent and sharp-toothed catfish.

Where: Exclusively in the upper Amazon River and Orinoco River basins in Northern South America. Usually buried in riverbeds, emerging only to feed or mate.

How: Numerous people report instances of *Vandellia cirrhosa* climbing up their urethras after they urinated in rivers, though no doctors have been able to corroborate this.

Outcome: The experience is painful, but short-lived, as the fish tend to die pretty quickly after entering our bodies.

the cell membrane is a formidable task, but the parasites come well-armed for their invasion. Their heads contain a ring of chambers that operate like the barrel of a revolver. When the parasites find a liver cell, they shoot out a blitz of molecules that opens a hole in the cell membrane. These protozoa can't swim, but they are equipped with little hooks that they use to grab the sides of the hole and pull themselves through. As they're doing this, the chambers on their heads shoot off another volley of molecules that clump into a protective shroud around the parasites, giving them cover as they work their way inside. When the parasites are completely in, the host cell's resilient meshwork conveniently—for the parasites, that is—seals the hole shut. The entire operation takes about 15 seconds. It is a breathtaking military operation.

Once inside the cell, the parasites start multiplying—eventually producing 40,000 or so offspring, called merozoites. The merozoites then spill out of the liver into the host's bloodstream to begin doing serious damage. But they face a problem: How can they escape the liver cell without getting killed by antibodies? The solution is a disguise. The parasite pulls off the membrane of the infected cell with its little claws and wraps the membrane around itself. Safely disguised as a wandering liver cell, the parasite can wander through the host's bloodstream to find new targets. Imagine this. It's like a B-movie prison break where the escapee mugs a guard and steals his uniform to make his getaway. When the parasites cut loose, however, they steal the guard's entire skin.

In the bloodstream, the protozoa pick out a healthy red blood cell to attack. Their military forces fire off another 15-second barrage of molecules as the parasite claws its way into its new home. Once safely inside, they strip off the liver cell costume and comfortably construct their lethal malaria factory. They begin drinking up the hemoglobin that fills the cell and, fortified with this precious nutrition, rapidly multiply. The growing horde of parasites eventually consumes the entire contents of the red blood cell, which turns into nothing more than a bundle of parasites surrounded by the original cell membrane. When there is no more hemoglobin to drink, the parasites, wrapped in the host's membrane, move through the bloodstream until they find another healthy blood cell to invade. The

In place of a tongue, you see a slimy, multi-legged creature.

process continues from one red blood cell to another, accelerating its pace as the number of parasites exponentially increases at each new stop. Blood cells eventually become infected en masse, and the host falls ill with malaria.

OUR IMMUNE SYSTEM is supposed to be our foremost judge and jury for deciphering what is us and what is outsider. This remarkably complex and sophisticated biological system has been honed over the course of evolution to ensure that we and our species endure. It's a Darwinian masterpiece, homeland security at its finest. If this biological system is so easily misled, is it any wonder we get confused about personal boundaries on the far more subjective level of social behavior?

One might argue that mimics like the parasites that cause malaria are just a band of thieves. Their only interest in our bodies is to steal what they can use. Molecular mimics are simply more sophisticated at being sneaky. Just because they live inside our skin doesn't mean they are now us. This argument gets shakier when the parasite lives inside our actual cells but, still, one might say, a bloodsucker is a bloodsucker.

What, however, if the visitors didn't simply destroy you but fundamentally changed you? Parasites like those that cause malaria are akin to irresponsible hotel

guests who could care less about trashing their suite. But there are other intracellular invaders who move in with the full intention of staying for the long run. These visitors act more like home buyers. Like most new buyers, they like to personalize the new place to suit their needs. There are, in fact, plenty of parasites like these who completely renovate their new quarters. For example, the larva of the parasite that causes trichinosis, a type of roundworm infection caused by eating raw or undercooked pork or wild game, move inside the host's cell and, over the next three weeks, first demolish and then reconstruct almost its entire interior: The trichina tear down existing filaments. They even rebuild the roads in and out by modifying the capillaries that control the blood flow to the cell. And the final takeover: They grow additional nuclei. They actually grow new nuclei. The host's tissue is just a pile of lumber as far as these architects are concerned. The trichina don't just hide inside the host. They transform the host's insides.

MY OWN NOMINATION for the weirdest biological crossover is *Cymothoa exigua*, also known as "the tongue-eating louse." This frightening parasite destroys an entire organ in its host and then replaces it with itself. It invades the mouth of a fish, devours the

fish's tongue and then squats down and neatly positions itself where the tongue was, attaching itself to the tongue's exposed muscles. The new tongue—the louse—does everything the old one did. It feeds its host just as in the preinvasion days, gripping and eating prey like a normal tongue. So, which is the host and which is the guest?

The louse lives off the fish's blood and other fluids. It's—trust me—beyond nauseating to look at. When the fish opens its mouth, in place of a tongue you see a slimy, multilegged creature, its beady eyes staring straight at you, its creepy claws reaching out to grab you or anything else that looks like food. But ugly as it may look, the louse doesn't appear to cause any significant damage to its host. In fact, it keeps the fish alive.

Imagine (apologies for the image) this hijacked fish were you. I'm sure you'd agree that the tongue you were born with is part of your self. But if a tongue-eating parasite moved in, you'd be acutely aware there was a foreign creature living in your mouth. Why, though, should you consider the parasite-tongue to be any less a part of yourself than your original tongue used to be? Is it because your new tongue once lived outside you, or that it has its own genes? Functionally, after all, it's the same arrangement as before: Both your old and new tongues take in food that keeps you alive, which in turn keeps your tongue alive. What if you had a disease that required your original tongue to be surgically removed? Once it was outside your body, lying pathetically across the room on a table, would you still consider it part of you? Probably not, or maybe you would say it used to be part of you. What if the doctors now fixed the tongue and sewed it successfully back in place? You would probably say it is part of you again, wouldn't you? So why is the parasite tongue forever an outsider? Just because it happens to have legs and eyes?

AT WHAT POINT do self and non-self merge? What if your own cells were built by an outsider and customized to house that outsider—who would be the tenant and who would be the landlord? Who makes that call? Richard Feynman once said about quantum mechanics, “If you think you understand quantum theory, you don't understand quantum theory” If you're not, by now, as confused as I am by what biology teaches us about the notion of a self, I offer one more organism:

The mitochondrion.

Parasites are predators. It's a one-sided relationship whereby the parasite wins and the host loses. At first glance, the tongue-eating louse fits this definition. After all, the little critter invades its victim and bites off its tongue. But, soon after, the louse and its host enter into a remarkable collaboration, what biologists refer to as a mutualistic relationship. Unlike Jerry Coyne's parasite, the louse is there to stay. It had better, because separation would spell starvation for both parties. Mutualism—give-and-take relationships with outside organisms—are equally essential to human survival. Every one of our cells is a microcommunity, each populated by multitudes of hard-working organelles with their own DNA. Without their work, we wouldn't last a second. Perhaps the best example of these collaborators are the mitochondria.

Mitochondria are the tiny organelles that generate the ATP molecules that provide the cell with energy. The mitochondria are the cell's power plant. There are lots of them, anywhere from a few hundred in cells that don't use much energy to thousands in energy hogs like the cells in our liver, muscles, and brain. It is mutualism at its best. Our life depends on them. They in turn are provided with a safe haven and a steady source of nutrients. The two of us exist as one. Or so it seems.

The mitochondria are so ubiquitous and embedded in our cells' functioning that it's easy to forget they're not technically us. Biologically speaking, the mitochondria are independent organisms. Eons before the formation of complex organisms like our own, they foraged through nature as free-living bacteria. Nowadays the mitochondria live a more domesticated life, commingling safely within the comfort of our cells. But they remain, in the last analysis, not really us: The mitochondria are the only organelles in animal cells that carry their own genetic material, their own DNA (mDNA). Mitochondria can grow, replicate, divide, and fuse independently of the cell surrounding them. And our own cells are incapable of manufacturing the mitochondria. Sure, they work for our welfare and we work for theirs, but where it counts—the perpetuation of one's DNA—they are autonomous agents. “They are much less closely related to me than to each other and to the free-living bacteria under the hill,” observes the biologist Lewis Thomas. “There they are, moving

about in my cytoplasm, breathing for my own flesh, but strangers.” The mitochondria are, by definition, others.

Sort of, that is. “I was raised in the belief that these (mitochondria) were obscure little engines inside my cells, owned and operated by me or my cellular delegates, private, sub-microscopic bits of my intelligent flesh,” Thomas remarks. But, as he learned more about these organelles, when he understood just how much claim they had to their own individuality, he was forced to alter his view of his own self: “Looked at this way, I could be taken for a very large, motile colony of respiring bacteria, operating a complex system of nuclei, microtubules, and neurons for the pleasure and sustenance of their families.”

Organisms living within organisms are nothing special in the world of microbiology. If you look inside many house plants, for example, you’ll find a little insect called a mealybug carrying out a life of its own. Look inside the mealybug and you’ll find collaborations of bacteria living their own lives. And inside these bacteria are smaller, separate bacteria. And there are plenty of other outsiders. The mitochondria, like the mealybugs, mock the notion of a self. Squint into a microscope, and these organelles within organelles look like independent creatures, each going about its own work. Step back, however, and the mitochondria appear to simply be one of many elements that compose the single complex unit we call a cell.

Are the mitochondria us or them? It doesn’t much matter how we answer this question. The fact is there are genetically independent organisms living, seamlessly enmeshed, throughout our bodies. Selves within selves. We’re like those Russian matryoshka dolls that open to reveal a succession of progressively smaller dolls inside. There are the little mitochondria dolls inside the bigger mitochondria dolls inside the biggest doll of all—us. But, hold on, how can we be sure there’s not a bigger doll yet? It’s a tough question.

IS THERE ANYTHING IN THE MIX we’re left to call our own? Lewis Thomas leaves us with a modest plea: “I only hope I can retain title to my nuclei.” It will be interesting, as microbiologists dig deeper into our structure, to see whether even this turns out to be true. For starters, what about those trichinosis parasites who enter our cells and grow their own nuclei?

Where does one draw the line between self and other? In biology, the answer boils down to genetics. A self, as Richard Dawkins famously argued in his classic book *The Selfish Gene*, is nothing more than a set of DNA intent on replicating itself. Different DNA, different self. By this definition, my mitochondria are individuals separate from me. Yet, even to geneticists, my mitochondria’s genetic individuality represents the essence of my own individuality, not simply who I am today but who I descend from. How can my ancestral fingerprint not be me?

But if the mitochondria are me, doesn’t this mean I have two sets of genes? Aren’t I a mosaic of both my own cellular DNA and that of my mitochondria? The fact is that all of the “others”—whether they are parasitic or mutualistic, cheaters or straight-shooters, long-term residents or one-night stands—have a significant characteristic in common: They each carry their own DNA. And this means that, for however long they are inside their host’s body, two genetically distinct organisms are living under the same skin and, to one extent or another, are biologically intertwined. Deep down, at the core of our tissue, we are a gigantic, symbiotic array, a ragtag assortment of organisms. All of these are to some degree us.

Then again, results are more important than who gets credit for what. The fact is that somehow—miraculously really—when the pieces are tossed together, the machine we call our body actually works. And the reason it does has less to do with competing than cooperating. As evolutionary biologists Lynn Margulis and Dorion Sagan point out, “Life did not take over the globe by combat, but by networking.” ☺

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How to Avoid Empathy Burnout

Caregivers can benefit by understanding a patient's pain without feeling it themselves

BY JAMIL ZAKI

WHEN ALLISON BASINGER GOT BACK to her office, she lay down on the floor, as though she'd suffered a migraine or toughed out a marathon. In fact, she had just finished a session with SAFEHOME, a Kansas City-area organization that supports teenage survivors of domestic violence. Under its auspices, Allison visited local middle and high schools to educate students about unhealthy relationships and teen dating violence. That day, like many others, a student had come forward with a horrific story of her own abuse, and Allison had done what she could to help. Afterward, laying there, she returned to her own struggle, one that many people in her line of work share. Once you open yourself to the suffering of others, it can feel impossible to turn off their pain.

Following a disaster, it's easy to pick out firefighters, police officers, and EMTs: They are the ones running toward the resulting chaos while everyone else runs away. Helping professionals—in fields such as

social work, psychotherapy, and hospice care—are the emotional counterparts to first responders, gravitating toward experiences the rest of us avoid. Basinger, for one, felt the pull within weeks of starting work at SAFEHOME. A deeply religious person, she had struggled to understand her own suffering, which included an abusive relationship and bullying severe enough for her to switch schools. SAFEHOME gave it a purpose: She could prevent the pain of her past from invading others' futures. As she puts it, "You want to rescue them from going through those things for the first time." Her experience is not uncommon. Surveys of career helpers find they are more likely to report family histories of abuse or substance dependence than professionals in finance, music, and science.

Patients thrive from emotional connection with nurses, social workers, and therapists, but helpers who provide this connection can wilt under its force. The stress of caring can lead to astonishing levels of job turnover. According to one review, 30 to 60 percent

of social workers in high-impact sectors, such as child abuse, leave their jobs each year. When caregivers flame out at such rates, it opens cracks in the continuity of care, through which patients frequently fall. Even helpers who do stay often harden themselves to their patients' emotions. Medical students report lower levels of empathy as their training progresses. Health-care professionals underestimate patients' suffering and even display blunted physiological signs of empathy for pain. Many helpers feel that they face a double bind. They can preserve themselves by growing emotional callouses and blunting their responses to those in need. Or they can throw themselves into building connections with their patients and risk being crushed by the weight of caring.

New research suggests a third way. Caregivers need to be empathetic, but empathy is not one thing.

Both neuroscience and psychology have uncovered an important distinction between two aspects of empathy: Emotion contagion, which is vicariously sharing another person's feeling, and empathic concern, which entails forming a goal to alleviate that person's suffering. Whereas contagion involves blurring the boundary between self and other, concern requires retaining or even strengthening such boundaries. Learning to practice one but not the other could be the best example of how caregivers can simultaneously look out for patients and for themselves.

IN BLUEBEARD, KURT VONNEGUT describes a dying neurosurgeon who, in his last moments, scribbles, "I was a radio repairman." His wife interprets these last words: "He had come to the conclusion that all the brains he had operated on were basically just receivers



CARETAKERS UNITE Legal advocate Hilda Fragoso, top, confers with client advocate Adaly Armenta inside a Ventura area battered woman's shelter. Support from colleagues can make helpers less likely to burn out.

of signals from someplace else.”

Vonnegut could have gone further. We are, simultaneously, receivers and the operators of those receivers, tuning ourselves toward frequencies we want to pick up. Amidst an avalanche of inputs, we focus attention, like a spotlight, on bits of it at a time. This allows us to make sense of the world and also shapes our emotional lives.

Consider empathy, our responses to others’ emotions. Psychologists tend to think of empathy as looking outward, toward connections with friends and strangers. Verging on science fiction, the best empathizers appear to read other people’s thoughts and feelings like a stock-ticker. This view of empathy, though, covers only half of it. Empathy just as often represents a decision not about others, but about ourselves.

If we empathized with every person’s suffering, it would be impossible to traverse a Manhattan block without collapsing into an anguished heap. Attention serves as a gate through which we sometimes let in other people’s emotions and at other times keep them out. Our needs, in turn, govern the ways we use this gate. Lonely people focus intensely on others’ minds in the hopes of connecting with others. In some cases, isolation drives us to empathize even with inanimate objects (think Tom Hanks in *Gastaway*). At the other extreme, prison guards and executioners ignore prisoners’ emotions, especially when the time comes for prisoners to suffer at the guards’ hands. Like pupils dilating and constricting in response to darkness and light, our empathic channels open when social connection is scarce and close when connecting could hurt.

Some people, though, chronically open themselves to others. Rene McCreary, a counselor also working in the Kansas City area, felt called to help others from an early age. Her parents described her as a mother hen to her siblings from the moment they were born. In school, she sought out classmates with struggles, sometimes treating them better than the rest of her peers. McCreary traces her impulse to her parents’ example. They once housed a mother and her seven children for a week to protect them from the woman’s abusive husband. This was the first time any non-white people had stayed in McCreary’s neighborhood, and her parents graciously faced the resulting neighborly scorn. “I learned at that time,” McCreary says, “that doing the

Concern requires retaining or even strengthening such boundaries.

right thing is hard sometimes.” That lesson shows in her hard choice of work: counseling sexually abused children, which she has done for the last 27 years.

But just because therapists, nurses, and social workers feel others’ pain doesn’t mean they have any special ability to cope with it. The emotional fallout they battle is often called secondary trauma. Unlike classic trauma, secondary trauma occurs not in response to the events that befall us, but rather what we see others endure. Even so, secondary trauma has very real effects on the lives of the people who suffer it. Professional helpers, for instance, often develop sleep problems, stress-related physical illnesses, or alcohol and substance abuse. Like victims of other forms of trauma, helping professionals find it difficult to detach themselves from the pain they witness. Their patients’ suffering follows them home. Basinger, for instance, remembers being out to dinner with her partner when a couple at a nearby table began fighting. Their angry lashing-out reminded her of how parents, boyfriends, and girlfriends treated her students. She found herself unable to tune out the fight, drifting away from the conversation at her own table. This happened to her elsewhere, too. A parent berating his kid at a gas station. Two friends mocking a third at a diner. Trouble polluted the air around her.

The ubiquity of suffering can also make helpers feel that their efforts are futile, like trying to drain an ocean with a Dixie cup. It saps meaning from anything helpers do outside of work. How do you go jogging when people nearby are likely being abused that very minute? How do you make dinner and listen to your kids complain about homework when others’ needs

are so severe? “To justify making time for myself when I could be helping someone else ... feels really wrong,” Basinger says. Athletes pride themselves on “leaving everything on the field,” exhausting themselves in the pursuit of winning. Helping professionals likewise pour out their energy until they’re left with almost nothing, and whatever they *are* left with feels like unfinished work. As Basinger puts it, “If I have any little piece of energy left at the end of the day, then I didn’t do all I could.” Helpers consider their distress a badge of honor, in what McCreary calls “a pull toward the romance of suffering.”

And it is not only professionals who feel it. Empathy fatigue could just as easily describe the modern style of parenting. It has become easy to mistakenly *define* good parenting through exhaustion, the sense that one has

The distinction between contagion and concern does not come naturally. It takes conscious training.

given everything to their child—and then a little more. And indeed, recent evidence indicates that parents exhibit physiological signs of immune distress from the strain of chronic caring. Professional helpers bear the brunt of full-contact caring every day, but most of us have lost ourselves to it at one point or another.

The people who are most inclined toward helping also suffer from its side effects the most. In study after study, helping professionals high in empathy are more likely to report secondary trauma. In one especially compelling investigation, the psychologists Jeroen Vaes and Martina Muratore asked professionals to describe their patients’ emotions. Vaes and Muratore were looking for signs of dehumanization—a kind of “anti-empathy” under which one person fails to grasp the richness of others’ emotional lives.

Dehumanization sounds bad, and often is. For instance, people who dehumanize members of other races are also more willing to enact violence against them. But Vaes and Muratore’s study flipped this logic on its head. Helping professionals who did *not* dehumanize their patients—instead granting them full and rich humanity—were the most likely to burn out.

DOES IT HAVE TO BE THIS WAY? Not necessarily. Helpers do not need to choose between empathy and dehumanization, because empathy is not one thing. Contagion and concern—two dimensions of empathy—need not travel together. For one, they are only weakly associated across people. Individuals who report high levels of contagion do not necessarily say they are also high in concern, and vice versa. These states also inspire very different actions. In a classic series of studies done in the late 1980s, psychologist Dan Batson and his colleagues presented undergraduate psychology students with a video of another participant receiving mild electric shocks. Participants reported feeling distressed (related to contagion) when watching the person in pain and also concern for that student (expressed through terms such as “moved” or “sympathetic”). These states, however, were only weakly related across people, such that Batson could identify some people who predominantly felt concern, and others who predominantly felt distress. Batson then gave participants the chance to help the other student by trading places with her and “taking” the shocks on her behalf. Crucially, Batson set up the experiment so that some participants could easily avoid helping (for instance, if they chose not to help, they would be able to leave without watching the other student receive more shocks), whereas others could not. People who experienced more distress than concern avoided helping when they could, whereas people who experienced the opposite emotional profile helped in either case. It seems that immersing yourself in the pain of others can neutralize action as much as mobilize it.

Batson argued that these data speak to the nature of empathy. In his view, distress points us inward, motivating us to feel better, whether by helping others or by avoiding them. Concern, though, keeps us focused outward. Nor is concern merely a diluted form of contagion. It drives us to approach others’ suffering even

in cases where contagion would turn us away.

Many helpers have rededicated themselves, through organizations such as the Secondary Trauma Resource Center, to help their colleagues maintain a healthy lifestyle. Their efforts connect with research suggesting that helpers' success hinges on their ability to experience concern while avoiding contagion. When other people's emotions flood into us, it can make it harder for us to help them. Patients, after all, are often too distressed to realize what might aid them; that is not a condition the helper should emulate. As one clinician put it, "Once you are in the shoes of your patient, you cannot possibly be of any help."

McCreary describes the state she strives for in her interactions with patients: "I try not to metabolize their trauma, which allows me to hear what they have to share and not *become* what they have to share ... I need to be as irrelevant as possible, and keep the experience about them." Basinger takes a different approach to detachment, trying to model for patients how much better they might feel after treatment: "I try to be the face of resilience, to show them how things could be for them."

Research suggests that these strategies can offer an antidote to burnout. In the 1980s, the psychologist Katherine Miller and her colleagues suggested that a key feature of successful therapy is therapists' communication of warmth and understanding toward their patients. She found that concern facilitates such communication, whereas contagion interferes with it. Therapists' ability to separate themselves from their patients' suffering also staved off secondary trauma.

For many helping professionals, the distinction between contagion and concern does not come naturally. It takes conscious training. Thankfully, research suggests, more and more, that empathy is not a fixed trait; it is under our control, growing and shrinking throughout our lives depending on the choices we make. Even if vulnerability to contagion is what calls people into helping professions, helpers can then train themselves to use empathy in different, healthier ways. In one remarkable demonstration of such empathic tuning, the neuroscientist Tania Singer engaged a group of subjects in Buddhist-inspired compassion meditation training. This practice, known as loving kindness, begins with concern for one's self. Practitioners

consider their own pain and extend warmth and care toward themselves. They then systematically "dilate" their caring: First toward close friends and family, then toward strangers, and finally toward all of humanity. In essence, compassion meditation provides practitioners with an exercise in sharpening and then expanding their concern.

Singer and her colleagues scanned participants' brain responses to others' distress before and after the meditation training. Before, people demonstrated physiological signs of contagion—for instance, engaging parts of their brain associated with feeling pain when watching others experience it. After the training, however, they shed this pattern and instead exhibited a pattern of brain activity more commonly associated with motivation and even positive emotion. Singer believes this type of training might allow helpers to "tune" empathy toward concern, working with it but not allowing it to take them over.

At least in this case, sustainable and deep empathic concern for others began with that ancient mandate: Love thyself. And self-love is often the most difficult kind. But helpers, and the rest of us, have a flexible emotional life and the power to shape our feelings to better suit our needs. This opportunity is especially important for people who work in empathy's trenches. To the extent that they can even out their emotional spotlight, they can benefit immensely. So can the lucky targets of their kindness. ☺

JAMIL ZAKI is an assistant professor of psychology at the Stanford Social Neuroscience Laboratory. His research focuses on the cognitive and neural bases of social behavior.



Why Nature Prefers Hexagons

The geometric rules behind fly eyes, honeycombs, and soap bubbles

BY PHILIP BALL

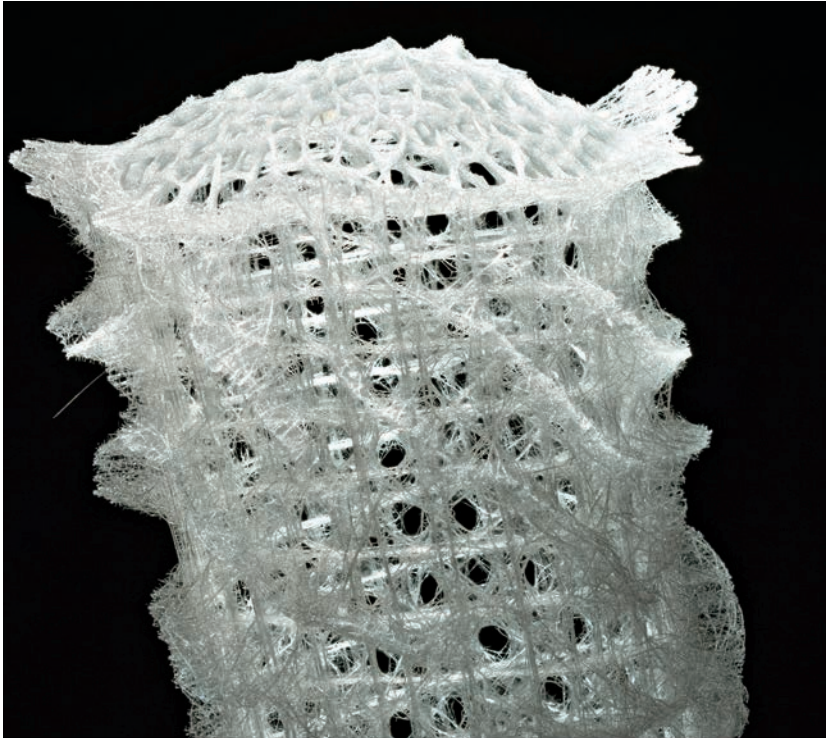
HOW DO BEES DO IT? The honeycombs in which they store their amber nectar are marvels of precision engineering, an array of prism-shaped cells with a perfectly hexagonal cross-section. The wax walls are made with a very precise thickness, the cells are gently tilted from the horizontal to prevent the viscous honey from running out, and the entire comb is aligned with the Earth's magnetic field. Yet this structure is made without any blueprint or foresight, by many bees working simultaneously and somehow coordinating their efforts to avoid mismatched cells.

The ancient Greek philosopher Pappus of Alexandria thought that the bees must be endowed with “a certain geometrical forethought.” And who could have given them this wisdom, but God? According to William Kirby in 1852, bees are “Heaven-instructed mathematicians.” Charles Darwin wasn't so sure, and he conducted experiments to establish whether bees are able to build perfect honeycombs

using nothing but evolved and inherited instincts, as his theory of evolution would imply.

Why hexagons, though? It's a simple matter of geometry. If you want to pack together cells that are identical in shape and size so that they fill all of a flat plane, only three regular shapes (with all sides and angles identical) will work: equilateral triangles, squares, and hexagons. Of these, hexagonal cells require the least total length of wall, compared with triangles or squares of the same area. So it makes sense that bees would choose hexagons, since making wax costs them energy, and they will want to use up as little as possible—just as builders might want to save on the cost of bricks. This was understood in the 18th century, and Darwin declared that the hexagonal honeycomb is “absolutely perfect in economizing labor and wax.”

Darwin thought that natural selection had endowed bees with instincts for making these wax chambers, which had the advantage of requiring less energy and



MINERAL MESH The filigree porous skeletons of sponges, such as this Venus's flower basket, are forms of "frozen foam" in which a mineral is cast around the junctions and intersections of bubblelike soft tissues.

time than those with other shapes. But even though bees do seem to possess specialized abilities to measure angles and wall thickness, not everyone agrees about how much they have to rely on them. That's because making hexagonal arrays of cells is something that nature does anyway.



IF YOU BLOW A LAYER of bubbles on the surface of water—a so-called "bubble raft"—the bubbles become hexagonal, or almost so. You'll never find a raft of square bubbles: If four bubble walls come together, they instantly rearrange into three-wall junctions with more or less equal angles of 120 degrees between them, like the center of the Mercedes-Benz symbol.

Evidently there are no agents shaping these rafts as

bees do with their combs. All that's guiding the pattern are the laws of physics. Those laws evidently have definite preferences, such as the bias toward three-way junctions of bubble walls. The same is true of more complicated foams. If you pile up bubbles in three dimensions by blowing through a straw into a bowl of soapy water you'll see that when bubble walls meet at a vertex, it's always a four-way union with angles between the intersecting films roughly equal to about 109 degrees—an angle related to the four-faceted geometric tetrahedron.

What determines these rules of soap-film junctions and bubble shapes? Nature is even more concerned about economy than the bees are. Bubbles and soap films are made of water (with a skin of soap molecules) and surface tension pulls at the liquid surface to give it as small an area as possible. That's why raindrops are spherical (more or less) as they fall: A sphere has less surface area

than any other shape with the same volume. On a waxy leaf, droplets of water retract into little beads for the same reason.

This surface tension explains the patterns of bubble rafts and foams. The foam will seek to find the structure that has the lowest total surface tension, which means the least area of soap-film wall. But the configuration of bubble walls also has to be mechanically stable: the tugs in different directions at a junction have to balance perfectly, just as the forces must be balanced in the walls of a cathedral if the building is going to stand up. The three-way junction in a bubble raft, and the four-way junctions in foam, are the configurations that achieve this balance.

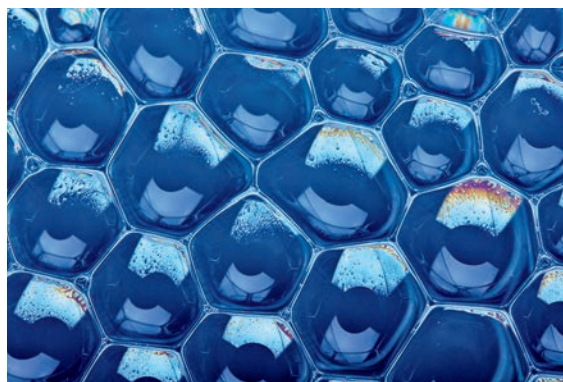
But those who think (as some do) that the honeycomb is just a solidified bubble raft of soft wax might have trouble explaining how the same hexagonal array of cells is found in the nests of paper wasps, who build not with wax but with chewed-up wads of fibrous wood and plant stem, from which they make a kind of paper. Not only can surface tension have little effect here, but it also seems clear that different types of wasp have different inherited instincts for their architectural designs, which can vary significantly from one species to another.

Although the geometry of soap-film junctions is dictated by this interplay of mechanical forces, it doesn't tell us what the shape of the foam will be. A typical foam contains polyhedral cells of many different shapes and sizes. Look closely and you'll see that their edges are rarely perfectly straight; they're a little curved. That's because the pressure of the gas inside a cell or bubble gets bigger as the bubble gets smaller, so the wall of a small bubble next to a larger one will bulge outward slightly. What's more, some facets have five sides, some six, and some just four or even three. With a little bending of the walls, all of these shapes can acquire four-way junctions close to the "tetrahedral" arrangement needed for mechanical stability. So there's a fair bit of flexibility (literally) in the shapes of the cells. Foams, while subject to geometrical rules, are rather disorderly.

Suppose that you could make a "perfect" foam in which all the bubbles are the same size. What then is the ideal cell shape that makes the total bubble wall



FORCES AT WORK Bees seem to have evolved capabilities for making perfectly hexagonal cells from the soft wax that they secrete. However, some researchers believe that surface tension in the soft wax might be sufficient to pull the cells into shape, in much the same way as it organizes bubbles in a bubble raft.



FITTING IN A single layer or "raft" of bubbles contains mostly hexagonal bubbles, albeit not all of them perfect hexagons. There are some "defects"—bubbles with perhaps five or seven sides. Nonetheless, all the junctions of bubble walls are threefold, intersecting at angles that are close to 120 degrees.



SHAPING A DROPLET When water sits on a water-repellent surface, it may break up into droplets. The shapes of these drops are governed by surface tension, which pulls them into roughly spherical shapes, as well as by gravity (which will flatten a droplet on a horizontal surface) and the forces that act between the water and the underlying solid surface. If those latter forces are strong enough, the droplets are pulled into lens-shaped pancakes. And if the surface isn't strongly water-repellent, the droplets may spread out into a flat, smooth film.

area as small as possible while satisfying the demands for the angles at the junctions? That has been debated for many years, and for a long time it was thought that the ideal cell shape was a 14-sided polyhedron with square and hexagonal faces. But in 1993 a slightly more economical—although less orderly—structure was discovered, consisting of a repeating group of eight different cell shapes. This more complex pattern was used as the inspiration for the foam-like design of the swimming stadium of the 2008 Olympic Games in Beijing.

The rules of cell shapes in foams also control some of the patterns seen in living cells. Not only does a fly's compound eye show the same hexagonal packing of facets as a bubble raft, but the light-sensitive cells within each of the individual lenses are also clustered in groups of four that look just like soap bubbles. In mutant flies with more than four of these cells per cluster, the arrangements are also more or less identical to those that bubbles would adopt.



BECAUSE OF SURFACE TENSION, a soap film stretching across a loop of wire is pulled flat like the springy membrane of a trampoline. If the wire frame is bent, the film also bends with an elegant contour that automatically tells you the most economical way, in terms of material, to cover over the space enclosed by the frame. That can show an architect how to make a roof for a complicated structure using the least amount of material. However, it's as much because of the beauty and elegance of these so-called "minimal surfaces," as because of their economy that architects such as Frei Otto have used them in their buildings.

These surfaces minimize not only their surface area, but also their total curvature. The tighter the bend, the greater the curvature. Curvature can be positive (bulges) or negative (dips, depressions, and saddles). A curved surface can therefore have zero mean curvature so long as the positives and negatives cancel each other out.

So a sheet can be full of curvature and yet have very little or even no mean curvature. Such a minimally curved surface can divide up space into

an orderly labyrinth of passageways and channels—a network. These are called periodic minimal surfaces. (Periodic just means a structure that repeats identically again and again, or in other words, a regular pattern.) When such patterns were discovered in the 19th century, they seemed to be just a mathematical curiosity. But now we know that nature makes use of them.

The cells of many different types of organisms, from plants to lampreys to rats, contain membranes with microscopic structures like this. No one knows what they are for, but they are so widespread that it's fair to assume they have some sort of useful role. Perhaps they isolate one biochemical process from another, avoiding crosstalk and interference. Or maybe they are just an efficient way of creating lots of "work surface," since many biochemical processes take place at the surface of membranes, where enzymes and other active molecules may be embedded. Whatever its function, you don't need complicated genetic instructions to create such a labyrinth: The laws of physics will do it for you.

Some butterflies, such as the European green hairstreak and the emerald-patched cattleheart, have wing scales containing an orderly labyrinth of the tough material called chitin, shaped like a particular periodic minimal surface called the gyroid. Interference between light waves bouncing regular arrays of ridges and other structures on the wing-scale surface causes some wavelengths—that is, some colors—to disappear while others reinforce each other. So here the patterns offer a means of producing animal color.



THE SKELETON OF THE SEA URCHIN *Cidaris rugosa* is a porous mesh with the shape of another kind of periodic minimal surface. It's actually an exoskeleton, sitting outside the organism's soft tissue, a protective shell that sprouts dangerous-looking spines made from the same mineral as chalk and marble. The open lattice structure means that the material is strong without being too heavy, rather like the metal foams used for building aircraft.



BUBBLE VISION The compound eyes of insects are packed hexagonally, just like the bubbles of a bubble raft—although, in fact, each facet is a lens connected to a long, thin, retinal cell beneath. The structures that are formed by clusters of biological cells often have forms governed by much the same rules as foams and bubble rafts—for example, just three cell walls meet at any vertex. The microscopic structure of the facets of a fly’s eye—beyond what is visible here—supplies one of the best examples. Each facet contains a cluster of four light-sensitive cells that have the same shape as a cluster of four ordinary bubbles.

To make orderly networks from hard, stiff mineral, these organisms apparently make a mold from soft, flexible membranes and then crystallize the hard material inside one of the interpenetrating networks. Other creatures may cast orderly mineral foams this way for more sophisticated purposes. Because of the way that light bounces off the elements of the patterned structure, such trellises can act rather like mirrors to confine and guide light. A honeycomb arrangement of hollow microscopic channels within the chitin spines of a peculiar marine worm known as the sea mouse turns these hairlike structures into natural optical fibers that can channel light, making the creature change from red to bluish green depending on the direction of the illumination. This color change might serve to deter predators.

This principle of using soft tissues and membranes as molds for forming patterned mineral exoskeletons

is widely used in the sea. Some sponges have exoskeletons made of bars of mineral linked like climbing frames, which look remarkably similar to the patterns formed by the edges and junctions of soap films in foam—no coincidence, if surface tension dictates the architecture.

Such processes, known as biomineralization, generate spectacular results in marine organisms called radiolarians and diatoms. Some of these have delicately patterned exoskeletons made from a mesh of mineral hexagons and pentagons: You might call them the honeycombs of the sea. When the German biologist (and talented artist) Ernst Haeckel first saw their shapes in a microscope in the late 19th century, he made them the star attraction of a portfolio of drawings called *Art Forms in Nature*, which were very influential among artists of the early 20th century and still inspire admiration today. To Haeckel, they



MAKING USE OF BUBBLES Bubbles and foams are put to use in nature. Here the common purple snail (*Janthina janthina*) hangs onto the surface of the sea from a buoyant raft made of bubbles coated with mucus. This enables the snail to feed on small creatures that live at the water's surface.

seemed to offer evidence of a fundamental creativity and artistry in the natural world—a preference for order and pattern built into the very laws of nature. Even if we don't subscribe to that notion now, there's something in Haeckel's conviction that patterns are an irrepressible impulse of the natural world—one that we have every right to find beautiful. ☺

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

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Why Do Taxonomists Write the Meanest Obituaries?

*The open nature of the science of classification
virtually guarantees generations-long fights*

BY ANSEL PAYNE

CONSTANTINE RAFINESQUE had only been dead a few months when Asa Gray sat down to eulogize him for the *American Journal of Science*. The year was 1841, and Gray, soon to join both the American Academy and the Harvard faculty, was well on his way to becoming the most respected botanist of his generation. *Grayia*, a new genus of desert shrub, had just been named in his honor.

Rafinesque, on the other hand, was *persona non grata*. Described by peers as a “literary madman,” the Turkish-born polymath had died of cancer the previous fall. Among the many works he left behind were rambling discourses on zoology and geology; a catalog of Native American burial mounds; a new interpretation of the Hebrew Bible; a 5,400-line epic poem (with footnotes); and, last but not least, a lengthy series of studies on North American plants.

It was these last that had attracted Gray’s attention. That’s because scattered among Rafinesque’s botanical works were descriptions of over 6,000 new plant

species, far more than any one person had managed to produce prior to that time—more, in fact, than anyone has produced since. It should have been an amazing accomplishment, and would have been, if only Rafinesque had been a decent botanist.

“Our task,” Gray began, “although necessary, as it appears to us, is not altogether pleasing ...”

While the professor wanted to do “full justice” to Rafinesque’s life, he felt “obliged, at the same time, to protest against all of his later and one of his earlier botanical works ... There can, we think, be but one opinion as to the consideration which is due to these new genera and species: They must be regarded as fictitious, and unworthy of the slightest notice.”

Through a lifetime of what historians would call a “nervous and appalling industry,” Rafinesque had somehow managed to produce thousands of pages of the worst work the field had ever seen. Full of errors and oversights, punctuated only by the occasional tirade, Rafinesque’s papers were case studies in sloppy



work. His descriptions were so vague that readers had trouble attaching them to actual plants, and his talents for misidentification were legendary: Many of his “new” species were actually just well-known weeds.

Toward the end, Rafinesque’s “passion for establishing new genera and species,” Gray wrote, “appears to have become a complete *monomania*. This is the most charitable supposition we can entertain.” Now, in the months after his death, the scientific establishment had assessed his work and passed its judgment. Rafinesque’s “absurd” botanical legacy, Gray wrote, amounted to little more than a “curious mass of nonsense.”

Gray’s note wouldn’t be the last unkind obituary in the annals of taxonomy, nor would it be the worst. That’s because the rules dictating how taxonomists name and classify living things bind these scientists in a web of influence stretching far back into the 18th century. When an agent of chaos like Rafinesque enters the scene, that web can get sticky fast. In a field haunted by ghosts, someone has to reckon with the dead.

TAXONOMY, THE ART AND SCIENCE of classifying life, really should be a civilized pursuit. It encourages solitude, concentration, care. It rewards a meticulous attention to detail. And while it might occasionally receive some good-natured ribbing from the popular culture—think of all those butterfly collectors stumbling around in *Far Side* cartoons—it continues to play a vital role at the foundations of modern biology.

It can come as a bit of a surprise, then, when that veneer of civilization cracks, and the field reveals itself to be one of the more contentious arenas in science, a place where arguments over names and classifications rage through the literature for decades. This is both a strength, as challenges to current classification keep the field dynamic and relevant, and an expression of its hardwired vulnerabilities.

For starters, there’s the problem of classification itself. Ever since Darwin gave us a framework for understanding common descent, the search has been on for a natural classification, an arrangement of nested groups, or *taxa*, that accurately reflects evolutionary relationships. In this scheme, a classification functions as an explicit evolutionary hypothesis—to say that five species form a genus is also to say that those

five species share a unique common ancestor. Ditto for families and orders, right up through classes and kingdoms.

On another level, though, higher-order classifications are all a bit arbitrary. So long as all the members of a genus share a unique common ancestor and some unifying trait, the size of that genus—the number of related species lumped together under that name—is really up to the classifier. This has created generational fights between two different camps of taxonomists: splitters, who advocate for more and smaller groups, and lumpers, who like their groups big and inclusive.

And then there’s the problem of identifying species in the first place. While each of the many different textbook definitions seems straightforward enough in theory, discovering the actual boundaries of a species in nature can prove frustrating. Are subtle variations between two populations meaningful? Or are they just background noise? Working from a limited number of specimens or a dearth of genetic evidence, taxonomists often have to rely on intuition and experience to make that call. The resulting species definitions are provisional, and can be overturned by new evidence in the form of more specimens, novel genetic data, or broader geographic surveys.

To accommodate all this hypothesis testing, the field has committed itself to the principle of taxonomic freedom, the right of any individual to change any classification based on new evidence and his or her best judgment. The practical result is that classifications tend to fluctuate in ways that are both healthy and natural, and that ultimately lead to better agreement between those classifications and evolutionary history. It’s a messy process, but it seems to work.

To complicate things further, the Earth has an extraordinary abundance of biodiversity. In the years since Linnaeus introduced the modern system of classification and nomenclature, more than 250,000 species of plants and over 1.2 million species of animals have been described by naturalists. Each carries a unique, two-part name, or Latin binomial, that indicates both its genus group (e.g., *Homo*) and its species (*sapiens*). Keeping track of all these names and their shifting histories requires specialists to maintain a near-encyclopedic familiarity with the literature of their group.

What can we say of his life? Nothing.

Now imagine if two taxonomists, working in different languages, at different times, or in different parts of the world, independently describe the same species. Unaware of one another's work, each would produce a different name for the same organism, only one of which can ultimately be correct. A similar problem occurs when taxonomists independently use the same name to describe two different species. To avoid the chaos that would result from either of these situations (known, respectively, as synonymy and homonymy), the field enshrines another principle, taxonomic stability, to serve as a counterbalance to taxonomic freedom. The idea is to find a classification that's stable enough to be useful, but flexible enough to incorporate necessary changes.

This tension between freedom and stability was long ago formalized in two sets of official and binding rules: the International Code of Zoological Nomenclature (ICZN), which deals with animals, and the International Code of Nomenclature for algae, fungi, and plants (ICN). Periodically updated by committees of working taxonomists, these documents set out precise, legalistic frameworks for how to apply names both to species and to higher taxa. (The animal and plant codes operate independently, which means that

an animal can share a scientific name with a plant, but not with another animal, and vice versa.)

Central to both, and to taxonomic stability itself, is the Principle of Priority, which states that the first valid scientific name applied to a group of animals is *the* valid name. If Linnaeus named a species in 1758, and that species is still recognized today, then Linnaeus' name stands. Priority forms the backbone of biological nomenclature; without it, classification would degenerate, Babel-style, into a panoply of competing and incompatible systems. One consequence of all this is that taxonomists are constantly combing through the older literature to uncover the proper name for any given species. Another is that current classificatory changes come with a high potential for downstream influence.

And there's the rub. In order to balance freedom with stability, the Codes generally remain silent on the question of *quality*: Any taxonomic proposal, no matter how outlandish, ill-informed, or incompetent, counts so long as it was published according to the barest of requirements set out in the Codes themselves. For the ICN, this means descriptions must be published in printed materials that are distributed to libraries and accessible to botanists. For the ICZN, which recently

The obituarist referred to Walker's work simply as the "evil."

relaxed its requirements, descriptions can come in either publically accessible printed materials or Internet-based digital publications. In neither case do the Codes require peer review; if you can print it and you can distribute it, then you can describe pretty much whatever you want.

While this freedom opens up a valuable space for amateur contributions, it also creates a massive loophole for unscrupulous, incompetent, or fringe characters to wreak havoc. That's because the Principle of Priority binds all taxonomists into a complicated network of interdependence; just because a species description is wrong, poorly conceived, or otherwise inadequate, doesn't mean that it isn't a recognized part of taxonomic history. Whereas in physics, say, "unified theories" scrawled on napkins and mailed in unmarked envelopes end up in trashcans, biologists, regardless of their own opinions, are bound to reckon with the legacy of anyone publishing a new name. Taxonomists are more than welcome to deal with (or "revise") these incorrect names in print, but they can't really ignore them.

And this, finally, is the context for Gray's posthumous hatchet job. Rafinesque's manic and reckless work on North American plants was more than just a

curious sideshow in the history of American botany; it was a problem that other botanists had to solve. While Gray may have advocated for ignoring Rafinesque's work wholesale, later taxonomists understood that kind of boycott as a violation, both in letter and in spirit, of the Codes of Nomenclature.

In fact, the extensive nature of Rafinesque's interventions—and the complication that at least some of his new species were actually valid—meant that taxonomists would still be untangling his mess well into the 20th century. As E.D. Merrill, the Harvard botanist who set out to index and correct much of this work in the 1930s and '40s, put it, "we would have been infinitely better off today had Rafinesque never written or published anything appertaining to the subject."

"MORE THAN TWENTY YEARS too late for his scientific reputation, and after having done an amount of injury to entomology almost inconceivable in its immensity, Francis Walker has passed from among us."

Walker's two-page obituary, in the November 1874 issue of the *Entomologist's Monthly Magazine*, sits between a short research note ("*Emmelesia unifasciata* three years in the pupa state") and some words on the passing of William Lello ("He leaves a considerable

collection of Lepidoptera ...”). Written anonymously, it pulled no punches when it came to the late taxonomist’s legacy: The vast majority of the tens of thousands of new species he proposed were “objects of derision for all conscientious entomologists.” More than once, the obituarist referred to Walker’s work simply as the “evil.”

And yet, the man’s career had begun with promise. His first work, a well-regarded study of the tiny wasps known as chalcids, had “marked an era in the study of its subject.” Despite considerable inherited wealth, he longed for a permanent position at one of Britain’s major collections. When that position failed to materialize, Walker, “in an unlucky moment,” instead took up the first in a long series of contract appointments cataloging insects for the British Museum.

This is where the trouble began. Moving from drawer to drawer through the collection, Walker took it upon himself to describe what he believed to be thousands of new species in virtually all major groups of insects, a task requiring skills far beyond what he, or anyone else, possessed. “The result,” the obituarist wrote, “was what might have been expected. The work was done mechanically: ‘new genera and species’ were erected in the most reckless manner ...” Through a Refined combination of industry and incompetence, the humble Englishman had begun to single-handedly wreak havoc on the classification of the world’s insects.

As Walker published more and more dubious names, in wider and wider groups, the entomological establishment grew ever louder in its condemnation. By the time he had exhausted most of the major insect orders, his once considerable “entomological reputation [had been] worn to shreds.” Walker, however, “appeared to be utterly indifferent to anything that could be hurled at him ... In his social relations he was amiability itself ...” When he died, at 65, the entomological community mourned the gentle soul who had walked the halls of the British Museum, but also let out a collective sigh of relief. “We earnestly hope,” the obituarist added, “that never again will it fall to us, nor to our successors in entomological journalism, to have to write such an obituary notice as this.”

But Walker’s name wouldn’t be the last to live in taxonomic infamy. In fact, his obituary seems downright

tactful beside Claude Morley’s note, from 1913, on the death of Peter Cameron, an infamous describer of Central American insects.

“Peter Cameron is dead, as was announced by most of the halfpenny papers on December 4th. What can we say of his life? Nothing; for it concerns us in no way. What shall we say of his work? Much, for it is entirely ours, and will go down to posterity as probably the most prolific and chaotic output of any individual for many years past.”

Cameron, a Scottish amateur with a penchant for Central American insects, left a legacy that echoed for decades. Fifty years after his death, Richard Bohart, a taxonomist at the University of California Davis, would reiterate that the entomologist’s “work was careless, his descriptions poor, his locality data were often vague or omitted, his generic assignments were characteristically erroneous and contradictory, and he eschewed illustrations.” Despite all that, or perhaps because of it, Bohart wound up with the thankless task of sorting through Cameron’s North American contributions to a small group of wasps known as the Odynerini. Of the hundred or so names Cameron proposed within the group, almost all, Bohart found, were invalid.

Meanwhile, modern taxonomy has its own outliers. In 2006, over 50 scientists signed an open letter to the administration of the University of Utrecht protesting the work of one Dewanand Makhan, an amateur entomologist who frequently listed the university as his institutional affiliation. (Makhan was a contract employee at the university’s herbarium, and not a member of the academic staff; his publications now list a personal address.)

“For many years,” they wrote, “Dr. Makhan has been a growing threat to taxonomy and zoological nomenclature, publishing a large number of new genera and species in groups as wide ranging as beetles, spiders, and gastropods. These publications are uniformly poor in quality and scholarship.” A group of ant experts put it more bluntly: A 2007 publication by Makhan, they wrote, was “one of the most inadequate papers that has ever been produced in ant taxonomy.”

Makhan’s descriptions are notoriously short on detail. In place of clear scientific diagrams, he illustrates much of his work with blurry, out-of-focus photographs. Most frustrating to fellow entomologists,

many of Makhan's "new" species are instantly recognizable, at least to them, as already described insects. Despite numerous articles and blog posts on the so-called "Makhan problem," new publications continue to appear, most in a small Australian journal without a traditional peer-review process. (As recently as last year, Makhan described a new species of waterbeetle, *Desmopachria barackobamai*—named, of course, for the 44th president of the United States.)

The story is a familiar one, but with a modern twist. That's because the growth of so-called "vanity journals"—publications that look to all appearances like mainstream scientific outlets, but lack rigorous peer-review—has produced new avenues for what some have taken to calling "taxonomic vandalism." As traditional boundaries between experts and amateurs dissolve in the face of digital publishing, more opportunities than ever exist for novel voices in science, journalism, and politics. Unfortunately, these opportunities come at a cost, as a growing tide of information challenges the discriminatory abilities of scientists and lay readers alike.

While discussions underway now could revise the Codes to include stricter controls on which publications count for classificatory changes, many taxonomists are wary of doing anything that might deter amateur contributions. With so many species left to discover, and with existential threats to biodiversity looming, they realize the field needs as much help as it can get.

In the struggle to balance its highest ideals with its unruliest practitioners, taxonomy teaches us an enduring lesson about science as a whole. While we like to think of that enterprise as an antidote to fallibility—a way of seeing that seeks, through meticulous care and relentless examination, to minimize our tendency toward error—it remains fundamentally, inescapably human. Somewhere in between is where real progress happens.

I was reminded of that when I found another obituary for Peter Cameron, this one from his hometown newspaper, the *Glasgow Herald*:

Much regret will be expressed in scientific circles throughout the world at the death of Mr. Peter Cameron, a well-known entomologist and a native of Glasgow.

For fifteen years, Mr. Cameron lived as a recluse at New Mills, Derbyshire, but for the last three years he had lodged at the cottage of a labourer named Price ... At the inquest, it was stated that Mr. Cameron's only relative was a sister in Dresden. A doctor expressed the opinion that he had neglected himself, and the jury returned a verdict that death was due to alcoholism... Of late, his circumstances had not been very bright, which prompted a certain section of the Royal Society to get together a sum of money, which was given to him at intervals to meet his needs.

In 2014, a team of entomologists from the Universidad de Panamá and Spain's Museo Nacional de Ciencias Naturales described a new species of gall wasp found in oak trees growing on the slopes of Panama's Volcán Barú. Less than three millimeters long and with four finely veined wings, the species differs from its relatives in the United States by an additional antennal segment and a minor difference in the shape of its thorax.

Its name?

Callirhytis cameroni. ☺

ANSEL PAYNE is a writer and naturalist in Tuscaloosa, Alabama.



Why Revolutionaries Love Spicy Food

How the chili pepper got to China

BY ANDREW LEONARD





IN 1932, THE SOVIET UNION sent one of its best agents to China, a former schoolteacher and counter-espionage expert from Germany named Otto Braun. His mission was to serve as a military adviser to the Chinese Communists, who were engaged in a desperate battle for survival against Chiang Kai-shek's Nationalists.

The full story of Braun's misadventures in China's Communist revolution is packed with enough twists and turns for a Hollywood thriller. But in the domain of culinary history, one anecdote from Braun's autobiography stands out. Braun recalls his first impressions of Mao Zedong, the man who would go on to become China's paramount leader.

The shrewd peasant organizer had a mean, even "spiteful" streak. "For example, for a long time I could not accustom myself to the strongly spiced food, such as hot fried peppers, which is traditional to southern China, especially in Hunan, Mao's birthplace." The Soviet agent's tender taste buds invited Mao's mockery. "The food of the true revolutionary is the red pepper," declared Mao. "And he who cannot endure red peppers is also unable to fight."

Maoist revolution is probably not the first thing that comes to mind when your tongue is burning from a mouthful of Kung Pao chicken or Mapo Tofu at your favorite Chinese restaurant. But the unlikely connection underscores the remarkable history of the chili pepper.

For years culinary detectives have been on the chili pepper's trail, trying to figure out how a New World import became so firmly rooted in Sichuan, a landlocked province on the southwestern frontier of China. "It's an extraordinary puzzle," says Paul Rozin, a University of Pennsylvania psychologist, who has studied the cultural evolution and psychological impact of foods, including the chili pepper.

Food historians have pointed to the province's hot and humid climate, the principles of Chinese medicine,

the constraints of geography, and the exigencies of economics. Most recently neuropsychologists have uncovered a link between the chili pepper and risk-taking. The research is provocative because the Sichuan people have long been notorious for their rebellious spirit; some of the momentous events in modern Chinese political history can be traced back to Sichuan's hot temper.

As Wu Dan, the manager of a hotpot restaurant in Chengdu, Sichuan's capital, told a reporter: "The Sichuanese are fiery. They fight fast and love fast and they like their food to be like them—hot."

THE CHILI PEPPER, GENUS *capsicum*, is indigenous to the tropics, where archaeological records indicate it has been cultivated and consumed perhaps as far back as 5000 B.C. Typically a perennial shrub bearing red or green fruit, it can be grown as an annual in regions where temperatures reach freezing in the winter. There are five domesticated species, but most of the chili peppers consumed in the world belong to just two, *Capsicum annuum* and *Capsicum frutescens*.

The active ingredient in chili peppers is a compound called capsaicin. When ingested, capsaicin triggers pain receptors whose normal evolutionary purpose is to alert the body to dangerous physical heat. The prevailing theory is the chili pepper's burn is a trick to dissuade mammals from eating it, because the mammalian digestive process normally destroys chili pepper seeds, preventing further propagation. Birds—which do not destroy chili pepper seeds during digestion—have no analogous receptors. When a bird eats a chili pepper, it doesn't feel a thing, excretes the seeds, and spreads the plant.

The word "chili" comes from the Nahuatl family of languages, spoken, most famously, by the Aztecs. (One early Spanish translation of the word was "*el miembro viril*"—tantalizing early evidence of the chili pepper's inherent machismo.) Botanists believe the chili pepper

originated in southwest Brazil or south central Bolivia, but by the 15th century, birds and humans had spread it throughout South and Central America.

Enter Christopher Columbus. On Jan. 1, 1493, the great explorer recorded in his diary his discovery, on the Caribbean island of Hispaniola, that “the pepper which the local Indians used as spice is more abundant and more valuable than either black or melegueta pepper [an African spice from the ginger family].”

In the 15th century, Spain and Portugal were obsessed with finding sea routes to the spice markets of Asia that would allow them to break the monopoly wielded by Arab traders over access to hot commodities like black pepper, cardamom, cinnamon, and ginger. Although Columbus was utterly wrong in his belief that he had sailed to India, he still succeeded in locating precisely what he had been seeking.

What he found was a potent, popular spice—the natives, observed Columbus’ physician Deigo Chanca, included chili pepper with every meal. The plant Columbus encountered is believed to be *Capsicum annuum* or *frutescens*, which he described as “like rose bushes which make a fruit as long as cinnamon.”

The chili pepper, like so many edible plants native to the New World, proved to be a wildly popular global sensation. Within a century of Columbus’ arrival in the New World, the chili pepper had made its way to places as far-flung as Hungary (paprika!), West Africa, India, China, and Korea.

The first mention of the chili pepper in the Chinese historical record appears in 1591, although historians have yet to arrive at a consensus as to exactly how it arrived in the Middle Kingdom. One school of thought believes the pepper came overland from India into western China via a northern route through Tibet or a southern route across Burma. But the first consistent references to chili peppers in local Chinese gazettes start in China’s eastern coastal regions and move gradually inland toward the West—reaching Hunan in 1684 and Sichuan in 1749—data points that support the argument that the chili pepper arrived by sea, possibly via Portuguese traders who had founded a colony near the southern Chinese coast on the island of Macao.

Historians and ethnogastronomes have been confounded by the fact that other parts of China with exposure to the chili pepper sampled it and shrugged.

Notably, in the southeast, the Cantonese easily resisted its blandishments while maintaining allegiance to their own much more subtly flavored cuisine. But in Sichuan, the chili pepper stuck. Clearly some constellation of factors made the province different.

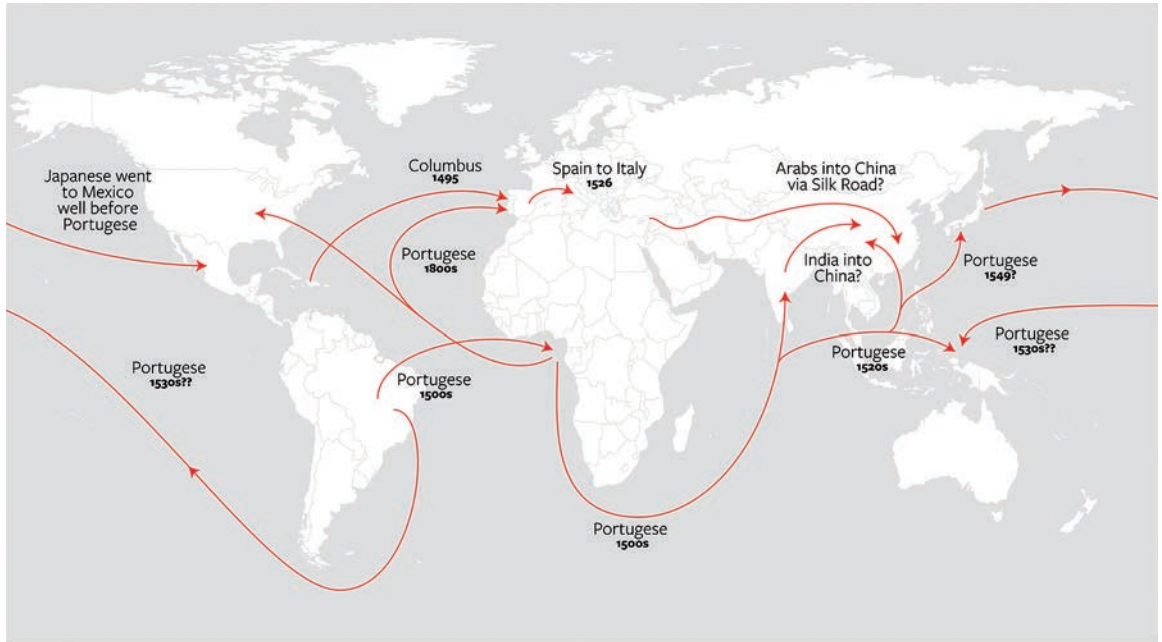
DUE IN LARGE PART to its dramatic geography, Sichuan has enjoyed a distinct historical identity in China dating back thousands of years. Separated from its neighbors by majestic mountain ranges and rivers, while at the same boasting a temperate climate and a fertile central plain so conducive to agriculture that the province was nicknamed the “Land of Plenty,” Sichuan has been a refuge when things were going wrong elsewhere in the empire.

One of the most dramatic events in Sichuan’s history came in the 17th century, as the Ming dynasty was collapsing and the Qing began to consolidate power. During the Ming-Qing transition, a devastating set of disasters—rebellions, banditry, famine—resulted in massive depopulation. The best guess is that as much as 75 percent of Sichuan’s population died or disappeared during this period.

Over the next century, one of the greatest instances of mass internal migration in the history of China substantially repopulated the province. The great majority of the new immigrants came from the two provinces directly to the east, Hunan and Hubei.

The historian Robert Entenmann wrote his doctoral thesis at Harvard on the great migration. According to his calculations, there were only around 1 million residents left in Sichuan by 1680, but between 1667-1707, 1.7 million immigrants arrived. So at about exactly the same time that the chili pepper had made its way as far inland as Hunan, the Hunanese were moving en masse to Sichuan, driven by overpopulation in their home province and sheer economic necessity.

Capsicum annuum is easy to grow in both tropical and temperate climates and maintains its potency when dried, making it ideal for long-term storage and transportation. At a time of great destruction, chili peppers were a relatively cheap source of flavor compared to salt and black pepper. As a Sichuanese folk saying goes: “Spicy peppers are the meat of poor guys.” Chili peppers also contain ample vitamin A and significant amounts of vitamins B and C. Flavorful, nutritious,



CHILI SPREAD Christopher Columbus encountered the chili pepper in the Caribbean in the late 15th century. Soon after, Spanish and Portuguese traders, obsessed with controlling the spice market, spread the chili around the globe. The red lines and dates chart the chili's path from country to country.

cheap, and easy to grow; from a purely pragmatic standpoint, the chili pepper's global adoption is easy to appreciate.

Another, more provocative explanation for chili pepper popularity holds that its geographical distribution can be explained by its purported anti-microbial properties. In a 1998 paper published in the *Quarterly Review of Biology*, Cornell's Paul Sherman and Jennifer Billing found a correlation between the mean temperature of a country (or region) and the number of spices called for in recipes representing the "traditional" cuisine of that region. The equation was simple: The hotter the temperature, the more spices consumed. Their theory: Spices performed an anti-microbial function especially useful in tropical or subtropical regions where meat was likely to go bad quickly.

Over the past decade, researchers have found evidence of anti-bacterial properties in chili peppers, and

broadly speaking, chili pepper consumption is more popular in tropical regions than elsewhere. The Sherman-Billing thesis also jibes with the traditional Chinese explanation of why Sichuan and Hunan love spice.

In her memoir *Shark's Fin and Sichuan Pepper*, Fuchsia Dunlop, an author of Chinese cookbooks, writes that the region's passion for spice is explained by the intersection between climate and traditional Chinese medicine: "In terms of Chinese medicine, the body is an energetic system, in which damp and dry, cold and hot, yin and yang, must be balanced."

Sichuan is notoriously humid—damp in the winter and hot in the summer. To counteract the soggy weather, the Sichuanese have historically spiked their diet with warming foods like garlic, ginger, and Sichuan pepper (a spice unrelated to the hot pepper that creates a numbing sensation on the tongue). When the chili pepper arrived, the Sichuanese plugged it



seamlessly into their preexisting palate.

To appreciate how deeply the hot pepper has become embedded in southwestern Chinese culture, says Gerald Zhang-Schmidt, an Austrian cultural anthropologist who lived for three years in Hunan, look at the vigorous rhetorical competition between the Hunanese and the Sichuanese on the question of which province is less afraid of the hot pepper. Both provinces, the core of China's "chili belt," exalt the stereotype of the "spicy girl" (*la mei zi*) who is "at least as irascible as the chili is hot," Zhang-Schmidt says. In a video of the pop song "*La Mei zi*" by Hunanese singer Song Zuying, scores of young, red-clad Chinese women frolic amid a harvest of tons of chili peppers, as Song Zuying sings:

As children, spiciness is not the spicy girls' fear
As adults, spicy girls don't fear the heat
Getting married, spicy girls fear that things might
not be spicy enough.

From spice girls to revolution may not, after all, be that big a step.

IN THE 1970S, ROZIN, of the University of Pennsylvania, studied the chili pepper-eating habits of Mexicans

in a small village in Oaxaca. Today he believes the fundamental reason that people all over the world eat the hot pepper is simple: for the flavor and the burn. But they're not born that way.

Unlike most foods humans are accustomed to eating, the chili pepper causes actual pain when ingested. That pain, scientists believe, is an artifact of evolution. When capsaicin comes in contact with nerve endings it trips a pain receptor whose normal function is to detect the kind of heat that is legitimately burning hot. The receptor, known as TRPV1, is designed to keep us from doing dumb things like picking up a burning branch with our bare hands, or biting into something so hot it would physically damage our mouths.

Based on his fieldwork in Oaxaca, Rozin determined that the act of eating chili peppers is an acquired taste in Mexico. Children do not come out of the womb craving a scorching hot cuisine. They're trained, by their families, to handle the chili's burn with small doses that gradually increase.

Little is known about the genetics of capsaicin sensitivity. Some variation may be linked to the same physical characteristics that make a minority of the population "supertasters," those especially sensitive to bitter tastes. However, initial adverse reactions can

be overcome by regular consumption. If you grow up in a culture where everybody eats chili peppers, you will likely become accustomed to eating chili peppers yourself, whether or not you are inherently more sensitive to capsaicin—or even more rebellious and thrill-seeking than your peers.

Nevertheless, Rozin saw that some people, even in Mexico, ate more chili pepper than others. And outside of traditional chili pepper-eating cultures, it is common to see people learn to love spicy food on their own. To explain this phenomenon Rozin came up with a theory he called “benign masochism.” A certain type of person, he theorized, was lured to the burn—the same kind of person, he suggested, who might be drawn to other “sensation-seeking” activities.

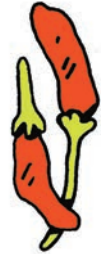
Eating chili pepper is like riding a roller coaster, he notes. “In both cases, the body senses danger and behavior normally follows which would terminate the stimulus. In both cases, initial discomfort becomes pleasure after a number of exposures.”

Linguistically and anecdotally, the association of “spice” with “excitement” rings true, but proof of Rozin’s theory did not arrive until decades after he formulated his original thesis. The missing link appeared in 2013, when two Penn State researchers, John Hayes and Nadia Byrnes, published “Personality Factors Predict Spicy Food Liking and Intake” in the journal *Food Quality and Preference*.

Hayes is an associate professor of food science at Penn State who received an NIH grant in 2011 to investigate the genetics of the TRPV1 receptor. Nadia Byrnes was one of his graduate students. In experiments conducted on 97 test subjects, Byrnes found a significant correlation between people who scored high on a “sensation seeking” scale and people who liked the burn. (Examples of questions that determined “sensation seeking” included “I would have enjoyed being one of the first explorers of an unknown land” and “I like a movie where there are a lot of explosions and car chases.”)

Byrnes, now a post-doc at the University of California, Davis, says her data shows that there are links between sensation-seeking and liking spicy food that align with Rozin’s theories “to an extent.” The data also suggest some provocative gender-based differences related to spice attraction. In comparison to women,

Eating chili peppers is like riding a roller coaster. It delivers a rush of danger and pleasure.



Byrnes says, men may be more motivated to eat hotter food because of the “extrinsic rewards” provided by society: the “cultural expectation that being male includes machismo and strength and daring—all these kinds of stereotypically male characteristics.”

So does this mean Mao was right? That there is a link between revolutionary fervor and the chili pepper?

Hongjie Wang, an associate professor of history at Armstrong State University in Georgia, specializes in Sichuan culture. In his essay, “Hot Peppers, Sichuan Cuisine and the Revolutions in Modern China,” he marshals some interesting data points supporting what one contemporary Chinese cultural observer called Sichuan’s inherent “potential for rebellion, so beautiful and marvelous.” In 1911, according to Wang, a protest against “imperialist” control of newly constructed railroads in Sichuan triggered national unrest that ultimately led to the fall of the Qing Dynasty, which means one can make the case that Sichuanese hot tempers set in motion the entire process of China’s modern political development.

In his essay, Wang emphasizes the insurgent fire of the Sichuan people. During the Sino-Japanese War between 1937-1945, he tells us, Sichuan provided nearly 3.5 million soldiers for the Chinese army, accounting

Both the Sichuan and Hunan provinces exalt the “spicy girl,” who is at least as irascible as the chili is hot.



for nearly a quarter of the total drafted forces during the wartime period. The Sichuan city of Chongqing served as Chiang Kai-shek’s war-time capital. Perhaps most compelling, he writes, of the 1,052 generals and marshals who served in the early ranks of the People’s Liberation Army, a whopping 82 percent hailed from China’s four spiciest provinces.

In Sichuan, Wang writes, “eating spicy food has come to be regarded as an indication of such personal characteristics as courage, valor, and endurance, all essential for a potential revolutionary.”

The puzzle starts to take shape. Personality: risk-taking immigrants on the move. Economics: a cheap and easy-to-grow option for adding flavor to a constrained diet. Weather and culture: a hot and humid climate, and yin and yang medical philosophy. Taken together, we see the formation of a culture, the beginning of an identity.

The final stroke cementing this modern act of identity-formation may not have arrived until the Sino-Japanese War, when the elite classes of China, fleeing to Sichuan from both the Communists and Japanese, found themselves in precisely the same kind of dire economic straits as those refugees who had immigrated to Sichuan centuries earlier. Then they too began to turn to the cheap, spicy, peasant fare that the lower classes had inadvertently nurtured into one of China’s great cuisines.

“The new wave of migration to Sichuan before and during the Anti-Japanese War in the 1930s finally witnessed the flourishing of Sichuan cuisine in today’s version,” says Wang.

SOMETIME LATE IN THE 19th century, a pock-marked woman known to history as “old lady” Chen started serving her signature dish, a blazing-hot stir-fried mixture of tofu and ground pork, in a small shop near the north gate of Chengdu.

Recipes for *Mapo doufu* vary, but a typical version includes fresh tofu stir-fried in a mixture of minced garlic and ginger, chili pepper paste, scallions, tree ears, water chestnuts, ground pork or beef, soy sauce, rice wine, rice vinegar, and Sichuan pepper. It’s impossible to single any one sensation out as more or less definitive than the other. It is the combination, the interaction of flavors, that tells the full tale.

To this day, there is a restaurant in Chengdu that purports to be the direct descendant of Chen’s original stall. And no wonder. The enduring popularity of the dish is not just about the interactive flavors. *Mapo doufu* offers an ideal metaphor for a society that thinks of itself as rebellious and revolutionary, that prides itself on its spiciness in every sense of the word.

The bite and the burn of the red chili pepper is a reminder of how the peasants of southwestern China, at the mercy of historical and economic forces, crafted culinary masterpieces from the basic instinct for survival. Out of poverty and war and the currents of globalization they fashioned fire for their palates, and ours. ☺

ANDREW LEONARD is a writer living in Berkeley, California, working on a book about Sichuan food, globalization, and the Tao.



Taste of Sichuan

If there is a single dish that most exquisitely captures Sichuan's love for the chili pepper, and perhaps its revolutionary fervor, it's *La Zi Ji*—"Spicy chicken."

The cooking process isn't too complicated—morsels of fried chicken are stir-fried with an enormous amount of chili peppers—though the visual impact is intimidating.

But have no fear, the look is scarier than the bite. The flavor of the chili pepper is blunted by the numbing tingle induced by ground Sichuan peppers (a condiment unrelated to either chili peppers or black peppers). The ensuing taste sensation is entirely unique to Sichuan cuisine.

My favorite recipe for this dish is the one below from Taylor Holliday, author of *The Mala Project*, a blog devoted to Sichuan food.

—Andrew Leonard

Chongqing Chicken With Chilies (La Zi Ji)

Ingredients

1 pound skinless chicken (dark or white), cut into 1-inch bites
 1 tablespoon Shaoxing wine
 1 tablespoon Chinese light soy sauce
 4 tablespoons potato starch (or cornstarch)
 1 tablespoon chili powder (Sichuan or, for a spicier version, cayenne)
 1 tablespoon ground, roasted Sichuan pepper
 1 heaping teaspoon kosher salt
 4 tablespoons oil
 4 garlic cloves, thinly sliced
 1 tablespoon ginger, thinly sliced
 2 tablespoons chili flakes (Chinese or Korean)
 1 tablespoon sesame seeds
 At least 3 cups, 3 ounces dried red chilies (Sichuan, Tianjin, or other medium hot chili)
 1 teaspoon red Sichuan peppercorns
 1 teaspoon green Sichuan peppercorns (optional)
 1 teaspoon sugar
 4 scallions, roughly chopped

Instructions

1. Marinate chicken pieces in Shaoxing wine and soy sauce while you prepare the other ingredients.
2. Mix potato starch, chili powder, ground Sichuan pepper, and salt in a large sealable baggie. Add the chicken pieces, leaving any accumulated juices behind. Shake the chicken pieces in the potato starch mixture until they are lightly coated.
3. Heat wok on high heat until starting to smoke and add enough canola or vegetable oil to deep-fry the chicken. If your wok or pan is large enough, you can fry it in one batch, but do not overcrowd the chicken. When oil is hot, add the chicken pieces and reduce heat to medium; the frying process should produce a medium bubble. When the chicken pieces appear to be cooked through, remove them from the oil. Return the oil to a high heat and add back the chicken. This time they should finish

frying at a high heat, about 375°F (190°C), with a large, fast bubble. Fry just until the chicken is crispy and golden brown, then remove to drain on a paper towel.

4. Pour off oil, clean wok, and return to heat. When wok starts to smoke, add the 4 tablespoons oil. Heat briefly on medium heat, then add the garlic and ginger and cook until softened. Stir-fry vigorously from now on, as you don't want anything to brown. Add the chili flakes and sesame seeds, stirring until lightly toasted, then add the whole chili peppers and Sichuan peppercorns. Stir until fragrant, then add the sugar.

5. Add back the chicken along with the scallions, and stir-fry until well mixed. Plate with chili peppers prominently displayed.



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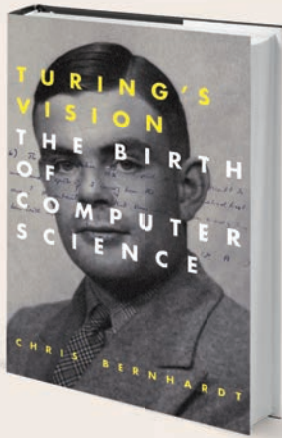
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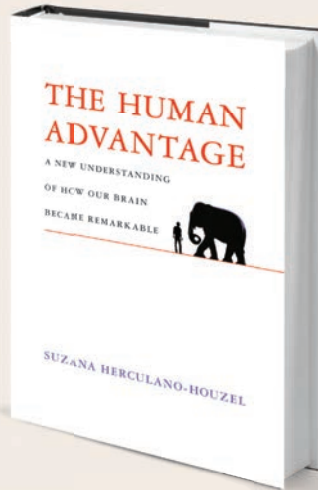
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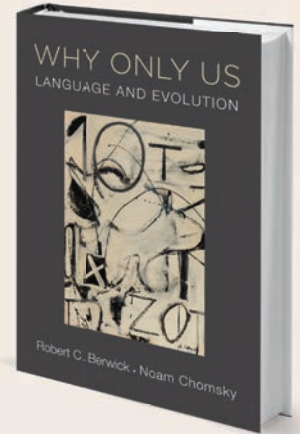
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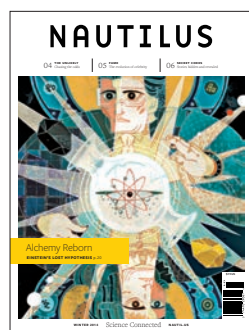
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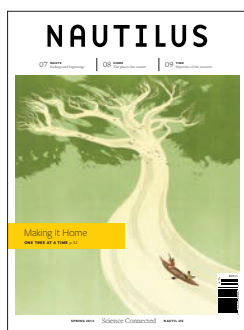
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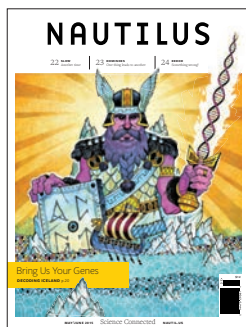
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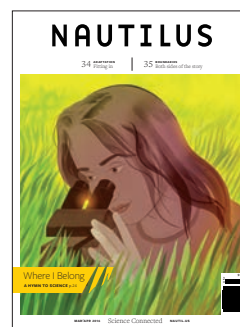
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Chiara Mingarelli

The astrophysicist reflects on the themes in Nautilus

INTERVIEW BY MICHAEL SEGAL

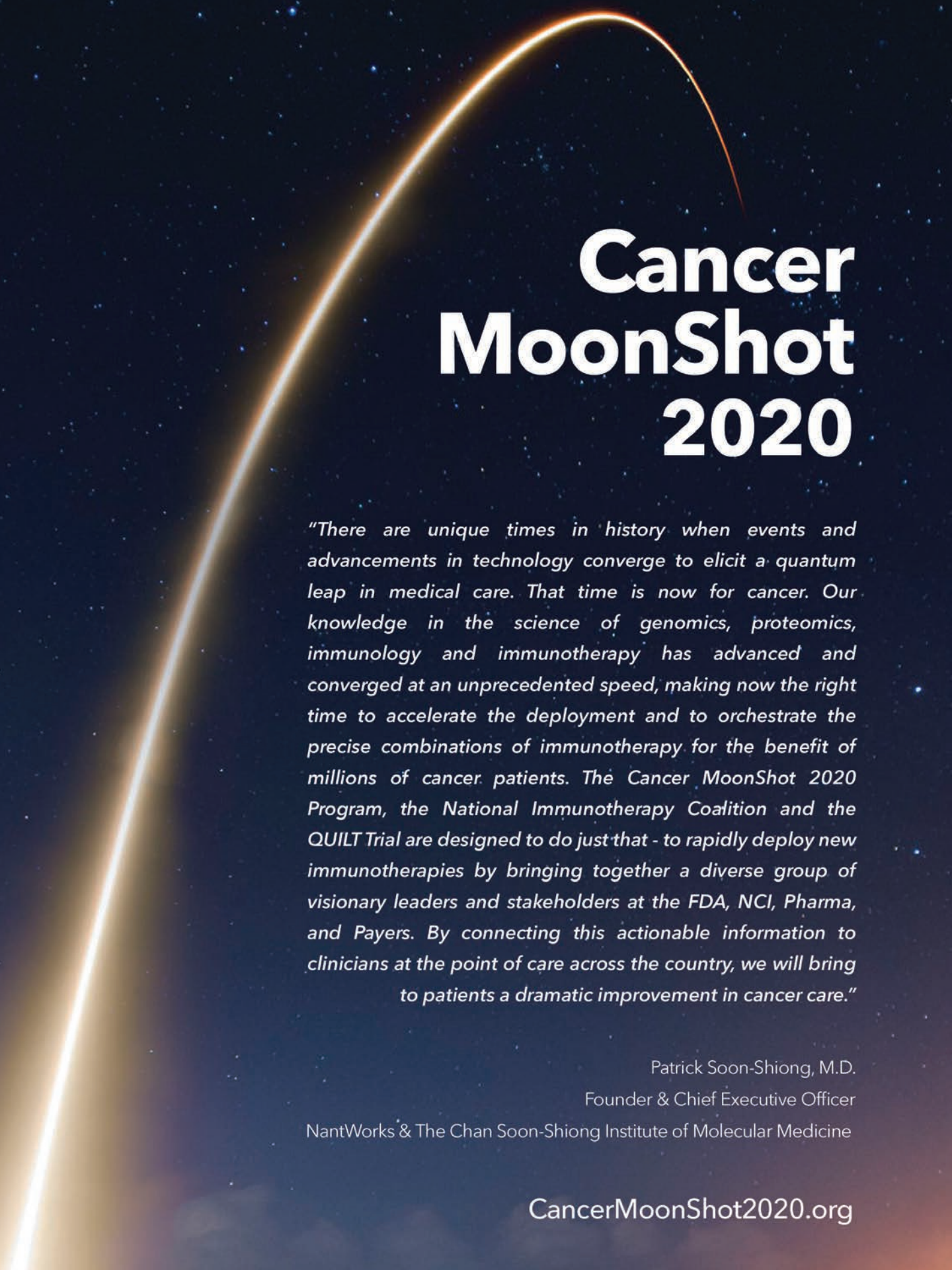
How successfully is science dealing with personal biases?

It's difficult because people have preconceived notions of what a scientist should look like, and people have implicit gender biases. You can take one of the Harvard implicit bias tests and find out that you take male scientists more seriously. Even I do! And I'm a female scientist! Acknowledging this bias exists is one way of getting rid of it. You should always try to keep that in the back of your mind when you're evaluating scientific research: Am I really looking at this objectively? It's been shown that science, when we have a lot of diversity, is just so much better. People bring in different ideas, you're more productive. But the hard reality is that people like what they know—they like having clubs who are all familiar to each other. That's really difficult to change, and I think change will come slowly.

How important is crossing boundaries in your own scientific work?

One of the things that I find the most fulfilling and enjoyable about my work with gravitational waves is looking at preconceived boundaries and then getting rid of them, using all of the information that people thought were separated into different categories and then putting it all together. This is what I did for example in a paper that I wrote with some of my Australian colleagues, where I looked at measurements of completely different gravitational wave frequencies, which when you put them together you get something much better. This is another reason why I enjoy researching the ability to bring together electromagnetic counterparts with gravitational wave signals, because again it's kind of two things which should be separate, but when you put them together you get so much more. ☺

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