

NAUTILUS

25 **WATER**
Beneath the surface

26 **COLOR**
Beyond the spectrum

27 **DARK MATTER**
All that you can't see



The Cloud Readers

HOW WE GOT THE WEATHER p.20

JULY/AUGUST 2015

Science Connected

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Popped Secret

The Mysterious Origin of Corn



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The Duel

THE WORLD, LADIES AND GENTLEMEN, is on the brink of new and terrifying possibilities.” So said Robert Angier to a hushed theater audience in the 2006 movie, *The Prestige*. “What you’re about to witness is not magic. It’s purely science.”

Among the audience was Angier’s bitter rival, Alfred Borden, who had been performing an increasingly popular teleportation trick. Desperate to copy it, Angier had approached the famed inventor Nikola Tesla, who built him a duplication machine—a real one. Angier had crossed from magic to science.

The Prestige evokes a 19th-century intellectual climate in which the ink was still drying on the modern scientific method, the boundary between science and magic seemed porous, and the public was invited to witness the latest developments in each.

It was such a climate that served as the backdrop to the duel between William Redfield and James Espy (page 20 of this issue). The two (real) American scientists played a pivotal role in the birth of meteorology, helping to transform weather from arcane to mechanistic. Both claimed to have secured the crucial insight: Redfield thought it to be circulating winds, and Espy, the rise and fall of air and moisture, driven by temperature.

Each accused the other of being wrong and stubborn, and each courted public and professional opinion through lectures and demonstrations. Among these was an attempt by Espy to create rain at will, which he failed to do, but which he preceded with such a string of boasts that the *Philadelphia Gazette* expressed concern that “men will have it in their power to fling tornadoes or chain lightning at each other, [and] we shall begin to tremble for the safety of our republican institutions.” For a *Gazette* reader, could this have been far from magic?

Of course Espy and Redfield were not Angier and Borden, because, among other things, they were not magicians, they did not try to kill each other, and their reconciliation was characteristically scientific: They were both right. Each of their observations and ideas were later subsumed in a broader, more correct and more comprehensive theory. Which might be the best magic trick of all.

Welcome to the July/August print edition.

—Michael Segal
Editor in Chief

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“At Olin I learned how to connect with people across disciplines and deal with uncertainty, skills that have been incredibly useful in a startup environment.”

- Maia Bittner '11
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Rocksbox

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Contents



Preludes

- 14 *Learning to conserve water from fiction; a language without color; the bog sacrifices; and, are there two kinds of liquid water?*

OCEANOGRAPHY

- 18 **The Ocean in Motion**

How Earth's seas get around

BY YVONNE BANG

METEOROLOGY

- 20 **The Dueling Weathermen of the 1800s**

A bitter dispute set the stage for the modern weather forecast

BY PETER MOORE

COVER Gérard DuBois

BACK COVER Scott Bakal

Themes

Each print edition identifies different themes in science and explores them from multiple perspectives.

- 34 **Water**

Beneath the surface

- 70 **Color**

Beyond the spectrum

- 100 **Dark Matter**

All that you can't see

THE LAST WORD

- 128 **Jeff VanderMeer**

The author of the Nebula Award-winning Area X: The Southern Reach Trilogy reflects on the themes in Nautilus

25



Water

“For years, I believed that my stories stood apart from myth. But that was before I visited the Tsangpo.”

—David R. Montgomery, p. 64

ASTROBIOLOGY

36 Will ET Drink Water?

The intricate compatibility of water and life on Earth may not extend to other planets

BY PHILIP BALL

GEOLOGY

44 The Last Drop of Water in Broken Hill

In the Australian outback, the future of drought has come early

BY MICHAEL GREEN

EXTRATERRESTRIAL LIFE

56 Why Discovering Martians Could Be Disappointing

There are two kinds of extraterrestrial life with very different implications

BY TIM FOLGER

MYTHOLOGY

64 The Real Landscapes of the Great Flood Myths

In Tibet, a geologist learns how folk stories may record actual catastrophes

BY DAVID R. MONTGOMERY

THEME ART Brian Stauffer



26



Color

“Before food gets to us, our eyes have already seasoned it.”

—Tom Vanderbilt, p. 78

PSYCHOLOGY

72 The Girl Who Smelled Pink

A mother wonders if we are all born with synesthesia
BY KIRSTEN WEIR

FOOD

78 The Colors We Eat

*Food color does more than guide us—
it changes the experience of taste*
BY TOM VANDERBILT

EXTRATERRESTRIAL LIFE

84 Life Beyond the Pale Blue Dot

*Our own oasis of life in the cosmos is blue,
but will others be?*
BY CALEB SCHARF

NANOTECHNOLOGY

90 The Nanopainter

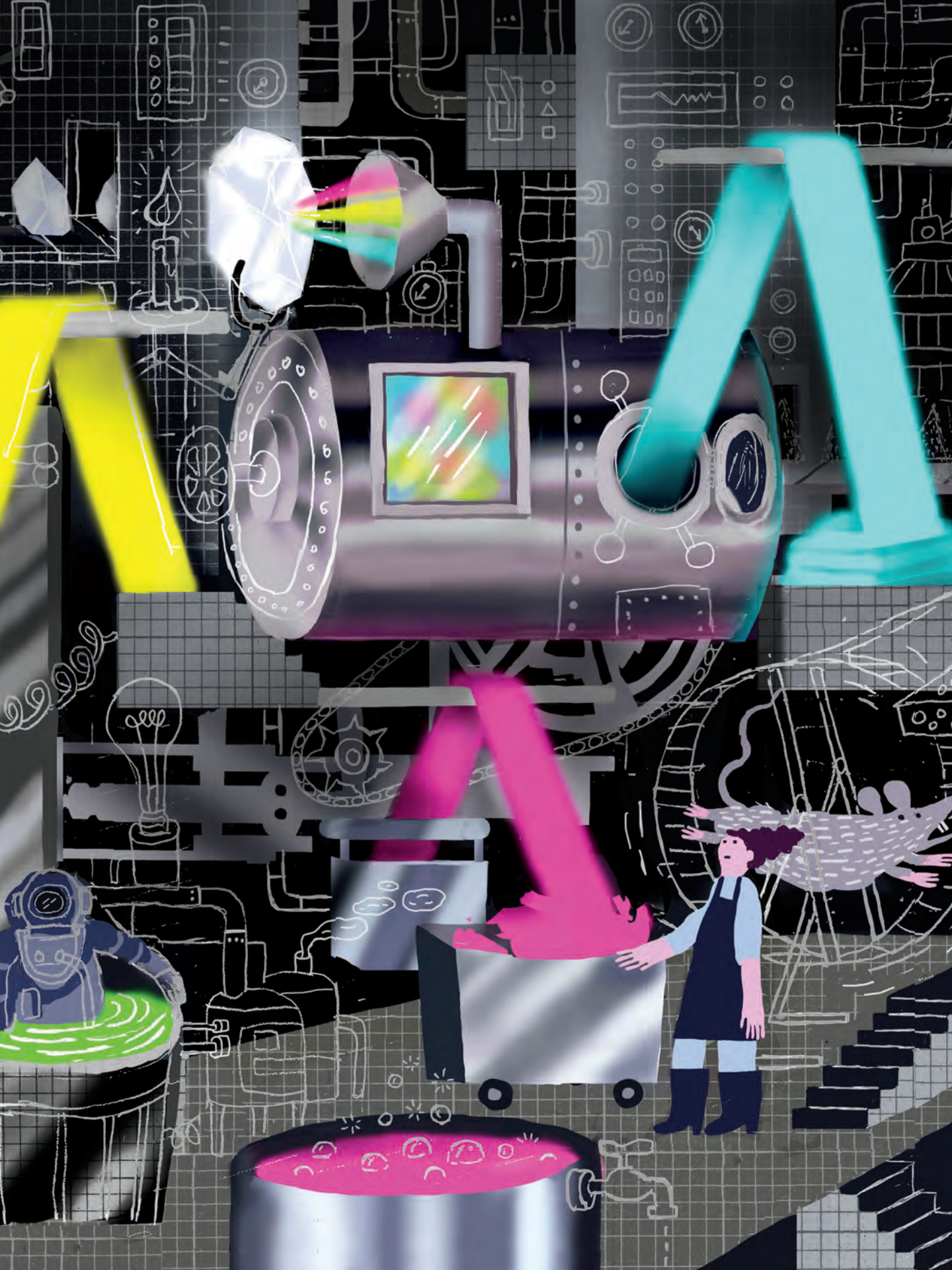
*To make new paints, artist Kate Nichols
heads to the lab*
BY JEANNE CARSTENSEN

ANTHROPOLOGY

92 About Your Skin

*What you should know about your body's
biggest organ*
BY STEVE PAULSON

THEME ART JooHee Yoon



27



Dark Matter

“Black enabled a pure abstraction.”

—Mark Peplow, p. 106

NEUROLOGY

102 Here's Why Your Brain Seems Mostly Dormant

The brilliant compromise between efficiency and ability in your head

BY KELLY CLANCY

FINE ART

106 The Reinvention of Black

As the means of creating the color black have changed, so have the subjects it represents

BY MARK PELOW

COSMOLOGY

114 What's 250 Million Light-Years Big, Almost Empty, and Full of Answers?

Astronomers are using new tools in their search for cosmic voids

BY MATTHEW R. FRANCIS

NEUROSCIENCE

118 The Neuron's Secret Partner

Glial cells are the brain's architects, doctors, police, janitors, and gardeners

BY FERRIS JABR

THEME ART Scott Bakal



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Preludes

TECHNOLOGY

To Save California, Read *Dune*

Survival on a fictional desert planet has a lesson for the drought-stricken state

FIFTY YEARS AGO SCIENCE-FICTION author Frank Herbert seized the imagination of readers with his portrayal of a planet on which it never rained. In the novel *Dune*, the scarcest resource is water, so much so that the mere act of shedding a tear or spitting on the floor takes on weighty cultural significance.

To survive their desert climate, the indigenous Fremen of *Dune* build “windtraps” and “dew collectors” to grab the slightest precipitation out of the air. They construct underground cisterns and canals to store and transport their painstakingly gathered water. They harvest every drop of moisture from the corpses of the newly dead. They dress in “stillsuits”—head-to-toe wetsuit-like body coverings that recycle sweat, urine, and feces back into drinking water.

Science fiction boasts a long history of influencing the course of scientific and technological development. “Anything one man can imagine, another man can make real,” wrote Jules Verne in *Around the World in 80 Days*. The future is as malleable as the written word.

So it shouldn’t be a surprise that two innovative thinkers devising means to address drought in California are talking about *Dune*. “I think about *Dune* a lot,” says Daniel Fernandez, a professor of science and environmental policy at California State University, Monterey. “In the book, they revere water, and ask, ‘what do we do?’ ”

Fernandez builds fogcatchers, remarkably *Dune*-like devices that have the property of converting fog into potable water. Miniscule droplets of water that make up fog adhere to finely meshed nets and drip down into a steel trough. Hoisted 10 feet above the ground, in a spot where offshore winds send Northern California’s mighty marine layer slamming into the coastal ridge, on a good day, a single fogcatcher can capture up to 8 gallons of potable water in 24 hours.

Peter Yolles, co-founder of a San Francisco water startup, WaterSmart, assists water utilities in encouraging conservation. “The cheapest water is the water we already have,” he says. WaterSmart’s strategy relies on

data crunching and clever behavior modification. Yolles says individual users are not inspired to cut back on their water use by appeals to their bottom line (cheaper bills) or potential environmental impact. What moves the needle is showing them how their use compares to their neighbors. In other words: water-shaming. The strategy is working. An independent study of one California water utility showed savings of about 5 percent after deployment of WaterSmart’s program.

The genesis of *Dune* came when Herbert worked for a string of California newspapers and wrote about a project to control spreading sand dunes with beach grasses on the Oregon coast. The project, he wrote, “fed my interest in how we inflict ourselves upon our planet.” He chose the title *Dune* because of its onomatopoeic similarity to the word “doom,” and hoped the novel would serve as an “ecological awareness handbook.” He would be delighted, then, that drip by drip, Californians are beginning to act like the Fremen of *Dune*.

— Andrew Leonard



LINGUISTICS

A Language Where Colors Are Metaphors

Does “red” mean red to you?

THE WAY DIFFERENT LANGUAGES convey information has fascinated linguists, anthropologists, and psychologists for decades. Some theorize that the way a language expresses certain concepts—like color—could have a direct influence on the way its speakers perceive the world.

According to some linguists, all individual languages have a set of specific color terms that partition the visible color spectrum. Devised by anthropologist Brent Berlin and linguist Paul Kay in 1969, the theory of “basic color terms” argued that all languages had at least terms for black, white, red, and warm or cold colors.

Not so in Yéli Dnye. In 2001, Steven Levinson, a researcher at the Max Planck Institute for Psycholinguistics, published a paper in the *Journal of Linguistic Anthropology* on Rossel Island in Papua New Guinea, which appeared to refute Berlin and Kay’s theory. Rossel Islanders speak Yéli Dnye, which is quite dissimilar to neighboring language groups. It has little specific color terminology—indeed, there is no word for “color.” Instead, speakers talk about color as part of a metaphorical phrase, with color terms derived from words for objects in the islander’s environment.

For example, to describe something as red, islanders say

In this language, color terms are derived from words for objects in the environment.

“*mtyemtye*,” which is derived from “*mtye*,” or “red parrot species.” Another example is “*mgîdîmgîdî*,” which can be used to say something is black, but is directly derived from the word for night, “*mgîdî*.” Not only that, writes Levinson, but the islander’s grammar reinforces this metaphorical slant. An islander would say, “The skin of the man is white like the parrot,” rather than “He is white.”

He also reports that in their art, islanders don’t tend to use unnatural dyes or shades, sticking to neutral tones and patterns as a means of decoration. This doesn’t mean Rossel Islanders have somehow evolved a different vision capacity from the rest of humanity. But their language may have a profound effect on how they interpret their world; it certainly impacts how they describe it.

— Claire Cameron



ARCHAEOLOGY

The Curious Case of the Bog Bodies

Why do so many corpses found in Europe's peat bogs show signs of violent death?

IN THE SPRING OF 1950, brothers Viggo and Emil Højgaard from the village of Tollund, in Denmark, were cutting peat in a local bog when they uncovered a dead man. He looked as though he had only just passed away. His eyelashes, chin stubble, and the wrinkles in his skin were visible; his leather cap was intact. The brothers called the police, but the body wasn't what it seemed.

Cracking the case required a special breed of forensic analysis. Danish archaeologist Peter V. Glob from the University of Aarhus at first thought the man's shuttered eyelids and pressed lips conveyed a peaceful expression, until he saw the noose around his neck. Glob arranged for the body, along with its bed of peat, to be excavated and transferred to the Silkeborg Museum. An examination of the contents of the dead man's stomach suggested—and radiocarbon dating later confirmed—that Tollund Man, as the corpse became known, had lived more than 2,000 years ago, in the pre-Roman Iron Age.

Since the 18th century, the peat bogs of Northern Europe have yielded nearly 1,000 human corpses dating from as far back as 8000 B.C. These so-called bog bodies are exquisitely preserved—their skin, hair, nails, internal organs, and even the remains of their meals and some of their clothes left in remarkable condition by the antibacterial properties of sphagnum moss. Like Tollund Man, many of the bodies seem to have been violently dispatched and deliberately placed in



People of the Iron Age saw the bogs as gateways to the spiritual realm.

the bog, leading some experts to conclude that the bog served as a sacrificial grave.

Radiographs of Tollund Man, for example, suggest that he died by hanging. But if he was murdered, he appears to have been laid in the bog with great care—his knees drawn up in the fetal position, his eyes and mouth gently closed. Glob and other archaeologists speculate that the people of the Iron Age saw the bogs as gateways to the spiritual realm. They left behind elaborate offerings, including jewelry, weaponry, armor, farming equipment—even butter. They may have also sacrificed humans, including failed kings, in brutal ritual killings meant to appease a fertility goddess.

—Kristen French

CHEMISTRY

One Question for Richard Saykally

Is another form of liquid water possible?



THIS IS CURRENTLY THE MOST hotly debated subject about water. It has been postulated for quite some time that when water is cooled below its freezing point there may exist two different types of liquid. Ordinary liquid water we would call the low-density form. It's proposed that there is a high-density form of water, too. Right now it's being ferociously debated, and has not been resolved.

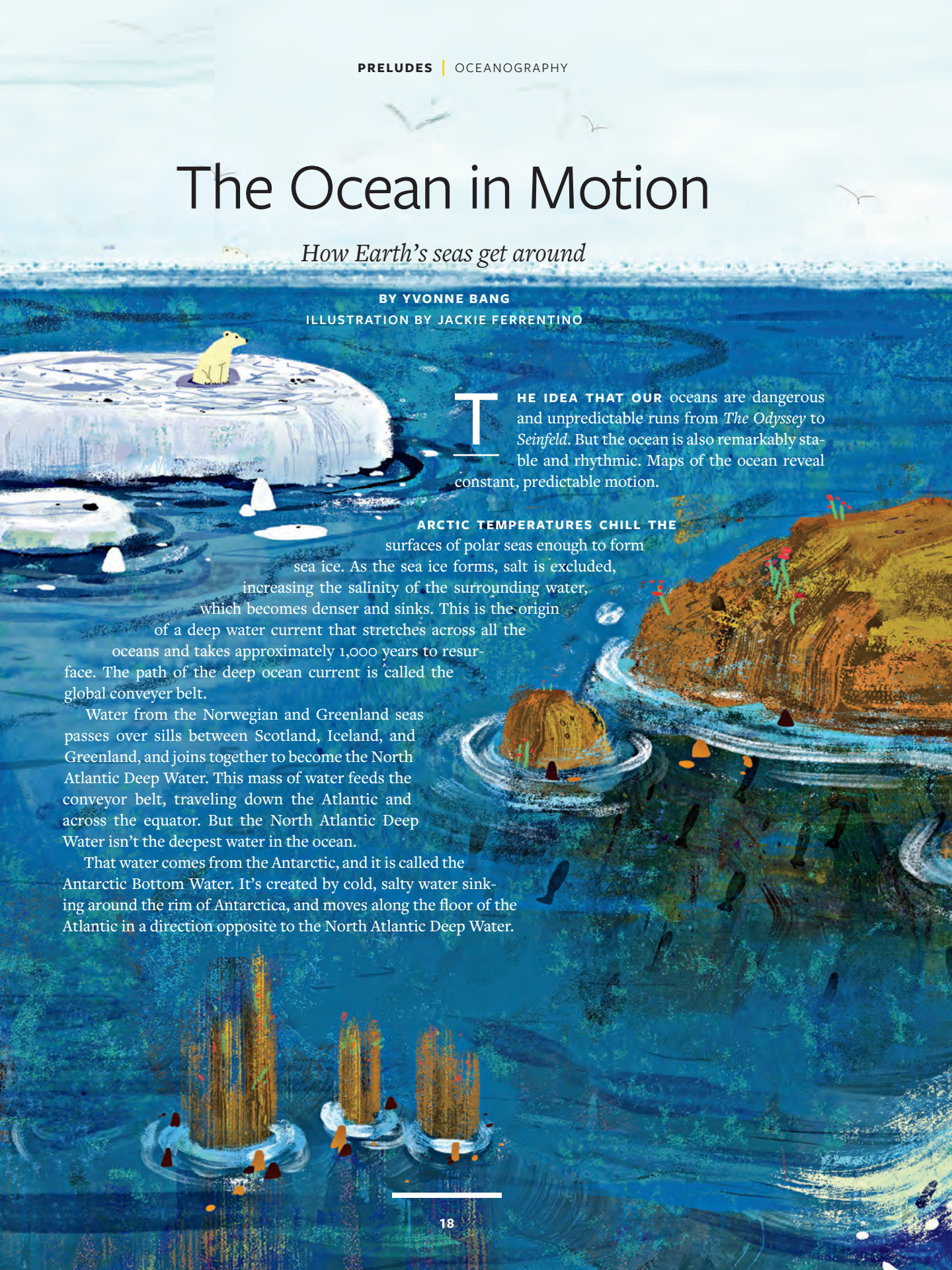
—Richard Saykally is a professor of chemistry at the University of California, Berkeley.

The Ocean in Motion

How Earth's seas get around

BY YVONNE BANG

ILLUSTRATION BY JACKIE FERRENTINO



THE IDEA THAT OUR oceans are dangerous and unpredictable runs from *The Odyssey* to *Seinfeld*. But the ocean is also remarkably stable and rhythmic. Maps of the ocean reveal constant, predictable motion.

ARCTIC TEMPERATURES CHILL THE surfaces of polar seas enough to form sea ice. As the sea ice forms, salt is excluded, increasing the salinity of the surrounding water, which becomes denser and sinks. This is the origin of a deep water current that stretches across all the oceans and takes approximately 1,000 years to resurface. The path of the deep ocean current is called the global conveyor belt.

Water from the Norwegian and Greenland seas passes over sills between Scotland, Iceland, and Greenland, and joins together to become the North Atlantic Deep Water. This mass of water feeds the conveyor belt, traveling down the Atlantic and across the equator. But the North Atlantic Deep Water isn't the deepest water in the ocean.

That water comes from the Antarctic, and it is called the Antarctic Bottom Water. It's created by cold, salty water sinking around the rim of Antarctica, and moves along the floor of the Atlantic in a direction opposite to the North Atlantic Deep Water.



THE LARGEST OCEAN CURRENT in the world, the Antarctic Circumpolar Current, runs around Antarctica. It's cold, with temperatures below 41 degrees Fahrenheit, and is motivated by strong winds. These winds also cause an upwelling—where deeper water is drawn up to the surface—of the North Atlantic Deep Water current, which joins the Antarctic Circumpolar Current.

An ocean upwelling lifts colder, deeper water to shallower depths. As the conveyor belt moves into the Indian and Pacific oceans, it loses density and rises, mixing with warmer waters above it. Surface weather, including tropical cyclones, can accelerate the mixing process.

THE OCEAN'S SURFACE CURRENTS are driven by wind and by tidal effects, which derive from gravitational forces and the rotation of the earth. Surface waters can move much faster than deep ocean currents—but they do not always result in waves. When waves do form, as the result of fast winds and other factors, they average about 12 feet in height. Fast-moving gales can kick them to 50 feet or higher. ☺



The Dueling Weathermen of the 1800s

A bitter dispute set the stage for the modern weather forecast

BY PETER MOORE

In 1800 the weather remained a mystery. The sky was the last part of nature to be classified: a relic of the arcane, chaotic world that had existed before Newton and the Scientific Revolution.

VERY FEW IN SCIENTIFIC CIRCLES would have heard of William C. Redfield's name before the publication of his storm paper in 1831. A New York businessman, he had made his name with his Steam Navigation Company. Redfield's steamers plied up and down the Hudson, from New York to Albany, carrying passengers and freight. Redfield's success had come through his natural instinct for innovation. In the 1820s, the early years of steam, passengers had been wary of traveling too close to the engines, worried that they might explode—as they often did. Redfield's solution to the problem had been simple but effective. He had designed “safety barges” for the passengers to travel in, precursors of the railway carriages of the future, drawn in strings

behind the steamer. Over time, as safety standards had improved and passengers had become more confident, he had switched his tactics: moving the passengers back into the steamer and filling the barges with cargo.

But Redfield was more than a wily businessman. He had worked as a mechanic in his youth in small-town Connecticut, and he had retained his interest in engineering. He relished the challenge of invention and was often involved in the innovation of his steamers, striving to produce his own simpler, cheaper, and safer forms of apparatus. In time, others had come to appreciate the quality of Redfield's work. He was that rare blend: a businessman with the knack of getting things done, and an inventor with an independent mind and a Yankee love of detail.

ILLUSTRATION BY GÉRARD DUBOIS

Traveling on a steamer from New York to New Haven one day in 1831 Redfield chanced to meet Denison Olmstead, professor of mathematics and physics at Yale. Spotting Olmstead on deck he had approached and “modestly asked leave to make a few inquiries” about a paper Olmstead had recently published on hailstorms in the *American Journal of Science*. Soon Olmstead and Redfield were talking about storms and it was then, for the first time, that Redfield unveiled his theory of whirling winds. It was a pivotal moment in the history of meteorology.

Redfield had devised this idea a decade before, after the “Great September Gale of 1821.” The gale—as the hurricane was then called—had sparked panic right along the northeastern coast, causing a storm surge that had flooded the New Jersey coastline as well as several streets on Manhattan Island. In the days afterward Redfield had been out walking with his son in rural Connecticut, which had been equally affected. He noticed that near Middletown, in the center of the state, trees had been blown over toward the northwest. But in neighboring Massachusetts the trees had fallen in the opposite direction, pointing toward the southeast. Redfield took this as proof that in just 70 miles the winds had reversed direction. To check his facts, he had collected newspaper reports and soon had sketched the path of the storm. It was then that, in Olmstead’s words, “the idea flashed upon his mind that the storm was a *progressive whirl-wind*.”

Not having any connection to the scientific establishment, Redfield kept his ideas to himself until his chance meeting with Olmstead in 1831. Intrigued, Olmstead persuaded him to write an article on the subject for the *American Journal of Science*. Redfield agreed, on the condition that Olmstead revise the manuscript and oversee its production. Several months later, Redfield’s article was published.

“Remarks on the Prevailing Storms of the Atlantic Coast” appeared in the July 1831 issue. Redfield, hitherto unknown, set out his case confidently. He progressed in logical steps: defining simple terms, distinguishing between winds, calms, storms, and hurricanes, “a *wind or tempest of the most extraordinary violence*. It has been stated as a distinguishing characteristic of hurricanes, that *the wind blows from different points of the compass during the same storm*.”

It was this confusion, Redfield announced, that he set out to explain. Using the September Gale of 1821, he presented his case like a prosecution barrister: noting where the storm had been at a specific time, revealing details of where the winds were blowing. He supported his claims throughout. “If our position be conceded then it is no longer difficult to explain the paradox, or mystery, which otherwise pertains to the phenomena exhibited by this storm ... We can discern the reason

The whole mechanics of a storm could be reproduced in any house in America at any time, with apparatus no more sophisticated than a cup of water and a spoon.

why, in seamen’s phrase, ‘a north-wester will never remain long in debt to a south-easter.’” He showed that the gale had begun in the West Indies on September 1, then had curled up along the coast, over Charleston in South Carolina and then Norfolk in Virginia and Delaware before thundering across New York. All the while the wind blew from different points of the compass, a fact he illustrated with an accompanying map.

This wasn’t all. Redfield claimed his whirlwind theory solved the century-old barometric conundrum. He asked the readers to perform a simple experiment:

Let a cylindrical vessel of any considerable magnitude, be partially filled with water, and let the rotative motion be communicated to the fluid by passing a rod repeatedly through its mass, in a circular course. In conducting this experiment we shall find that the surface of the fluid immediately becomes depressed by the centrifugal action, except on its exterior portions, where owing merely to the resistance which is opposed by the side of the vessel, it will rise above its natural level, the fluid exhibiting the character of a miniature whirlpool.

If true, Redfield had not only explained away the

lowering reading that accompanied the center of a storm, he had also demonstrated why the barometer should up in the moments before it arrived. The whole mechanics of a storm could be reproduced in any house in America at any time, with apparatus no more sophisticated than a cup of water and a spoon.

For the first time, too, Redfield had demystified the eye of the storm—that moment of comparative and eerie quiet when the wind died away. According to his theory this was the vacuum at the core of his whirlwind.

JAMES ESPY WAS BORN ON MAY 9, 1785 in Westmoreland County near Pittsburgh in western Pennsylvania, just east of the Ohio River. This was frontier land, an uncertain, dangerous territory. While Espy was in the crib United States troops were still marching west to Fort Washington to quell uprisings by Shawnee and Miami Indians. News from the wars filtered back in terrifying dispatches. Murderous ambushes, scalped soldiers, raids—this was Espy’s childhood world, far away from the settled east coast where the majority of the population lived in tight, secure pockets. It was a nomadic childhood, too. As the troops advanced west, so the Espy family followed—first to the Miami Valley in newly admitted Ohio and then on to the vast savannahs of the Bluegrass region of Kentucky. It was there that Espy displayed early signs of the conviction that was to characterize his life. Antagonized by slavery on the tobacco plantations

after he finished a law degree at Transylvania University in Lexington, he resolved to leave the frontier for good.

Espy was ambitious and fiercely determined. Having progressed quickly through academic ranks, by the 1830s he had become head of the classics department at the Franklin Institute in Philadelphia. There Espy worked alongside Professor Alexander Bache, the great-grandson of Benjamin Franklin and future professor of natural philosophy at the University of Pennsylvania. To Bache’s mind he was “one of the best classical and mathematical instructors in Philadelphia.” His talents did not end there. In the late 1820s he had discovered his great passion: meteorology.

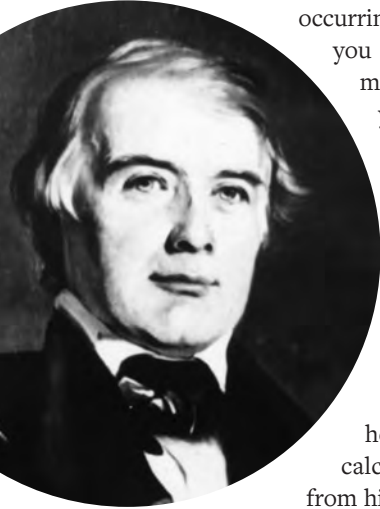
Initially Espy’s meteorological speculations were confined to short, niche papers discussing the daily fluctuations of the barometer. But using his position at the Franklin Institute, he soon established himself

as an authority. By 1834 he had risen to become the chairman of a joint committee of the American Philosophical Society and the Franklin Institute, formed to analyze storms. One of the key ambitions of the committee was to collect atmospheric data, and Espy eagerly set to work, searching for potential correspondents. He wrote to government officials, college professors, lawyers, and journalists in towns and cities across the states, petitioning them to keep weather journals. Espy cajoled his correspondents to record the wind direction and the “character of clouds”



three times a day. No one had done anything like this in America before. Soon Espy had 14 regular weather diarists sending him data from Maine in the north to Tennessee in the south. In recognition he was elected a member of the American Philosophical Society, a sign of a man on the rise.

Above all, Espy had one specific instruction for his correspondents. “We also particularly request,” he wrote, “that if you hear of any storms



occurring in your neighbourhood, you will collect all the information concerning them in your power.” Espy had a reason for making such a request. He had read Redfield’s essays in the *American Journal of Science* with increasing skepticism. Could storms really be great whirlwinds? This seemed to run against everything he had deduced in his own calculations. With the data from his network as proof, by the early 1830s Espy was already plotting to catch Redfield out.

By 1836, it was seven years since Espy had begun to formulate his own theories. Later he would describe his meteorological awakening in grandiose terms. It had come in two distinct stages. First when he was reading an essay by the British meteorologist and chemist John Dalton:

I was much struck with one of his results; namely, that the quantity of vapour in weight, existing at any time in a given space, could be determined with great accuracy in a few minutes, by means of a thermometer and a tumbler of water cold enough to condense on its outside a portion of the vapour in the air. It occurred to me at once, that this was a level with which the meteorologist was to move the world.

Excited, Espy had begun a forensic analysis of vapor. It turned out to be a fruitless enquiry. He later wrote of the labyrinth of contradictions he encountered as he battled to explain how water remained suspended

in air. Here he floundered until his second burst of inspiration—a moment on which his life shifted. It came while he was studying the precise moment when vapor condensed into the droplets that formed a cloud. Espy focused on what he termed the “latent caloric”: hidden energy trapped inside vapor as it underwent the change in state from a solid to a liquid and from a liquid to a gas. What Espy discovered startled him:

The result was an instantaneous transition from darkness to light. The moment I saw that a rapidly forming cloud is specifically lighter in proportion as it becomes darker, a thousand contradictions vanished, and the numerous facts, ‘a rude and undigested mass,’ which had been stowed away in the recesses of my memory presented themselves spontaneously to my delighted mind, as a harmonious system of fair proportion.

What Espy had realized was of crucial importance. The sudden liberation of the vapor’s “latent caloric” (today called latent heat) explained how the clouds expanded outward and formed distinct shapes. He conceived an atmospheric vision of invisible columns of air rising upward like modern-day fuel pumps to feed the clouds with condensing water vapor. This process completed a vital link in what we today call the hydrological cycle. He had shown that the atmosphere was not bound together by an electrical field or agitated into action by fumes. Instead he had discovered that it functioned according to strict mathematical principles, with water vapor the essential component in a circulatory system—like blood being pumped around the human body.

Studying water vapor was nothing new. Ever since René Descartes had challenged the orthodoxy that all invisible gas was air in the 1630s, philosophers had considered the study of vapor an important enquiry. Descartes had argued that vapor existed independently of air, and that it somehow had the ability to rise upward. But it was difficult to explain where it got its buoyancy from. And, from there, more troubles emerged. Once vapor had transformed into cloud droplets, how did it stay afloat? If clouds contained thousands of metric tons of water, how could they possibly be suspended in the sky when water is hundreds of times denser than air? For centuries this had been one of nature’s great paradoxes.

The most widely held theory was that clouds

comprised minute particles called “vesicles,” fragments with their own distinct gravity that kept them buoyant. Vesicles were “innumerable small globes filled with damp air, analogous in some way to soap bubbles,” or better imagined as minute aerial zeppelins that roamed the skies. The Swiss physicist Horace-Bénédict de Saussure claimed to have seen vesicles on an Alpine hike, the drops floating “slowly before him, having greater diameters than peas, and whose coating seemed inconceivably thin.” It was a vivid image, but the theory was dogged with problems. How did vapor transform into vesicles? Where did this gravity-defying power come from? What were vesicles? And how did they transform into rain, snow, or hail?

The accepted theory of rain was proposed by James Hutton to the Royal Society of Edinburgh in 1784. Hutton believed rain was caused by the “mingling together of great beds of air of unequal temperatures, differently stored with moisture.” The mixture of these beds of air created what Hutton called an atmospheric imbalance that resulted in rain. Espy’s idea, though, was different from the start. He concentrated on columns of rising air. This notion of an ascending current had appealed to several scholars before, particularly the French physicist Marcellin du Carla and more recently another Frenchman, Joseph Louis Gay-Lussac. Both du Carla and Gay-Lussac had published papers on the subject, catching the attention of the German geologist Leopold von Buch. In turn von Buch had told the Berlin Academy of Science that “the principle of ascending currents of air should really be called the key to the whole science of meteorology.”

Espy had witnessed these currents himself. A member of the Franklin Kite Club of Pennsylvania—an organization with impeccable meteorological credentials—he had often noticed how his kite was tugged up by rising air. These columns (today known as thermals) were most prevalent on days when the cumulus clouds formed “rapidly and numerous.” The updraughts become “so familiar,” he wrote, “during the course of their [the kite-flyers’] experiments that, on the approach of a columnar cloud just forming, they could predict whether it would come near enough to affect their kites.”

Certain he had unlocked the process behind the formation of clouds, Espy was confident enough to dispel

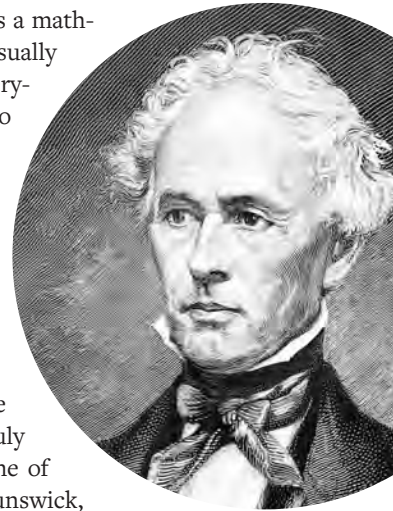
the old belief that they floated at all:

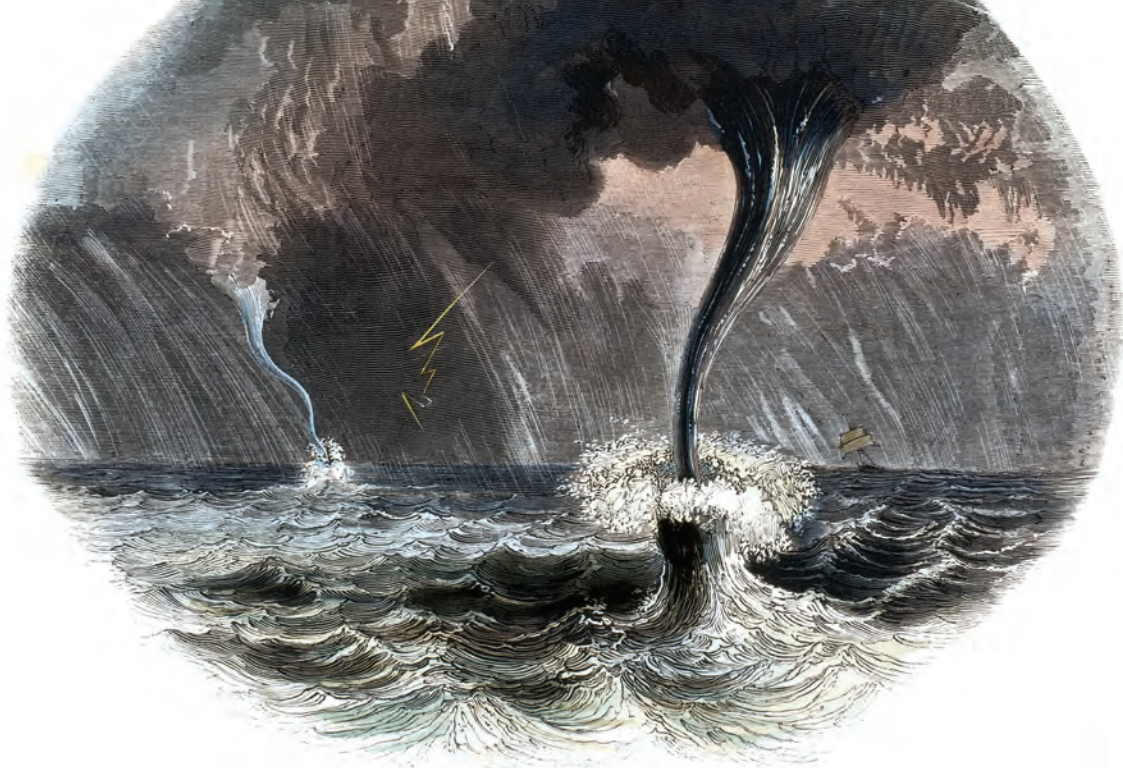
It is not necessary to inquire, as is frequently done, by what power are the clouds suspended in the air, unless it can be shown that they are suspended, of which I think there is no probability ... We have every reason to believe ... that the particles of cloud begin to fall through the air ... as soon as they are separated from the up-moving column of air, by means of which the cloud was formed.

By now Espy was envisaging an entire dynamic weather system: ascending currents of warm air drawing up vapor, the vapor condensing at a specific height, expanding and forming clouds, and then the water droplets falling back to earth. Under different atmospheric conditions, Espy realized, this system of vaporous circulation was capable of producing every type of precipitation: rain, snow, or hail. His task then became to calculate specific circumstances. What temperature was needed to produce snow? What expansion of water vapor would be required to generate a 20-mile-wide hailstorm?

He worked at these calculations in the backyard of his Philadelphia home on Chestnut Street. His background as a mathematician made him unusually adapted to this work. Everything became a problem to be solved through minute study. His elevation to chairman of the Meteorological Joint Committee gave him the opportunity to model his theories using real-life data and he sought to augment this data store whenever he could. In July 1835 he raced to the scene of a whirlwind in New Brunswick, determined to write up the case.

William Redfield, too, visited the site in the hope of gleaning evidence for his theory of whirling winds. Although Espy did not meet Redfield he was well aware of his ideas. He had studied them in the scientific journals. Espy bided his time, saying nothing.





Redfield's idea of circular winds was clearly perplexing. Espy could find no reason why winds should dart about the central axis of a storm. Eventually he concluded that Redfield was wrong. A more logical answer, Espy reasoned, was that winds rushed toward the central column at the core of the storm as air in a room would be drawn in toward a burning fire—cool air from beneath replacing the warm heat traveling upward. The science behind this idea was sound. In a powerful storm, Espy thought, the effect would simply be magnified.

Espy chose to unveil his ideas in the inconspicuous *Transactions of the Geological Society of Pennsylvania* in 1834. It was a cautious move, testing the water. Another two years passed until he was ready to bring his case before the wider scientific community, in April 1836. He now turned to his spiritual home, the *Journal of the Franklin Institute*. He aimed to impress. Full of confidence he announced:

Gentlemen, I send you now, for publication, the first of a series of essays on rain, hail, and snow, water-spouts, land-spouts, winds, and barometric fluctuations, in which, I hope, it will be found that I have successfully traced these phenomena to their true causes ... I promise the reader, in advance, that he will find developed in the following essays, a law in meteorology, which, founded on acknowledged dynamical principles,

explains at once, with a simplicity which nothing but nature can equal, all the seven phenomena mentioned above.

The importance of this law will be readily admitted, when it is understood that by it may be known whether there is a great storm raging at any time within four or five hundred miles of the observer, and also the direction of that storm, with the means of avoiding it, if the observer is at sea.

Yours, James P. Espy

It was a grandstanding announcement, the words of someone who did not doubt himself; not for a moment. Espy set out his case with a study of hail. He showed the evolving path of water vapor: rising from the earth, freezing in the atmosphere, falling over a specific area. He supported his argument with press reports and using his powers of rhetoric learned from his 25 years of teaching.

So bold was Espy's theory that it instantly caught attention. Admiring articles appeared in the press and were republished across the Atlantic. For his Theory of Hail he was awarded the prestigious Magellanic Prize by the American Philosophical Society. Suddenly the Pied Piper of American science, he turned his pen to a new purpose: to destroy all opposition to his ideas. This included Redfield and his concept of whirling

winds. He resolved to take an axe to Redfield's theory and chop it down piece by piece.

REDFIELD FIRST BECAME AWARE of James Espy in early April 1835, though he did not quite know it. His attention was caught by an anonymous article, "Notes of an Observer," that had been published the previous year in the *Journal of the Franklin Institute*. The piece was a critique of one of Redfield's articles for the *American Journal of Science*. Couched in the deferential style of the day, it had begun by praising Redfield's nimble prose as well as his "laborious" efforts on behalf of science. Then it changed tack. The anonymous author revealed that he was disturbed by a number of Redfield's assertions. They were, he pointed out, "so anomalous and inconsistent with received theories" that he could not put entire trust in them, "and shall continue to doubt until I have the most certain evidence of the facts."

The "Notes of an Observer" was a short article with enormous incendiary capacity. Issues like this were often chewed over in public but by several measures the piece fell short of the strict norms of the day. Firstly it was published in a journal unconnected to Redfield—making it likely that he would not see it and thus robbing him of the right of reply. Secondly it skipped over the central tenet of Redfield's argument. No mention, however brief, was made of his theory of circular winds. Such silence gave the piece a contemptuous air, bound to nettle. It was no surprise that Redfield remained entirely unaware of it for 14 months until, in his own words, he chanced upon it. Aggravated, he sought to swat it away. Keen that his prolonged silence should not be misinterpreted, on April 8, 1835 Redfield sat down at his desk in New York City and dashed off a reply. The author of the anonymous piece was James Espy and this would be far from the end of the matter. It would mark the opening volley in a long war of attrition.

Redfield's response was curt. He sent it straight to the editor of the *Journal of the Franklin Institute*. He admitted that his claims about barometric variations in Edinburgh were wrong but brushed aside the other criticisms. Redfield was particularly scornful of the suggestion that his idea was speculative and "inconsistent" with known science. Why should an idea be rejected or doubted for no better reason than being inconsistent or eccentric? "Before we consent to give credence to new

theories it may be well, perhaps, to inquire when and in what manner the 'received theories' in meteorology have been demonstrated to be true."

Redfield asserted that he had read a sufficient amount to convince him of the folly of studying the flow of heat. He dismissed this as an "error into which the whole school of meteorologists appear to have fallen." Heat flow, Redfield wrote, might plausibly affect local weather—land or sea breezes—but it was far from being the prime factor in macro-atmospheric events. He repeated his assertion that storms were whirlwinds and, he added, this is caused by "the rotative motion of the earth upon its axis."

Redfield's thinking had progressed. No longer did he restrict his atmospheric investigations to storms: He was projecting them on to a bigger scale. He was beginning to see the sky as a theater of moving parts governed by Newtonian laws of force and attraction. Essentially his ideas were drawn from his background as a mechanical engineer. He thought the atmosphere had a collection of great cogs and wheels like those of his steamers or George Stephenson's revolutionary locomotive Rocket.

There matters rested until April 1836, when Espy's series of meteorological essays started to appear. At first Espy concentrated on establishing his own ideas but by July he was ready to attack Redfield openly. In "Examination of Hutton's, Redfield's and Olmstead's Theories," Espy set about dismantling Redfield's ideas with the confidence of a man triumphant. No longer firing his arrows from the shadows, he was happy to attack his opponents directly. His critique of Redfield focused on the central claim of his theory: the evidence of the 1821 September Gale. "Now it will appear by little reflection that all these facts agree with the idea of an upward vortex more consistently than with a horizontal whirlwind," he pointed out. What would happen, Espy argued, when the winds that Redfield claimed rushed at each other met in the atmosphere? "All the facts lead to the conclusion that in the storm at least the wind in the neighbourhood of the storm blew directly towards the centre and if so, it follows beyond all doubt, that there was an upward vortex in the middle of the storm."

Not only was Espy's prose bold, it also had a pompous edge. Academic discourse was governed by the

same strict code of gentlemanly civility that dominated intellectual society, from politics to religion. At times Espy seemed waspish and condescending. None of his barbs would have cut deeper than the claim:

If Mr. Redfield should perceive that all the interesting facts which he had with such laudable industry collected, are fully explained by a theory which accounts also for the rain, I am sure he will not be very tenacious of his horizontal whirlwind; especially when he does not pretend to show that either the whirlwind is the cause of the rain, or the rain the cause of the whirlwind ... I should be proud to list Mr. Redfield under the banner of a true theory.

But Espy was about to discover that Redfield was no timid opponent. He hit back seven months later, in February 1837. Writing in the *Journal of the Franklin Institute*, he titled his piece bluntly, “Mr Redfield in Reply to Mr Espy on the Whirlwind Character of certain Storms.” He announced that he had no wish to defer to Espy’s theory of an atmospheric chimney. Instead he stood by the validity of his data and revealed that he had much more evidence than he had yet published. Redfield’s reply covered 15 scornful pages and stretched to around 10,000 words.

Already both men were entrenched. To Espy, Redfield’s position was weak. He had no overarching theory, just a mere collection of nebulous observations about tides, and his great claim of whirling winds did not fit with any facet of known science. To Redfield, Espy was plain wrong. Enamored with his idea he had grown too cavalier, too bombastic, and as a result he had closed his mind to the realities of fact. “Mr Espy says that steam is the moving power in storms,” Redfield wrote, certain he had caught Espy out on a point of logic, “but there is a much smaller supply of this moving power in winter than in summer and yet the greatest storms appear in winter.” How could it be?

Espy ignored the point. And while a resolute Redfield vowed to produce more data to consolidate his position, Espy opted to take his ideas out on the road. The first of his lectures took place in November 1836 when he spoke before a “large and respectable body of merchants, under writers, masters of vessels and others” at the Exchange in Philadelphia. “The views of the Lecturer are not only new, but exceedingly ingenious

Espy had formed a new pet idea and had started to advertise it at his lectures. He was claiming to be able to create rain.

and interesting, and calculated to convince any one who had not hitherto examined the subject,” reported the *New Bedford Mercury*.

Espy’s Philadelphia lecture was a prelude to a tour of the popular Lyceum circuit over the next four years that would take him to Harrisburg, New York City, Nantucket, Boston, and a host of other locations. Standing on the stage with his charts and his nephelescope cloud chamber, he employed his gift as an orator and his natural charisma to make science accessible for a wide audience, logically explaining his arguments and citing his position as chairman of the Joint Committee as proof of his authority. It was a formidable combination. Glowing reviews followed in the local newspapers, and the appearances had the secondary benefit of boosting the size of his weather network. On April 1, 1837, the legislature allocated a \$4,000 grant to a state-wide, Espy-led meteorological investigation, and in January 1838 the Pennsylvanian representatives were handed a petition that called for Espy to be appointed as official meteorologist of the state.

His ambitions did not stop there. With his friend Professor Bache poised to depart on a European tour in 1836, Espy wrote, “Please present to Dalton, Faraday, Brewster, Forbes, Airy, Apjohn, Daniell, Whewell, Scoresby or if not convenient to them to any others you may find interested in the science, those essays of mine already published on the Theory of Rain, &c.” Europe was an exciting proposition. Espy knew that in America he had already gained an influential power base. But to plant his theory on an immovable footing he needed the backing of at least one of the great European men of science, a name whose reputation would dazzle. What such support could mean—funding from Congress, moral authority—he could only guess. Espy

knew that a meeting of leading British scientists would take place in Newcastle upon Tyne in August 1838 and with Bache as his ambassador he hoped to have his ideas presented to the judges that mattered. But, unknown to Espy, his wily combatant Redfield would soon outflank him. Waiting in the wings Redfield had acquired an ally of his own who was about to tip the scales. His name was William Reid.

BY 1838 REID HAD BEEN RESEARCHING storms for six years. He had worked with military precision, exploiting contacts during his spell in the Caribbean to locate as many sources as possible. The notes had piled up, and by the start of 1838 he had started to draw them together. By February 1 he had progressed enough to introduce himself to Redfield. He began a letter to Redfield in New York, telling him he had read “with good attention” his ideas on storms and that he had been “impressed with the importance of the subject.” He said he was planning to publish a paper on storms for the Corps of Engineers and he sent him some example charts. “I think what I am giving will be gratifying to you; and I beg leave to say it will give me great pleasure to hear from you on the subject.”

It had taken two months for Reid’s letter to reach New York, but when he read it Redfield was delighted. “It affords me much satisfaction to find that inquiring into the true nature of storms is beginning to excite interest on your side of the Atlantic, and the observations which a residence in the West Indies has afforded must give you peculiar advantages in pursuing the subject.” It marked the beginning of a long and warm friendship. During the spring and summer of 1838 Reid and Redfield corresponded often.

They shared data from ships’ logs, newspaper cuttings, and plans for publishing ideas. Redfield congratulated Reid on the quality of his charts, which he thought “beautifully executed.” When Reid mentioned that he had noticed some of Espy’s essays on sale in London, Redfield cautioned him. “I am informed that he is an ardent and at the same time an amiable man; but having examined his evidence in the cases on which he relies, and collated it with such facts as are in my possession, I feel justified in stating that not one of his cases can be sustained.”

The friendship between the men was already

blossoming by August 1838 when Reid decided to travel, by “some degree of accident,” to the annual meeting of the British Association for the Advancement of Science. Some of the pre-eminent minds of British science steered its executive committee, including Sir John Herschel, the exceptionally able, famous son of Sir William Herschel. Now 46 years old, Herschel had already founded the Astronomical Society, served as secretary of the Royal Society, made huge contributions to both physics and astronomy and written his fabulously successful *Treatise on Astronomy*. Others on the committee included Sir David Brewster, the Scottish “Father of modern experimental optics” and inventor of the kaleidoscope, and John Frederic Daniell, respected for the Daniell cell battery as well as his hygrometer. The Association meeting for 1838 was to be held in Newcastle upon Tyne—in an effort to get away from London a different provincial town was chosen each year—and more than 2,000 tickets had been sold to the lectures that were to be held on a range of topics.

Among the speakers was William Reid who, by chance, had been asked to present a lecture on his storm research. His lecture on Monday, August 20 before a packed crowd turned out to be one of the highlights of the week. Reid introduced Redfield’s theory of circular winds, explaining how reading the article had set him off on his quest. It was the first that many in the room had heard of Redfield and Reid explained how he had endeavored to test the theory against as many historical examples as he could find. “The more exactly that this was done,” Reid revealed, “the nearer was the approximation to the tracks of a progressive whirlwind.” One by one Reid presented a series of eight historical examples. “My object is not to establish or support any theory,” he said, “but simply to arrange and record facts.” It was an enterprise of pure Baconianism, free from faction and bias. His audience loved it. He left them with a final, tantalizing finding: that while all the storms he studied in the northern hemisphere blew in an anticlockwise direction, he believed all those in the southern hemisphere revolved in the opposite way. His theories, he told the audience, were collated in his forthcoming book, *An Attempt to Develop the Law of Storms*.

Reid’s *Law of Storms* turned out to be a highly practical work crammed with expert research. It included

tips for mariners, accounts of exemplary storms, and cut-out diagrams, charts, and real-time maps for reference in a storm. It was reviewed enthusiastically.

When his copy arrived in New York in October, Redfield was thrilled. "It is just such a work as I have long wished to see undertaken by one who comprehended the subject and had leisure and means to establish the subject in a detailed manner." An unexpected hit, the book also managed to catch the attention of Whitehall's political elite. Reid was appointed governor of Bermuda, as it was "a position peculiarly favourable for carrying on his valuable researches." More developments followed. On Jan. 3, 1839, Reid wrote to Herschel revealing that Lord Melbourne's government was putting its might behind his project. Lord Glenelg, Secretary of State for War and the Colonies, had told British governors across the globe to keep weather journals and to record any unusual meteorological phenomena. Results were to be transmitted to the Colonial Office every six months. The Admiralty had acted also. As well as purchasing a number of Reid's books to distribute among intelligent officers, they had ordered ships' captains as well as ports, harbors, and lighthouse keepers to begin observations, too.

Reid's appearance at the British Association was a watershed moment. Years of patient research had combined to show Britain's scientific community what was possible. In the months before he left for Bermuda he became a familiar

name in the newspapers. His election to the Royal Society was fast-tracked. His nomination slip read, "Lieutenant Colonel William Reid, CB, of the Royal Engineers a Gentleman much attached to science and author of a Work On the Law of Storms." Among his proposers were Sir John Herschel, future president Edward Sabine, polymath William Whewell, and the old weather hand Francis Beaufort.

AFTER THREE YEARS in the ascendancy in America, Espy's ideas had been swept away with barely a whisper in the halls of European science. News of Reid's triumph traveled across the Atlantic along with a copy of Reid's *Law of Storms*. Espy was shocked. Expecting to hear that his theories had been heard and praised, instead he learned that even Sir John Herschel had sided with Reid and Redfield. Espy responded in indomitable style. He sought to discredit the data in Reid's

book, twisting it to fit his own model rather than Redfield's.

He did not tolerate conflicting facts and derided them as errors that needed stamping out. This was too much for Redfield, who by now was monitoring the *Journal of the Franklin Institute* like a hawk. For some time he had hoped to settle the dispute. "I have contented myself thus far with an attitude towards him which is strictly defensive," he wrote. Another time he had even knocked at Espy's door in Philadelphia to introduce himself. Unfortunately, Espy was out.

In the spring of 1839 Redfield's tone



changed. He wrote apologetically to Reid, “Mr Espy continues to busy himself with his theory of aqueous condensation. His late amusements, as I am informed, have given offence to the savants of Philadelphia to whose friendship & support he is mainly indebted.” Another time he raged, “It is a matter of sincere regret with me that our friend Espy is not content with his own conclusions ... relating to the storm of 1821, as you have seen in the March number of the *Journal of the Franklin Institute*. To this I have felt it necessary to reply and speak with some freedom as well as candor of his general course of proceeding in this matter, all of which I was desirous to avoid.”

It was not long before Espy felt the full force of his invective. In July 1839 two waspish articles appeared in the *Journal of the Franklin Institute*, the one true beneficiary of the brouhaha. Redfield expressed his objections with caustic lucidity. He pulled Espy’s analyses apart storm by storm. He derided Espy’s mission to “explain nearly all the physical phenomena of the atmosphere by the theory of aqueous condensation” and regretted that he had been supported by “plausible but erroneous inductions” and “friendly, though perhaps injudicious support and announcements from highly respectable sources; and aided also by the favor and guardianship of the Philadelphia press.” He lampooned Espy’s “modest” announcement of April 1836 and complained that he had spent far too much effort trying to fit the facts to the theory rather than the theory to the facts. Espy’s attempt to connect every single atmospheric process to his ideas, Redfield complained, had become “not unlike that of him who in essaying to climb should commence at the last and highest step in the ladder.”

No longer friendly joshing, by now the furor was generating national coverage. *The Knickerbocker*, perhaps the most influential literary magazine in America, rejoiced in Redfield’s assault, proclaiming Espy’s ideas “essentially demolished.” Suddenly Espy’s reputation was in danger of unraveling. Partly this was due to Redfield’s exposé but it was also due to something even more improbable. Over the last few months Espy had formed a new pet idea and had started to advertise it at his lectures. He was claiming to be able to create rain.

ESPY COULD HAVE HARDLY CHOSEN a more inflammatory path. Many had toyed with meteorological

Benjamin Peirce, the Harvard mathematician, said: “Even storm kings are intolerable in a republic.”

theory over the years, but few had aspired to command the elements themselves. But while the rain-making idea seemed ridiculous, to Espy it was merely a logical extension of his thinking. Now he had demonstrated how clouds and rain were formed, what better than a practical demonstration to prove him right? The 1830s had seen a craze for public experimentation most recently with early demonstrations of Daguerre’s photographic process. For a country growing increasingly used to ground-breaking inventions—the decade had already seen the appearance of ether-based anesthesia, grain elevators, a hand-cranked ice-cream machine, the first combine harvester, a steam shovel, and a lockstitch sewing machine—the idea of creating rain tapped into the spirit of the age. Anything was possible.

Espy reasoned that if he produced a steady, controlled column of ascending air it would draw up the atmospheric vapor. When this vapor reached the ideal altitude it would condense into water. All that was needed was to produce a steady column of heat and the atmosphere could be modeled artificially. In some places this already happened, Espy told his audiences. He cited London—the most populous city on the planet—as an example, claiming that the hundreds of thousands of billowing chimneys combined to create a rainy micro-climate in the Thames Valley.

The American government was currently overseeing a vast process of deforestation in the newly settled states and Espy seized on this. If the government would let him start strategically placed fires in the west, he could exploit the prevailing winds to bring rains to the eastern states. The benefits would be immense. Canals could be filled with water to prevent drought. Farmers would be able to manage precipitation to produce perfect crops.

At the start of 1839 Espy approached Congress,

proposing to test his idea. The plan excited and terrified in equal measure. The *Philadelphia Gazette* published a succinct appraisal of the dilemma:

If our indefatigable friend Espy should succeed in establishing his theory with respect to the rains he will have effected a more wonderful improvement upon the weather, which, it must be confessed, is often sadly deficient in rectitude of conduct. The times of drought and ‘some potatoes’ will cease—for every farmer will have it in his power to burn a pile of wood, and grow his own thunderstorm. Think of taking out the copyright of a tempest or a patent for a whirlwind! The danger is, we think, if Espy succeeds, and the *modus operandi* of his system becomes known, that any one who likes will take possession of it, and create much mischief thereby—Naughty persons would cultivate storms from malice aforethought;—and they would come in time we fear, to conflict with the freedom of elections. The fires of party spirit would result in a deluge; and success, irrespective of the merits of measures or men, would crown the side that could make the most water! The progress of storms may yet be so great that a man may travel whithersoever he listeth by fastening to his carriage front a huge boiling tea pot, on wheels, and when this shall come to pass, and men will have it in their power to fling tornadoes or chain lightning at each other, we shall begin to tremble for the safety of our republican institutions.

Elsewhere Espy’s proposal elicited different responses. In February 1839 the *New Hampshire Sentinel* politely wondered whether “Mr Espy would put his weather machine in motion and give us a good storm of snow—just enough to make good sleighing and no more—we would thank him in the name of the thousands of people who have not heard a set of sleigh bells this winter.” In July the New Orleans *Times-Picayune* revealed, “On Friday we prayed for a ‘forty horse Espy power’ when lo! on yesterday morning, while yet in our gown and slippers, performing our diurnal ablutions, the rain descended in torrents, and with a force and velocity as if impelled by a power unknown to modern mechanics. Flash! flash! flew the lightning—and Boom! boom! went the thunder.” Indeed some wit in the *Times-Picayune*’s newsroom had developed a special interest in the story. The writer tracked Espy’s lecture tour, noting the strange frequency with which his arrival in a town was preceded by a sharp shower. The paper started to refer to Espy as “Professor of Thunder and Lightning.”

Once Espy even inspired the *Times-Picayune* to poetic rapture: “I feel myself dissolving now—up in the clouds that’s plain! Where’s Mr Espy? In thin air, Diffused—evaporated, Without him, ne’er again I fear, To be precipitated.”

His friends realized that Espy was risking his reputation. He seemed to have forgone the sure and steady ground of science for a hopeless, hubristic scheme. His rain-making claims certainly brought him attention—the English essayist William Hazlitt once wrote that “The world loves to be amused by hollow professions, to be deceived by flattering appearances, to live in a state of hallucination; and can forgive everything but the plain, downright, simple, honest truth”—but was it the type of attention he needed? Bache ruminated on the “strange course recently taken by my friend Mr Espy,” while another of his circle, Joseph Henry, worried that he sometimes exhibited a “want of prudence.”

But Espy continued. In 1839 he petitioned Congress to back him publicly, asking for a grant of \$25,000 in return for making rain over 5,000 square miles or \$50,000 in return for an area over 10,000, “or in such quantities as shall keep the Ohio River navigable during the whole summer.” In the middle of a crippling financial crisis, it was no surprise that Espy’s request was turned down. Instead he was left to debate with Professor Olmstead, Redfield’s ally, at a series of public lectures in New York. The lectures were typically heated—both Olmstead and Espy passionate advocates of their ideas. Redfield kept Reid abreast of all this in his letters. “Mr Espy ... has lately given a course of lectures in this city, which was rather thinly attended. He maintains a thorough system of newspaper *puffing* and in this he has full swing, no one being disposed to enter the field as his antagonist.”

Espy’s aggrandizement was beginning to annoy some. Benjamin Peirce, the Harvard mathematician, moaned about Espy and his “air of self-satisfaction: Even storm kings are intolerable in a republic.” Espy succeeded in also irritating the old president, John Quincy Adams, who observed, “The man is methodically monomaniac, and the dimensions of his organ of self-esteem have been swollen to the size of a goitre ...”

Such attacks did not seem to bother Espy, who had exchanged the familiarity of his Philadelphian base

for the society of Washington. His efforts were soon rewarded. In August 1842 Congress set aside \$3,000 for meteorological observations at military posts throughout the country. As the most prominent man in the field, Espy was chosen to oversee the project, making him, in 1843, the first ever official meteorologist of the United States of America. Espy's task was to write and circulate reports and to expand the network of weather-watchers.

In 1849, Espy finally had his chance to make rain. He made his experiment in Fairfax County, Virginia, where he set fire to 12 acres of pine forest and waited for the rain. It never came. Thereafter little more is to be found of Espy's rain-making ideas in the newspapers although in private he explained away the failure of his experiment as the result of interfering factors.

REDFIELD DIED ON FEB. 12, 1857, a distinguished man in American life, one of the founders and first president of the American Association for the Advancement of Science. The news shocked his friend William Reid. For 20 years the two friends had been in constant communication, writing hundreds of letters, passing on observations about storms right to the end. Reid himself would die the following year, bringing to an end a life which had seen him serve as governor of Bermuda, the Windward Islands and Malta. "His efforts for the improvement of agriculture and education and for the promotion of circumstance were unremitting," declared Redfield's son, "and well-earned for him the title of 'The Good Governor' applied to him in Dickens' *Household Words*."

Reid and Redfield's deaths were followed by that of their great foe James Espy in 1860. Espy's contributions to the infant science in the 1830s had been vital and profound, yet his ambition to be seen as a Newton of the air would never be realized. For all his brilliance, Espy had been hampered by pugnacious perseverance in a theory that was too bold in its extent, and too colorful in its application. More than anything else he would be remembered as Espy the rainmaker—a slight that is unfortunate, but of his own making.

Meteorology had to wait until 1856 for the solution to the storm controversy. It came from a quiet but brilliant mathematical scholar, William Ferrel of Nashville in Tennessee. In "Winds and Currents of the Ocean,"

Ferrel explained why the wind should twist around the center of a storm. He demonstrated that this was caused by the rotary motion of the earth, which deflected air moving toward a center of low pressure. Once the earth's rotation was added to Espy's theory, a true picture of atmospheric circulation arose. Ferrel based his calculations on the work of a French mathematician Gustave Coriolis, who had calculated the deflective effect of the earth's rotation. Ferrel's achievement was to apply this to winds for the first time. It was a joining of the dots that linked observation and theory in an enticing new way. Puzzlingly, it meant both Espy and Redfield had been half right. The winds did rush upward as Espy had argued and they did revolve around a central point as Redfield claimed. Neither Espy nor Redfield, who had spent so much of their working lives in internecine warfare, lived to see their theories joined together. Perhaps it was just as well. ☺

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25

GALILEO GALILEI ENGAGED in a series of debates about why ice floats on water in 1611. His opponents contended that it was because of the shapes it took, and even tried to sway Florentine opinion with public experiments involving ebony spheres and splinters.

Today, we know they were wrong. But, even 400 years after Galileo, we still don't understand all the details.

This was the message of the 2013 Aqua Incognita conference. Also held in Florence, it focused on the foundational physics and chemistry of water, including questions like those Galileo debated. Richard Saykally, a professor of chemistry at the University of California, Berkeley, spoke at the conference, and says the topic of the conference surprised some people. Like his mother. "What could we not know about water?" she asked him. "It's wet. It comes from rain."

There are plenty of paradoxes besides water's deceptive simplicity. It covers most of the Earth, but is regularly in short supply. It is intimately involved in the processes of life, but life on other planets may not need it. It is inscrutable and unpredictable, but we try to price it. The debates show no signs of ending.

Welcome to "Water."

—MS

"Not all of water's unique characteristics help life—some are outright hindrances."

PHILIP BALL

"Will ET Drink Water?" p. 36

Water

BENEATH THE SURFACE



Will ET Drink Water?

The intricate compatibility of water and life on Earth may not extend to other planets

BY PHILIP BALL

A TEAM OF ASTRONOMERS ANNOUNCED this year that they had found no fewer than eight planets orbiting the so-called Goldilocks zone around their parent stars, inside which the temperatures are neither too hot nor too cold to support life as we know it on Earth. Two of these, called Kepler-438b and Kepler-442b, are the most Earth-like candidates yet seen among the 1,900 or so exoplanets (planets outside our solar system) now known to exist.

“Earth-like” means, in part, that a planet has a good chance of carrying liquid water—something more likely to be true inside the Goldilocks zone. “Follow the water” has become a mantra for astrobiologists seeking signs of life elsewhere in the cosmos. With the new ability to detect the characteristic fingerprint of water in the light reflected from the atmospheres of exoplanets, some astronomers hope to spot a world that hosts life soon.

But is liquid water really necessary to life?

There’s a long history to the belief that it is. In 1913, the Harvard biochemist Lawrence Henderson proposed a curious inversion of Darwinian evolution, in which organisms become “fit” for their environment by adaptation. Henderson’s book *The Fitness of the Environment* argued that the cosmic environment is itself peculiarly fit to host life.

Henderson pointed out that water, in particular, seemed replete with “biocentric” attributes, as if it were uniquely designed as life’s solvent. The fact that it is a liquid at all on Earth is more unusual than it might seem. Other simple hydride molecules—methane, hydrogen sulfide, ammonia, hydrogen chloride—are all gases at room temperature and pressure—but not “oxygen hydride,” H₂O. There seems to be some extra stickiness binding water molecules together.

And because water has a high heat capacity (it can absorb a lot of heat without much increase in temperature), ocean currents can redistribute huge amounts of solar heat and help make planetary conditions more

uniform and stable. What's more, while most liquids shrink and get denser when they freeze, ice expands and floats. As a result, ponds don't freeze solid from the bottom up and then become almost impossible to thaw; instead, a frozen lid insulates the water beneath.

Water also dissolves a wide range of substances, so that it helps to carry essential nutrients and elements to organisms that need them. Without water's exceptional ability to host ions (electrically charged atoms and molecules), we wouldn't have photosynthesis or nerve impulses. The large surface tension of water makes it possible for sap to rise up great distances through capillary action, so that plants can stand tall. And so on.

This was deeply puzzling. How could an *environment* acquire fitness? After all, the chemical ingredients of a planet—water, rocks, air—don't mutate and reproduce, the key attribute for achieving Darwinian fitness. Yet some of these vital attributes of water had been noted before. In the mid-19th century, several British scholars were commissioned by the Earl of Bridgewater to write a series of books showing “the Power, Wisdom, and Goodness of God, as manifested in the Creation”—in other words, how God's wisdom was revealed in the discoveries of science, an objective called natural theology. In one of these Bridgewater Treatises, published in 1834, the English chemist William Prout asserted that liquid water's expansion close to its freezing point was an example of this divine providence.

Henderson was not so ready to cede ground to God, but he admitted that it was not easy to find any alternative explanation for water's apparent “fitness.” All he could say was that there was “exceedingly little ground for hope that any single explanation of these coincidences can arise from current hypotheses and laws.” If they are ever to be understood, he said, “it will be in the future, when research has penetrated far deeper into the riddle of the properties of matter.”

The century or so of research since Henderson has revealed a compatibility between water and life as we know it that is even more remarkable and intricate than was imagined.¹ But it has also shown that the relationship may not be especially exclusive—the strange harmony between life and water may just be another example of the remarkable adaptability made possible by Darwinian evolution.



IT FLOATS! Ice floats, and we forget how weird this is. Most liquids shrink and get denser when they freeze, so that the solid sinks to the bottom.

FROM THE MODERN VIEW, water is far from being a passive backdrop on which life's biomolecules play out their dramas. It is, instead, an active participant.² A delicate web of weak chemical bonds between water molecules, called hydrogen bonds, is draped around those biomolecules in ways that weave them into the tapestry of the liquid. This unites the biomolecular solute with its solvent in a mutually responsive dance. To do their job of catalyzing biochemical reactions, proteins have to be rather flexible, changing shape as they guide a reaction along the right path. But these shape-changes remold the surrounding shell of water too, while the wobbles and fluctuations of the water “inject” dynamism into the protein.

Such interplay can be astonishingly subtle. For example, researchers at the Ruhr University of Bochum in Germany and the Weizmann Institute of Science in Israel have found that, as a protein binds its target molecule (called its substrate) in preparation for transforming it, the water molecules close to the binding site seem to slow down, almost as if thickening to hold the substrate in place.³ And there are subtle gains and losses of energy and entropy, connected to changes in the amount of hydrogen bonding and to the freedom of the water molecules to move around, which can dictate

and drive a number of exquisitely tuned and highly selective biochemical processes.

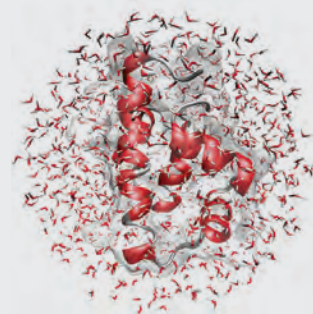
These include the binding of an enzyme with its target molecule or substrate, when water gets expelled from nooks and crannies to make room for the substrate; the folding of a newly made protein chain into the compact shape of an enzyme; the assembly of proteins into multi-part biomolecular machinery; and the assembly of fatty lipid molecules into cell membranes. Each of these processes benefit from the fact that immersion in water somehow induces an attractive force between water-repelling (hydrophobic) parts of molecules.

Water molecules often act like snap-on tools attached to a protein's surface, thereby extending an enzyme's reach and helping it bind or transport small molecules. And chains of water molecules threading through channels in enzymes act as "proton wires" that can conduct hydrogen ions, allowing cells to move hydrogen atoms to new locations or a new molecule, or to build up and discharge gradients in hydrogen-ion concentration that can be tapped to generate energy, just as water wheels tap the flow of water down a hillside. Small changes in the web of water molecules threaded amongst the double helix of DNA can affect how easily the molecule bends, and how proteins stick to it to turn the activity of genes on and off.

ALL THIS SHOWS THAT water's role in life is even more complex and comprehensive than Henderson could have appreciated. But how much of it is unique to water, and to what extent does life depend on such abilities? Some of water's roles, such as in hydrophobic attraction, have analogues in other solvents: If dissolved molecules don't have much affinity for their solvent, whatever that might be, they'll tend to stick together. And the conduction of hydrogen ions in water wires, say, is very important for life on Earth, but it's not obvious that extra-terrestrial biochemistry would find it indispensable.

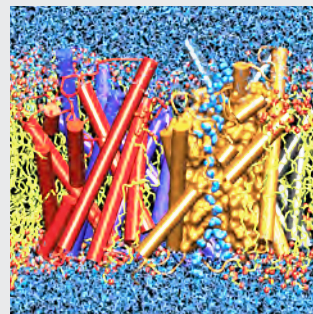
Another way to pose this question is to ask: What if water were *less* like water and more like an ordinary liquid? Chemical physicists Ruth Lynden-Bell of Queen's University Belfast in Northern Ireland and Pablo Debenedetti of Princeton University in New Jersey have explored models of "counterfactual water," in which the feature that lies at the heart of what makes water unusual—its particular hydrogen-bonding arrangement—can be tuned continuously just as if turning a dial. How much tuning is permitted before water's anomalous nature is lost?

One of the simplest theoretical models of water treats hydrogen bonding as purely electrostatic: An attraction between slightly positively charged hydrogen atoms and negatively charged "lone



All Wrapped Up

The "hydration shell" of water molecules surrounding biomolecules such as proteins can be extremely responsive to the biomolecule's structure and motion.



Tiny Plumbing

A "water wire" made of a chain of hydrogen-bonded water molecules (blue) threads through the water-transmitting protein channel, aquaporin. Each water molecule is about 0.3 billionths of a meter across.

pairs” of electrons on the oxygen atoms of neighboring molecules, with these charges dispoorted at the corners of tetrahedra. This attraction, dictating a particular geometric arrangement of molecules, operates on top of the more general attraction that all atoms and molecules feel for one another owing to the sloppiness of their clouds of electrons, called van der Waals or dispersion forces. In simple liquids such as liquid argon or carbon dioxide, it’s just the van der Waals forces that keep the molecules from flying apart into vapor.

Lynden-Bell and Debenedetti devised a computer model of water in which the relative strengths of the electrostatic hydrogen bonding (which promote tetrahedral ordering) and the van der Waals attractions (which are the same in all directions) could be varied at will.⁴ Informally, they called this hypothetical stuff “not-water.” What they found was that water-like anomalies are not really just a matter of degree. Rather, the sort of ordering that comes from hydrogen bonding, and the sort that comes from van der Waals attractions of simple spheres, thanks to the way they pack like cannonballs, are distinct and incompatible. In between these two extremes, you get the worst of both worlds: The molecules are less ordered than at either extreme. Water is, in other words, qualitatively different from a liquid that lacks hydrogen bonding, in which the molecules just bump up against each other. Water isn’t, however, the only molecule to make hydrogen bonds—ammonia and even hydrogen chloride can do it, too. The difference is that water molecules can form vast three-dimensional networks because of their

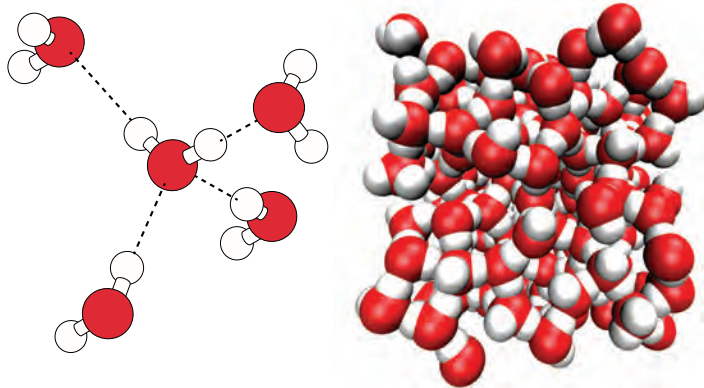
Not all of water’s unique characteristics help life—some are outright hindrances.

tetrahedral pattern of sticking together, while other hydrogen-bonders can only manage chains. The three-dimensional hydrogen-bonded network is the reason why frozen water is less dense than liquid water, something not true for ammonia and hydrogen chloride. Score one for water being unique.

But what about geometry? If you altered the angle of the bent H_2O molecule, so that its hydrogen bonds weren’t so nearly tetrahedral, or if you made the bonds longer, would water’s unique properties disappear? When they tried doing this with “not-water,” Lynden-Bell and Debenedetti found that they could still get anomalies such as a maximum liquid density before the freezing point, so long as the changes weren’t too big—for example, so that the water molecule wasn’t too sharply bent. “There is a fair degree of latitude in the [geometrical] parameters,” says Lynden-Bell. The precise degree of variation allowed before a specific property vanishes “depends on which water property

Water Webs

Hydrogen-bonding in water (dashed lines) unites water molecules into a tetrahedral arrangement (left). In liquid form (right) these bonds link water molecules into an extended network. Here oxygen atoms are red, and hydrogen atoms are white.



one is looking at,” says DeBenedetti.

Water’s hydrogen-bonded structure is also often invoked to explain the hydrophobic attraction of solutes it carries. But after looking at “not-water” with differing hydrogen-bond strengths and bond angles, Lynden-Bell, DeBenedetti, and their coworkers concluded that the main reason why hydrophobic particles are pretty insoluble in water (and so tend to clump together) is because water molecules are so small that it takes a lot of energy to “scoop out” a space for the particles, and not because of the hydrogen bonding itself.⁵ So pretty much any liquid with small molecules should show something similar.

On balance, then, water is unique in some ways but not others: special, but not *that* special. Plus, not all of its unique characteristics help life—some are outright hindrances. For one thing, it’s quite reactive. The lone pairs of electrons on the oxygen atoms are drawn to parts of molecules with a positive charge, where they may break up existing bonds and fragment or reconfigure the molecules in a process called hydrolysis. The carbon atoms in peptide bonds—the linkages that hold together amino acids in protein chains—are susceptible to this sort of attack, giving water a tendency to split proteins. Water may do the same thing to chains of sugar molecules, like those in biological polysaccharide compounds such as cellulose and starch.

“This is not so much a problem today in living systems, which have enzymes that repair the damage done by water,” says chemist Steven Benner, a distinguished fellow at the Foundation for Applied Molecular Evolution. But it would be important for the origin of life, he says, when proto-biological molecules had to form and persist in water without the help of enzymes. “If water was engineered to be the perfect biosolvent by God, she certainly did a bad job of engineering,” says Benner.

He sees no fundamental reason why solvents such as ammonia, formamide (CHONH_2), or liquid hydrocarbons like those on Saturn’s moon Titan shouldn’t also support different kinds of biochemistry.⁶ After all, a lot of organic chemistry in laboratories and in industry is carried out in non-aqueous solvents (that is, solvents other than water), often precisely because water is too reactive. Benner is particularly interested in the idea that Titan’s hydrocarbon oceans might host hydrophobic life. He and his coworkers recently

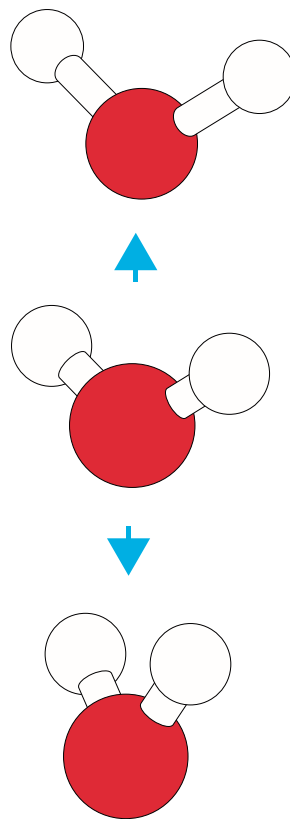
carried out experiments to see if they could build a “genetic polymer”—one that might encode information in a sequence of molecular building blocks in the way DNA and RNA do—that could work in such a liquid.

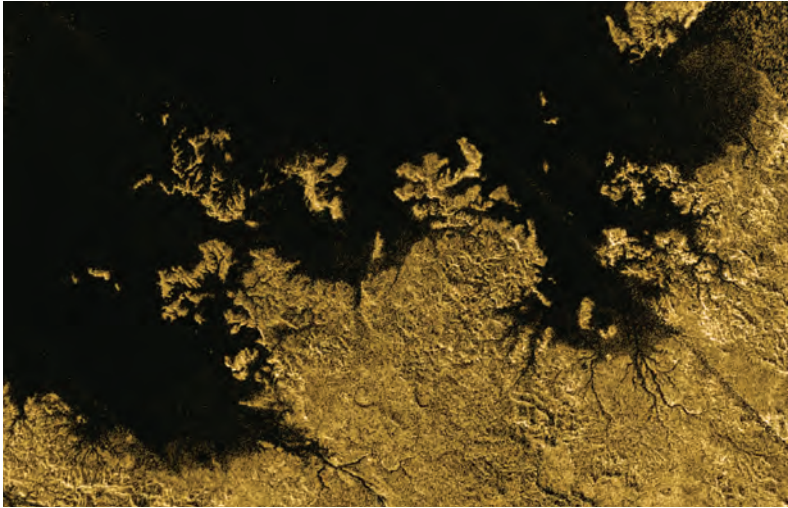
They found that chain-like molecules called polyethers, in which carbon and oxygen atoms alternate along the backbone, dissolve pretty well in liquid propane (C_3H_8) at temperatures of around negative 94 degrees Fahrenheit (negative 70 degrees Celsius).⁷ Benner argues that polyethers could serve as genetic databases in such a solvent.

But Titan is much colder than that: Its hydrocarbon

Making Other-Water

Lynden-Bell and DeBenedetti toyed with the bond lengths (top) and angles (bottom) of water to see what would happen.





TOO COLD Titan's hydrocarbon oceans, as photographed by the Huygens probe of the joint NASA/ESA Cassini-Huygens mission in 2005. Similar hydrocarbons are capable of acting as a solvent for chain-like polymers that encode information, although only at higher temperatures than are found on Titan.

oceans, consisting mostly of methane (CH_4) and ethane (C_2H_6), have a temperature of around negative 288 degrees Fahrenheit (negative 178 degrees Celsius).⁷ At such frigid extremes, the polyethers don't dissolve significantly. Benner concludes that liquid methane on Titan is therefore "simply too cold to support the solubility of almost anything necessary to create the properties that we value in life." But, he says, that's not because hydrocarbons are bad solvents and water is a good one—it's just that liquid water is warmer, and stuff dissolves better in warmer liquids. "A warmer Titan," he says, "with the temperatures in a habitable zone around the sun at approximately the orbital distance of the planet Mars, would have hydrocarbon oceans that include propane, butane, and even pentane." These solvents would remain liquid at temperatures where they can actually dissolve significant quantities of material.

Another promising alternative to water championed by Benner is formamide, which can be formed from either carbon monoxide and ammonia or hydrogen cyanide and water—all of them simple molecules that can be found in interstellar and extraterrestrial environments. "Formamide is very much like water in terms of its solubility power (possibly even greater) as well as its liquid range (much greater)," says Benner: at one atmosphere pressure, formamide melts at

37 degrees Fahrenheit (2 degrees Celsius) and boils at 411 degrees Fahrenheit (210 degrees Celsius). And it doesn't have the same tendency as water to bust polymers apart. Benner and coworkers have recently shown that, in the presence of a boron-containing mineral to act as a catalyst, a phosphate chemical group can be added to the molecule adenosine in formamide to make adenosine phosphate, one of the basic building blocks of RNA and DNA.⁸ In contrast, water tends to split apart adenosine phosphate, making it *harder* to build nucleic acids.

IF IT IS TRUE that solvents besides water can serve just as well for other life elsewhere in the universe, then the intimate pairing of water and life here on Earth may really be a reflection of the extreme opportunism that adaptation confers on life. Terrestrial organisms use to the full everything that this strange liquid has to offer. It seems ironic that we might be overestimating the importance of water in astrobiology while at the same time underestimating the significance and subtlety of the jobs it does in terrestrial biology.

Indeed, the very adaptability that we find on Earth should give us pause before we elevate water to the *sine qua non* of life. There are organisms living in cracks in the rock in the hot, pressurized depths of the Earth where oil forms, and within the ice of sub-surface

Antarctic lakes. Microbes survive in the baked, dry soil of the Atacama Desert, and whole communities thrive around volcanic hydrothermal vents spewing scalding water in the deep sea. Organisms can survive in extremely salty water, they can tolerate high concentrations of toxic heavy metals and even exposure to the highly ionizing radiation of outer space. While no known organisms can sustain metabolism without at least some water, microbes can adapt to life in heavy water, while some isolated enzymes can work in more or less totally water-free conditions. Given all this, it seems tempting to believe that, once Darwinian evolution gets going, it will find its feet in almost any circumstance.

Lynden-Bell agrees that we shouldn't underestimate the ability of natural selection to find ways of sustaining life in all kinds of environments. "I personally believe that evolution can exploit the environment that it finds and that it is possible to imagine alternative scenarios," she says. Life can also change its environment to suit itself. Colin Goldblatt of the University of British Columbia in Vancouver points out that, while cold and moist worlds are the only ones that look habitable from our current perspective, exactly where the zone of habitability lies depends on what else is in the atmosphere: On Earth, carbon dioxide (maintained partly by life) keeps most of our planet above the freezing point.⁹ In other words, "habitability depends on inhabitance," he says. To put it another way, we can't easily judge if a water world could support life without knowing if it already does.

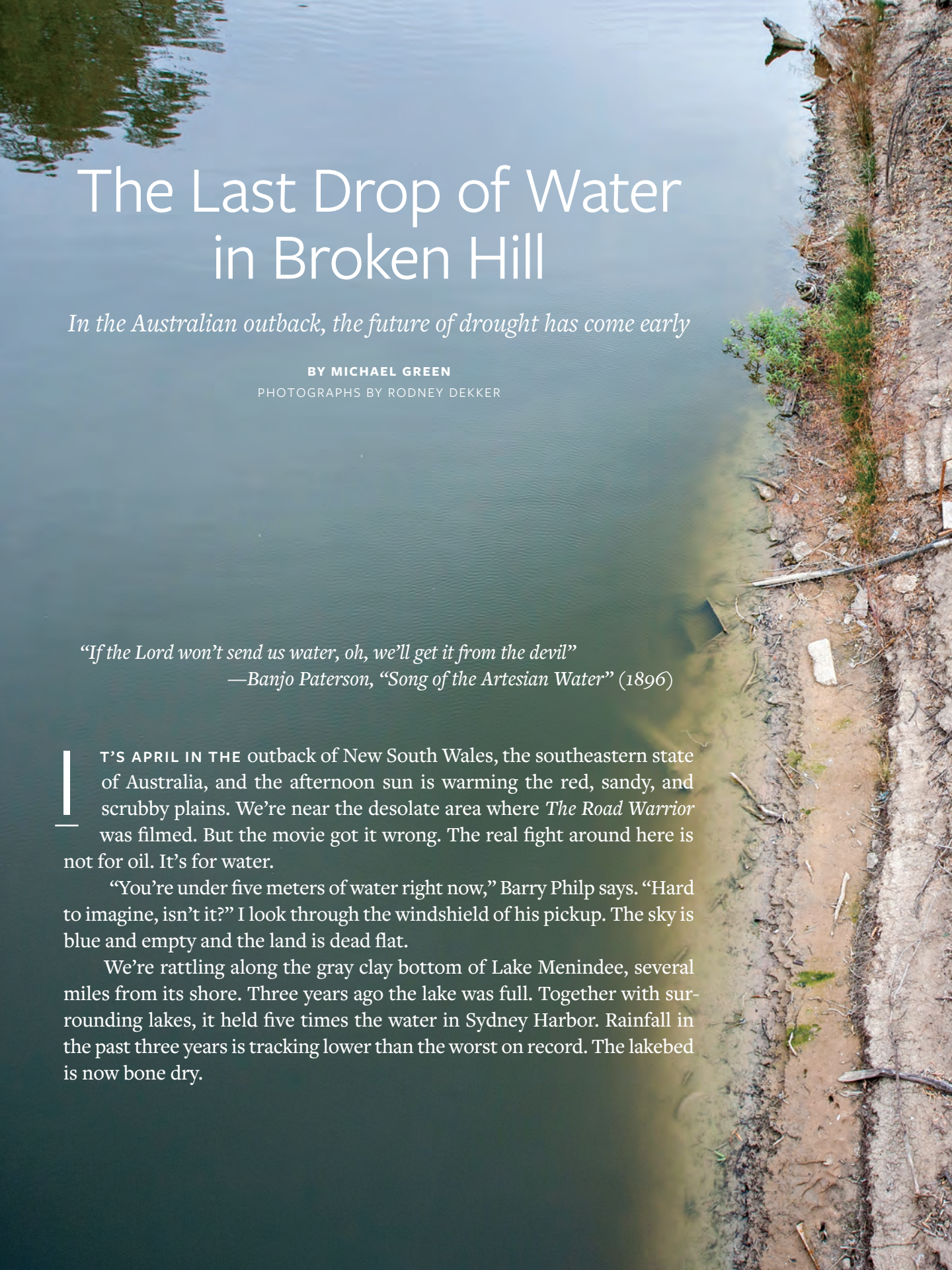
Now, multiply that adaptability by the number of planets that could host it. Judging by the current statistics, just about every star in our galaxy has at least one planet on average, and one in five sun-like stars are likely to have Earth-like planets in their habitable zone. That makes at least 11 billion of these worlds in the Milky Way alone—and there are at least 100 billion galaxies in the observable universe.

In this picture, can we really insist that water be the only solution? ☹️

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

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The Last Drop of Water in Broken Hill

In the Australian outback, the future of drought has come early

BY MICHAEL GREEN

PHOTOGRAPHS BY RODNEY DEKKER

“If the Lord won’t send us water, oh, we’ll get it from the devil”

—Banjo Paterson, “Song of the Artesian Water” (1896)

IT’S APRIL IN THE outback of New South Wales, the southeastern state of Australia, and the afternoon sun is warming the red, sandy, and scrubby plains. We’re near the desolate area where *The Road Warrior* was filmed. But the movie got it wrong. The real fight around here is not for oil. It’s for water.

“You’re under five meters of water right now,” Barry Philp says. “Hard to imagine, isn’t it?” I look through the windshield of his pickup. The sky is blue and empty and the land is dead flat.

We’re rattling along the gray clay bottom of Lake Menindee, several miles from its shore. Three years ago the lake was full. Together with surrounding lakes, it held five times the water in Sydney Harbor. Rainfall in the past three years is tracking lower than the worst on record. The lakebed is now bone dry.



OH, DARLING Waters recede from the fickle Darling River, main artery of Australia's biggest river system. It gets flooded in places by rains, and sapped dry in others by evaporation. Critics say it has been over-tapped.

Philp, a solid man in his late 40s, manages the Menindee Lakes system. The system was built in the 1950s to secure a water supply for the mining town of Broken Hill, 70 miles northwest. It diverts water from the nearby Darling River, storing it in plains and lakes that previously filled only in floods. For the second time this century, it's on the point of failure.

This past December, government officials estimated Broken Hill, population 18,000, would run out of water in August. Amid news about coming droughts around the world, and record temperatures forecast to get even hotter, I've come to an iconic Australian town to see how it's reached the brink of running dry.

The struggle for water draws out the character of the continent and the dreams woven deep into the psyche of the people who settled here. "We have a major problem," says John Williams, former chief of the land and water division of Australia's national science agency. "It's a clash between what the land can do and how it works, and our aspirations for a stationary, Western civilization."

Philp pulls up to a blue rig rising above the plain, surrounded by trucks and men. He grew up nearby, in the hamlet of Menindee, where his mum, Beryl, was born on the Menindee Aboriginal Station. As a local resident who also works for State Water, Philp is stuck between a desert and a dry place. He's welcoming but reserved, as if he's decided fewer words will upset fewer people. He must implement unpopular water-policy decisions made elsewhere by the New South Wales government. We're visiting the latest controversy: a bore-drilling program searching for underground supplies.

We look on as water gushes from a bore, muddy at first, then clearer. Nick, a geo-hydrologist from Canada, takes samples. It had taken less than a day to bore a hole—about 55 meters deep—and prepare the site to pump water up through a narrow pipe from the aquifer. The scientists will pump the water nonstop for two days, evaluating its flow rate and quality.

While the drillers are working around the clock, the residents of Broken Hill are agitating for them to stop. They're worried about contaminants in bore water and believe drilling for groundwater is a government plot to decommission the lakes altogether. "We've been fighting the New South Wales government for 200 years," says Mark Hutton, a retrenched miner and

longtime water activist, one of the leaders of a grassroots group called WE WANT ACTION.

Chemists define it as H₂O, but to understand water as a substance that brings hope and despair, you need a more complex formula. In Broken Hill, add salt and scarcity, erosion and evaporation, intractable politics and intergenerational memory, speedboats and roses. Stir and stand back because the state government is about to announce an emergency water plan for the town.

I WALK INTO THE CENTER of Broken Hill to meet Mayor Wincen Cuy, also a hotelier and tourism operator. Today, an unusual cold snap has filled its famous wide-angle blue sky with gray clouds. It feels a century apart from other Australian towns. Instead of the typical big-box stores and cement-sheet houses, its broad, empty streets are lined with old-time architecture: solid miners' cottages, some with corrugated iron roofs and fences, whose owners keep their yards bare and shutters drawn; small brick warehouses; and, on the corners, thick-walled hotels with faded Victorian splendor, where workers once slaked their underground thirsts.

The town was named after a diary note by Captain Charles Sturt, a 19th-century English explorer, obsessed with discovering an inland sea on the Australian continent. One exhausted day, resting on a craggy black outcrop, which Aboriginal people called Willyama, he jotted "Broken Hill" in his journal. Four decades later, the hill would be pegged for a mine. It would become the world's largest silver, lead, and zinc mining field. Broken Hill is also known as Silver City.

Today, though, the hill has been truly broken—dug over three times. Now known variously as the line of lode, the mullock heap, the skimp dump, or the slag heap, the hill remains the town's defining, if surreal, geographical feature. It runs parallel to the main street, 50 meters high, separating the north and south suburbs. A restaurant and a memorial to the miners who died on the job sit on top of the heap. But the restaurant has shut down, and all the road signs to the lookout have been removed. Both buildings have outlines like ships, and there they sit, marooned and precarious, as if waiting for the Flood.

"Water is a major concern for us," says Cuy, who owns the lease on the shuttered restaurant. "We owe it



to the citizens of Broken Hill to explore every possibility, whether it's palatable or not."

Cuy and I are sitting outdoors at a diner in the town's wide main street. It's a casual place but Cuy wears a gray suit. Two days earlier, Cuy had tangled with the activists, after interrupting their meeting with the visiting state water minister. "For the sake of the community, I wasn't prepared to let the minister get railroaded," he says. "They have a point of view that we shouldn't have bore water," as it can indeed contain harmful microorganisms. "Do I want bore water? No. Do I prefer bore water over no water? Absolutely!"

Cuy speaks with conviction, but looks deeply tired, glancing sidelong while he speaks, monitoring the passers-by. His great-great-grandfather lived here when the town was founded. He knows its volatile history. As a 1968 chronicle of the local water board, *Water Carts to Pipelines*, by historian Bobbie Hardy, put it, "The ancient dry wrinkles of the Barrier Ranges were never meant to foster a city. From the beginning, the greatest problem of the isolated settlement was water, and water it has remained."

The first water protests were held less than four years after the ore body was discovered in 1883. Then, in 1888, nearly three-quarters of the population—12,000 residents—gathered in front of the

GRAPES OF WRATH

Near the town of Menindee, a local farmer examines a pump he bought from a grape grower, who gave up and left town. If the lake ever fills again, he'll get to use it.

Residents are prohibited from watering their gardens during the day. They must wash their cars and paving with buckets, not hoses.

town's Grand Hotel, protesting the decision by the mining minister, Francis Abigail, not to permit water to be railed in from a nearby source. The next night, protesters made an effigy of the minister, drew it on a hearse to a gallows and proceeded to hang and burn it. "It was," reported the local newspaper, *Silver Age*, "the most brilliant appearance that the Hon. Francis Abigail is ever likely to make in Broken Hill."

Emergency water supplies were carted in by train that year, and again for long periods in the 1890s, the 1900s, and the 1940s. And now the town is on the edge of emergency again.

In December, water restrictions were introduced, prohibiting residents from watering their gardens during the day and filling empty swimming pools. They must wash their cars and paving with buckets, not hoses. The town's consumption fell by a fifth from the previous year. Still, for Cuy, maintaining the town's greenery is a matter of honor. "Have you seen Sturt Park?" he asks, pointing to an undulating expanse of lush green grass. "It's our pride and joy. In the semi-arid environment we live in, it's a great spectacle."

AUSTRALIA IS A LAND OF EXTREMES. It is the driest inhabited continent on Earth, susceptible to floods, which inhabitants expect someday will come. But they won't reach Broken Hill.

The town stands at the far western edge of the Darling River's catchment. The river is long and meandering; many of its tributaries run dry, others connect with it only rarely. The bottom line: If you need water, don't depend on the Darling. The same year Broken Hill was founded in 1883, a paddle-steamer named *Jane Eliza* set off from the town of Morgan, downstream, to navigate the river. It took three years to reach Bourke, a town only 700 miles north as the crow flies.

Most rivers have a variation of fivefold or less between their peak and low flows. During wet years on the Darling, however, monsoon rains in its far northeast bring volumes 15 to 20 times its minimum, making it among the most variable in the world.

Together with the Murray River, farther south, it comprises the Murray Darling Basin, a vast, largely flat catchment covering one-seventh of the continent. The basin spans the territory of 30 Aboriginal language groups, and now it is home to 2 million people, who



produce a large proportion of the nation's cereals, oranges, apples, grapes, pigs, sheep, cattle and dairy, and nearly all of its cotton.

The region's geology is ancient. Highlands lifted to the east 60 to 32 million years ago; while to the west, the basin subsided over a shallow saucer of 350-million-year-old rock. Over millions of years, the seas advanced and retreated, depositing salt and sand and forming river plains, as the climate oscillated between very humid and very arid. In the present climate, rainfall outpaces evaporation only in the eastern margins. From there, the waters move slowly west and south through semi-arid and arid plains.

In modern Australia, the Murray Darling Basin has been overlaid with a diabolical political geography: It traverses one national government, four states, and 98 local councils.

In November 1991, a regional water office issued a warning: Landholders should not drink from the Darling River and should keep livestock clear of its banks. By December, the beginning of summertime, a spectacular, toxic bloom of blue-green algae had spread more than 600 miles along the river. Breeding in stagnant waters and fed by fertilizer and livestock manure runoff, it formed the world's largest recorded algal bloom. The New South Wales government declared a state of emergency.

At the time, Williams was in a senior role at



THE RABBLE-ROUSER

(p. 48) Mark Hutton, a former miner, leads a battle for a river pipeline to quench Broken Hill.

THE WATER MANAGER

Barry Philp has the unenviable job of overseeing the town's beleaguered lake and reservoir system.

Australia's national science and research organization, in charge of researchers working to solve the crisis. "The water storages off the Darling were green, just green from side to side," he says. "These were our water supplies—it was a frightening, panicky thing. It woke us up to the fact that we'd taken too much out of the river."

The second half of the 20th century was wetter than the first half and irrigation boomed. The capacity of dams in the Murray Darling Basin grew sixfold and by the 1990s the volume of water being taken from the river was approaching the system's average natural flow to the sea. All this irrigation, along with the clearing of woodlands and forests, caused salty water tables to rise and discharge to the rivers. But with fewer floods reaching the river mouth, the salt stays on the land.

The algal blooms shocked policymakers into capping diversions from the catchment, but the freeze applied only to surface water. Afterward, groundwater extraction surged.

The big Australian cities cling to the coastline. Situated on rivers, they are supplied by large dams in their immediate water catchment. But inland, where surface water is scarce, miners and farmers—and increasingly, householders—look underground. In New South Wales about four in 10 rural towns rely on bores, partly or wholly, for their potable water.

Most groundwater in Australia comes from rainfall. Flood water seeps into the land, filtering down

until it becomes trapped and stored in porous soils and rocks. Likewise, during dry times, shallow groundwater feeds the flow of the rivers. Over time, fewer floods will mean less groundwater, and less river flow.

Williams, the son of generations of farmer-settlers, has been on the frontlines of Australia's water battles for decades. To him, water problems run deeper than the elements. In 2003 he wrote an article in *Australian Science* magazine called "Can we myth-proof Australia?" He argued that the national psyche is "dominated by dreams of water."

"It isn't the drought that is the problem," he wrote. "It is our delusions. Like the lotus-eaters, we inhabit a dream world where water is plentiful and the landscape resembles the soft, green hills of Europe. It is time to awake and accept where we live."

Ever since British colonization, Williams says, Australians have failed to learn about the landscape and live within its means. When the "First Fleet" of officers and convicts arrived in Sydney Cove in 1788, they established camp by the "Tank Stream." During an early drought, tanks were constructed along its banks. Before long, the stream was a watering hole for livestock, a sewer, and a drain for industrial waste. It was undrinkable. Its source, a nearby marsh, was used up and drained, as was the settlement's subsequent water source, the Lachlan Swamps.

The Tank Stream is "a classic case" of the Australian



GHOST LAKE Lake Pamamaroo is part of the Menindee Lakes water system. The tree trunks are white to where the water reached when the lake was full.



approach to water, Williams says. “We polluted it within 12 months of getting there. Yet Aboriginal people had been managing it for 50,000 years.”

By the beginning of the 20th century, the settler society’s water dreams became known as “Australia Unlimited,” after a 1,000-page patriotic book written by journalist Edwin Brady. The dreamers proposed outlandish schemes, from channeling the sea inland and turning tropical rivers south, to mining immense volumes of groundwater. You can still hear some of them today.

But Australia is limited. From 1995 to 2009, Australia experienced the “millennium drought,” which ranked among the worst dry spells since the British colony began. In 2002, as the drought dragged on, Williams and other scientists gathered for dinner at Sydney’s Wentworth Hotel. All of them were worried about patterns of land use and abuse, the depletion of water and soils, and the consequences for farmers. After the meal, they formed the Wentworth Group of Concerned Scientists, an unpaid, independent expert group determined to influence the media and public policy.

In 2012, a bruising, years-long political process culminated in the federal government’s “Basin Plan,” a blueprint, supposedly, for the rivers’ sustainable management. The Wentworth Group scientists damned it: The plan still allowed a volume of water to be diverted from the river that would rival its total flow.

To make matters worse, the modeling assumed climate change wouldn’t pose a risk to river health, even though projections suggest significant reductions in rainfall and runoff for southeastern Australia, land of Broken Hill. Mid-sized floods have vanished from the system, groundwater no longer recharges, and salts aren’t flushed to the sea.

The basin is a “boom and bust system” evolved for flooding, Williams says. Because the catchment is so flat, water flows slowly along a meandering course. Beyond its banks are vast floodplains. When the floodwaters spread onto those forests and grasslands, a food chain builds up from fallen vegetation, bacteria, fungi, zooplankton, crustaceans, and fish, and it flows back into the river.

An earlier version of the plan had proposed significantly less water for irrigation, but it provoked a hostile response. Infamously, one group of farmers burnt copies of it in the basin town of Griffith. After that,

catchment politics ruled over catchment science.

“The people were on a crutch and we kicked the crutch from under them,” Williams recalls, “and wondered why they got angry.”

PHILP DRIVES ME THE LENGTH and breadth of the Menindee Lakes system. We drive past paddocks of old grapevines, withered or pulled from the ground. The last grape grower has just left town. Philp stands on the main weir on the Darling, looking back over the stark landscape. He wishes I could see the river full, when the water spanned the horizon, so I’d fully understand. “All you could see is the top of the trees,” he says, with wonder. “No land at all.”

Before the Menindee Lakes were dammed, they were natural, ephemeral lakes, filling from the Darling River only in times of flood. Vast and shallow, they were formed by wind erosion from the prevailing westerly weather patterns, which blew sand and clay sediment into crescent-shaped dunes on the lake margins.

Basically, they’re evaporation pans. When storages subside to 480 gigaliters—a quarter of their capacity—authorities manage them to prioritize the water supply for Broken Hill and surrounding users. That amount is seen as enough to serve the area for a year and a half, if no more flows come from upstream. Broken Hill, in that time, consumes, at most, only 15 gigaliters. But that doesn’t necessarily leave a reserve. The rest can vanish into thin air.

In recent months, Philp’s team has dredged a channel, built embankments, and pumped as much of the remaining water as they could access into the deepest lake, Copi Hollow, an old quarry and one of two man-made reservoirs in the system. By reducing the surface area, and the evaporation rate, the works would extend the town’s supply for a few precious months. The dams’ storage is now at 4 percent. At its lowest, before the last floods, it plunged to 1.6 percent.

Back then, during the millennium drought, the increasingly salty water corroded household appliances in Broken Hill—evaporative coolers, washing machines, and hot water heaters—causing millions of dollars of damage.

Hutton, of WE WANT ACTION, tells me he had to buy a new cooler, with salt-proof plastic components. He lives in South Broken Hill, the small suburb on the



southern side of the mullock heap. He stands slightly stooped, and in conversation, gives the impression of leaning forward attentively. Broken Hill's population peaked at about 30,000 in the 1960s and has been steadily declining since, as were the jobs in the mines. By the 1980s, thousands of men had been laid off, pushed out by automation and falling metal prices. They included Hutton, 58, who spent two years doing odd jobs, before landing work as a receptionist at the hospital. "The money's not as good but the conditions are much better," he tells me. "You get to see daylight."

In his lifetime, Hutton says, water in the Menindee Lakes has become scarce, a consequence of more irrigation upstream and, recently, increased flows reserved for river health. And above all, in the last 20 years, rain simply hasn't been falling.

Hutton recalls childhood camping trips to the lakes on weekends and all his school holidays, after the dams had been built. "There was nothing flash," he says, "just a tarp on the ground, a couple of blankets and that was about it. It gave me an appreciation of the beautiful river system in those days. I feel terrible that the kids of today don't see what I saw back then. I'm disappointed and angry—that's why I'm outspoken."

Hutton keeps a speedboat in his shed, and has a trailer site at the lakes' main recreation park. Like

NO FISHING

At Menindee Lakes Caravan Park, outside of Broken Hill, a boat sits on the shore of bone-dry Lake Menindee, victim of Australia's harsh elements and water politics.

Three years ago the lake was full. Together with surrounding lakes, it held five times the water in Sydney Harbor. The lakebed is now bone dry.

“Like the lotus-eaters, we inhabit a dream world where water is plentiful and the landscape resembles the soft, green hills of Europe. It is time to awake and accept where we live.”

other residents in the action group, he fears that if the government finds a permanent supply of groundwater, it will never fill the lakes again—and instead sell the valuable commodity elsewhere. They also don’t trust the quality of bore water, no matter how it’s treated. “Why should we drink water from 250 meters underground, when for the last 50 years, we’ve had a never-ending supply of perfectly good water?” Hutton asks.

Most people around town express a similar sentiment: they deserve better. The remote town’s mineral riches had built Sydney. For what?

Instead of bores for their emergency supply, the residents want a long pipeline built north from the Murray River, to replenish the lakes, and from there, to supply Broken Hill. Along with a fierce opposition to upstream irrigation, among the group’s most common grievances is the belief that too much was released downstream when the lakes were full. They see the stagnant riverbed and mourn for the water they remember. “I think we’re going to lose the river,” Hutton says, sadly. “I’m not as optimistic as I was a few years ago.”

Not far from his house, only a few minutes’ drive along the wide, quiet streets of South Broken Hill, Bob Pascoe motions for me to wait a moment. “I’ll show you where it all went wrong,” he says, then gets up from the chair on his porch, and shuffles inside. We had been admiring his bed of roses—the 64 bushes flowering in his front yard. A towering subtropical Illawarra Flame Tree, which he planted in 1950, cast a dappled sunlight across the whitewashed walls. In springtime, the tree blooms deep red.

Pascoe is a barrel-bodied man of 85, an old-time miner, and a revered and outspoken stalwart of town affairs. Gardening is his passion. He coordinates the annual flower and rose competitions for the Silver City Garden Club.

In his backyard, Pascoe had guided me through his wisteria-covered archway, and pointed out 17 trees, as well as several palms, cacti, and dozens of flowers. The narrow black pipes of his watering system snake to every corner of the block.

In the last three months, he spent \$800 on his water bill. In summer, from December to February, it was \$1,300. “I use massive amounts. I’ve got to cut back,” he chuckles, then has second thoughts. “Nah, I love it.” The postman does too; on hot days, he rests a few

minutes in the shade of Pascoe's oasis.

Pascoe returns to the porch with a large map of the Darling River catchment and spreads it across the table. He is missing the tip of one finger. "Part and parcel of life," he explains, and recounts various encounters with death underground throughout 32 years as a miner.

"Why isn't the water coming down here?" he says, then points toward the northern reaches of the catchment, the irrigation zone where water extraction boomed after World War II. "Up there, they're bloody pulling it out!"

The day before, I met Pascoe's grandson, Jaymie Norris, who recently moved back to Broken Hill, bringing his young family. Sitting in a café, Norris, who wears black-rimmed glasses, speaks with great affection about his grandfather's feats as a gardener.

In his years away, Norris worked as a policy expert on climate change and fire risk. When he returned, he noticed a change in the streetscape. There were fewer green grass lawns around town. As a kid, he says, you had to be careful visiting the park, "because they'd turn the sprinklers on at any time of the day."

Around Broken Hill, climate change projections are for slightly more rain in summer, but significantly less in winter. Evaporation rates are anticipated to rise even further. "What the trees and plants will feel is a net loss," Norris says.

He's the first person to mention the need to further reduce water use in the town, and even recycle some back into the supply. He also sees the downside of piping it from the Murray basin, which is over-extracted too. "I think about the system as a whole, and that's just moving the stress from one part to another." He pauses. "Running out of water is a real possibility in our cities."

Days later, the government announces its emergency water plan. Estimates show existing surface water will run out in November. But if the town's desalination and reverse-osmosis treatment plant—which removes salt, heavy metals, and parasites—is upgraded, water could last through spring. (A recent estimate extends the date to winter 2016.) After that, if no rains have come, Broken Hill will switch to bore water. The local water activists are incensed. One of the group's leaders summarizes the plan: "Deplorable, Unacceptable, Offensive, Disgraceful."

The next morning, on orders to preserve the last of

the Darling's water for the residents of Broken Hill, Philp drives out to the weir and adjusts the regulators, stopping all downstream flow in the river channel, cutting off the last trickle for farmers and communities below.

BROKEN HILL WAS THE PERFECT PLACE for a mine, but not for a town. The Menindee Lakes, a mid-20th-century solution, are no longer a solution. They have been drained by irrigators and successive droughts, and undermined by the increasing extremes of climate change. Most townsfolk have been dutifully following the new restrictions and conserving water. But they know conservation is trumped by evaporation. If they don't use the water, they lose it.

In 2015, Broken Hill was listed as the first city on Australia's National Heritage Register, recognized for its history of mining and workers' rights, its outback architecture and community spirit. News reports stated residents had lobbied for 10 years for the listing. In January, under the morning sun, outside the Broken Hill Town Hall, a proud Mayor Cuy declared to a small crowd, "Our past is our future. We do have a great story to tell." ☺

MICHAEL GREEN is an Australian journalist, based in Melbourne.



Why Discovering Martians Could Be Disappointing

There are two kinds of extraterrestrial life with very different implications

BY TIM FOLGER

WHILE SOME SCIENTISTS search for extraterrestrial life by landing rovers on Mars, launching telescopes into space, and scanning the skies with giant radio dishes, geobiologist Joseph Kirschvink thinks that the first telltale signs of alien life may be sitting on a shelf at NASA's Johnson Space Center, bundled in a Martian rock that conveniently fell to Earth.

On the wall of Kirschvink's office at Caltech hangs a black and white photo of the meteorite. Radioactive dating shows that the rock formed 4 billion years ago, when Mars was a warmer, wetter place. It was propelled to Earth about 16 million years ago, after a meteorite impact blasted fragments of the Martian surface into space.

Eventually the rock landed on the ice cap of Antarctica, in an area called Allan Hills, where meteorite hunters found it in 1984. Scientists named it ALH84001 after the date and location of its discovery. They traced its Martian origin by analyzing gases trapped in the

rock's pores. Those gases matched the atmospheric chemistry measured by the two Viking spacecraft, which landed on Mars in the 1970s.

What's more, ALH84001 seemed to contain signs of life, suggesting not only that life could have once existed on Mars, but that it could have made its way to the Earth across the void of space. In fact, Kirschvink thinks it's likely that life arose only once in our solar system—and that it didn't start on Earth. "I think there were bacteria on Mars 4 billion years ago," he says.

For Chris McKay, this would be something of a let-down. "My job is to search for life on other worlds," says McKay, a planetary scientist at NASA's Ames Research Center in Mountain View, California. "Not just for life, but for what I call a second genesis."

The distinction, McKay tells me, is a crucial one. If we discover living things elsewhere in our solar system, for example, and they turn out to have a biochemistry similar to our own—with DNA, and familiar proteins, say—then we would still have no way to assess whether

life in the universe is rare or common. Mars might have infected Earth with life, or vice versa. In either case Mars and Earth could be flukes, exceptional cases in an otherwise sterile cosmos.

If instead we find a true second genesis, it would be evidence for a fecund universe where life is the norm. “The difference between one [genesis] and two is astronomical,” says McKay.

THERE WERE FOUR INDEPENDENT lines of evidence suggesting that ALH84001 contained signs of life. The most photogenic was the presence of microscopic tubular shapes embedded in the rock, resembling fossils of bacterial cells that have been found on Earth. Scientists also detected traces of mineral deposits that are often byproducts of biological activity, and globules of organic chemicals commonly produced by terrestrial microbes. What got Kirschvink most excited was the fourth line of evidence—the meteorite contained tiny magnetic crystals known as magnetosomes, which some types of bacteria use to sense Earth’s magnetic field.

These observations prompted NASA to make a life-on-Mars claim in 1996 at an enormous press conference, and in a paper published in the journal *Science*. President Clinton lauded the research. “If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered,” he said. Biologists, geologists, planetary scientists, and physicists requested that NASA send them fragments of the rock so they could set to work trying to confirm or refute these claims.

Over the years that have followed, most scientists have concluded that the evidence doesn’t hold up, at least not solidly enough to prove something so extraordinary as the presence of life on another planet. A number of experiments have shown that the “fossil bacteria,” the mineral deposits, and the organic chemicals could all have formed by natural, non-living processes.

But, to this day, Kirschvink maintains that the crystals of magnetite are tough to explain as being anything other than the remains of an indigenous Martian form of life. He was one of the scientists who received a sample in 1996, which he and some colleagues found contained several billion magnetite crystals. Using a scanning electron microscope—the crystals are typically



SIGNS OF LIFE The meteorite Allan Hills 84001 was found in Antarctica in 1984. Although it originated on Mars, it contains tiny magnetic crystals that some types of Earthly bacteria use to sense the planet’s magnetic field.

only a few billionths of a meter in size—they found that 27 percent of the crystals were indistinguishable from those produced by earthly bacteria.

They published their result in 2000, and Kirschvink says there is still no plausible inorganic mechanism that accounts for the magnetosomes. “The easiest explanation? Biology.”

In his office, Kirschvink pulls up some images of magnetosomes on his computer; they look like minuscule beads. The magnetosomes found in earthly bacteria and in the Martian meteorite, he says, share two distinctive qualities: their shape and purity. Magnetosomes consist of crystals of magnetite, a common magnetic mineral. In their naturally occurring form, magnetite crystals are octahedrons. But in bacteria, evolution has molded them into elongated beads, strengthening their magnetic properties and making them better compasses.

The crystals in magnetosomes are also exceptionally pure compared with those of ordinary magnetite. “Magnetite is a garbage-bag mineral,” says Kirschvink. “It will suck lots of different contaminants in at the cost of its magnetism. These crystals are pure,” he says, tapping an image on his computer screen. “We’ve never seen these things outside of biology.” Of the four lines of evidence that the NASA researchers presented in 1996, only the magnetosomes have not been

falsified, he says. “Not even close. A lot of people have tried, but I have seen nothing [non-biological] that can make those crystals—not even one crystal with those characteristics.”

Even so, most of Kirschvink’s colleagues aren’t convinced by his arguments. McKay says that magnetosomes in bacteria always occur in long chains, like a string of pearls, not as individual crystals. “It would be convincing to everyone, not just Joe, if the magnetosomes were in a necklace. If Joe found that in a meteorite, I would say ‘verily, it is so!’” Would the discovery of a string of magnetosomes be irrefutable evidence that Mars once supported life? “The string would,” says McKay. “Single crystals [aren’t].”

Steven Benner, a biochemist and the director of the Foundation for Applied Molecular Evolution in

That would make us the descendants of spacefaring microbes from Mars.

Gainesville, Florida, agrees with McKay’s assessment, but says Kirschvink’s ideas haven’t been falsified. “Joe’s is a minority view,” he says. “It’s an interesting hypothesis. At the end of the day I don’t think the case for Martian life [in the meteorite] has been completely dismissed. And I think Joe has the strongest example of an argument for there being a biosignature in that meteorite.”

Kirschvink is familiar with the objections, and knows he must find a magnetosome chain to convince his fellow scientists. The problem, he says, is that it’s

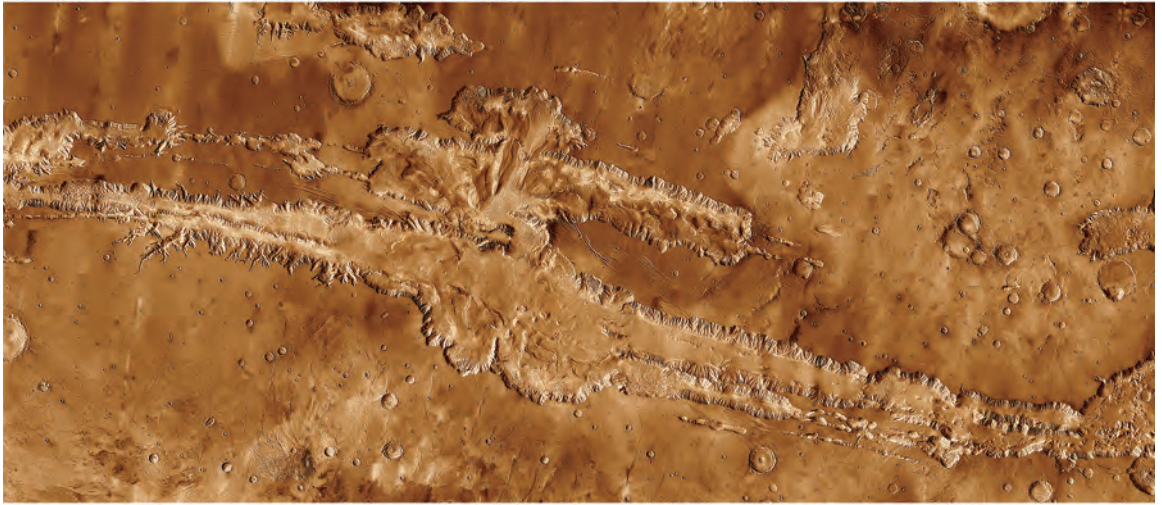
exceedingly difficult to isolate magnetosomes from the hard rocky matrix of the Martian meteorite without obliterating the very things you're looking for. The only instrument capable of such precision cutting is something called an ion milling machine, which would fire beams of atoms at the meteorite, slicing material around the magnetosomes. That might reveal whether the single crystals detected so far are actually parts of chains extending deeper into the rock. Kirschvink is planning to dissect the rock this way with the help of researchers in Japan.

ALH84001 IS OLDER THAN the earliest known life on Earth. So if Kirschvink finds his beads, it means life probably started on Mars before it did on Earth. Although Mars is now cold and arid, with an atmosphere only one-hundredth as thick as Earth's, it was much warmer and wetter 4 billion years ago. NASA rovers now trundling across the surface of Mars have uncovered ancient lake and stream beds, suggesting

If Mars was the mother planet, Earth would have been the nurturing planet.

the planet likely once had shallow seas blanketed by a much thicker atmosphere.

While many scientists consider liquid water to be the most essential ingredient for life, Earth may once have harbored too much water. "The best evidence we have suggests that early Earth was completely covered by oceans," says Kirschvink. Without some dry land, he says, it would have been difficult for the basic chemical



THE GRANDEST CANYON At more than 2,500 miles long and up to 23,000 feet deep, the Valles Marineris canyon system on Mars is one of the largest in the solar system. Scientists think liquid water played a role in its formation.

ingredients of life to form. “The reason is very simple ... if you link two amino acids together to make a protein, you have to remove water.” And that would have been impossible if the amino acids were immersed in an ocean. Life needed some land—literally a beachhead—to get started. Ancient Earth might not have had any dry land, but Mars certainly did.

“All this is controversial since we’re talking about a world 4 billion years ago,” says Kirschvink. “But it’s very clear that Mars had southern highlands, and what is looking more and more like a north polar ocean basin. If you’ve got volcanic terrain sticking up, with rainfall and streams and rivers—if life had managed to get started there, it would have thrived.” That scenario, which seems very likely to Kirschvink, has some remarkable implications: Life, after its genesis on Mars, might have spread from there to Earth, borne here by meteorites. And that would make us—and every other living thing on Earth—the descendants of spacefaring microbes from Mars. According to Kirschvink, we won’t find our first ETs on some other world—we just have to glance in a mirror. “I really think we’re Martians,” he says. For Kirschvink, life on Mars is unlikely to represent the second genesis that McKay is looking for.

Although the idea that life may have been seeded

on Earth by comet or meteorite impacts is at least a century old, it remains a minority view among scientists, most of whom aren’t ready to accept a Martian pedigree for Earth’s life. Mars lies more than 30 million miles away—a long journey for man or microbe. But a rock blasted from Mars could have reached Earth in as little as six months, and given what we know about bacterial hardiness, the rock’s germy cargo could have arrived shielded and alive. Bacteria spores have survived on the outer surface of the International Space Station for 18 months, completely exposed to the vacuum and deadly radiation of space. In one recent experiment, Swiss researchers smeared strands of bacterial DNA onto the exterior of a rocket—the DNA remained viable even after the spacecraft’s fiery re-entry through Earth’s atmosphere.

If Martian bacteria did land here billions of years ago, they would have been released into a giant nutrient broth—Earth’s ocean—filled with dissolved carbon dioxide, iron, and phosphorous. Although it might be difficult for life to arise in a water world, once life had evolved—in some drier place—it could have thrived in Earth’s seas. And the newly arrived Martians wouldn’t have had any competitors. “Everything life would need would be in that ocean ready for life to come,” says

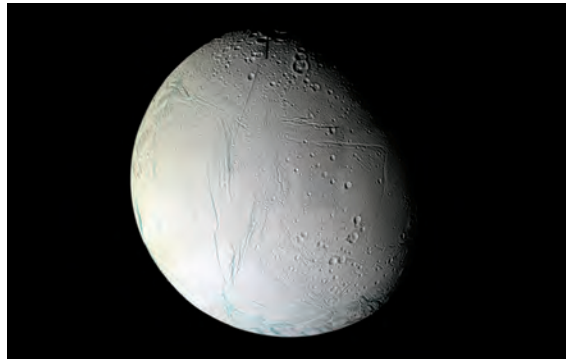
Kirschvink. “And then: Splash! You get a meteorite from Mars breaking up, freeing entombed bacterial spores. One bug that can reproduce can grow exponentially, so the first self-replicating bug that could get here would take over.”

What happened to Mars? Why, if life originated there, did Mars never become another Earth, with its own diverse ecosystems replete with plants and animals? Why did those ancient Martian rivers and oceans disappear? Mars, it seems, was simply too small to sustain life indefinitely. With barely one-tenth the mass of Earth, and less than half the gravity, Mars couldn’t hold on to its atmosphere. The gases essential for life slowly leaked into space. Without an insulating sheath of air Mars gradually became the cold desert world it is today.

“If Mars was the mother planet, Earth would have been the nurturing planet,” says Kirschvink. In his telling there’s a tragic element to life’s origins. One of the very conditions that might have made Mars an ideal birthplace for life—its small size, which allowed it to cool faster from its primordial molten state than Earth did, so life could get an earlier start—also meant that living things could not continue to flourish there. “You may need a special solar system where a Mars-like mother planet can infect its neighbors. It may be that those mother planets are doomed to die, and neighboring planets, like Earth, adopt the kids.”

WHILE KIRSCHVINK SCOURS ALH84001 for magnetosome chains here on Earth, other scientists are gearing up to scour the surface of Mars. Scientists at NASA’s Jet Propulsion Laboratory have drawn up plans for a mission that would return Martian rock samples to Earth. While that mission has no timeline or funding for the time being, McKay says if bacteria ever did exist on Mars, their fossil remains will be there, waiting to be found. “Magnetosomes are pretty robust,” he says. “They are the bacterial equivalent of bones.”

Some researchers think future missions might find more than magnetosomes and fossils on Mars. Life may still survive there, sheltered underground, says Gaetan Borgonie, a biochemist at the University of Ghent, in Belgium. He says those organisms might look something like the ones he discovered in our own planet’s deep subterranean ecosystems, which have barely been explored.



HOME, ICY HOME Chris McKay would start his search for extraterrestrial life on Enceladus, if he had the choice. One of Saturn’s moons, it has more than 100 geysers that spit ice into space.

Beginning in late 2008, Borgonie led a team that found the deepest-dwelling land creatures on Earth—a new species of worm living more than 2 miles below the surface in a South African gold mine. The researchers named it *Halicephalobus mephisto*, after the demon in the Faust legends. Although the worm is only about half a millimeter long, it is far larger and more complex than the simple bacteria the scientists expected to exist at those depths. The worm from hell, as some news reports called it, feeds on bacteria that subsist on minerals in the rocks.

That discovery is helping guide scientists in their search for aliens. Most life on Earth is small, dumb, and deep, and the same might be true on Mars. “If life originated there, those animals or plants have had 3 or 4 billion years to evolve, and they might still be there. Life always finds a way. Always,” Borgonie says. “If NASA or ESA [the European Space Agency] starts digging on Mars, they will have to dig deep, but I think there’s a better than 50 percent chance we’ll have our first alien.”

Kirschvink echoes this sentiment. When I ask him, Martian to Martian, if life might still survive on mother Mars today, he tells me it’s definitely not on the surface. “The atmospheric pressure is so low that water boils. Most of the planet is well below freezing most of the time. But we do know that once life evolves it can move into extreme environments. It’s done that on

Earth. It's gone deep; it's gone high. It didn't evolve in those environments but it moved into them. It's pretty clear that if life got started on Mars it probably moved into those other environments and might still be eking out an existence."

Not everyone agrees. To Steve Mojzsis, a planetary geologist at the University of Colorado at Boulder, the lack of obvious signs of life on Mars argues against the possibility that it ever existed there. "Life on Earth occupies the driest desert, the coldest glacier, the tallest mountain, the deepest sediments—it permeates the planet; there's a kind of biological activity on our planet. Mars? There is no hint of it whatsoever. We've sent a fleet of invading spacecraft to Mars—it's like the inverse of 1950s space horror movies—and we can't find anything."

The resolution may come with more digging. McKay is pushing for a mission that would search for underground Martian life by drilling about a meter into frozen ground at a site near the planet's north pole. Icebreaker Life, as the project is called, would launch in 2018 if NASA approves it. McKay originally wanted to drill 10 meters down to penetrate below surface layers that might be sterilized by intense solar radiation. But mounting a drilling rig more than 30 feet long on a spacecraft would have broken the mission's budget.

Another option—packing a disassembled drill on a spacecraft and putting it back together on Mars—wouldn't be feasible either, since no existing robot has enough dexterity for the task. So McKay and his team have settled for a single meter-long drill that would swing into an upright position after the spacecraft lands.

McKay has tested some of the components of Icebreaker Life in Antarctica, and showed that a prototype drill can penetrate 3 feet of frozen ground in about an hour. When fully operational, Icebreaker Life would use a brush to collect samples after every 2 inches of drilling, passing them to instruments that would test for enzymes and other signs of life—perhaps even intact, living microorganisms.

IF LIFE ON MARS WERE FOUND, its relationship to life on Earth would be determined by genetic analysis. Either Kirschvink's hypothesis about Mars as a mother planet would be confirmed, or McKay would have his second genesis. But even without a second genesis on Mars, the

possibility would remain that life has arisen elsewhere independently—on one of the hundreds of planets that scientists have discovered orbiting stars light-years away, or even farther out in our own solar system.

At the very top of McKay's wish list of where to search for life is Enceladus, a Saturnian moon. It has an ocean sloshing beneath miles of ice. But Enceladus also has more than 100 geysers that spew ice hundreds of miles into space. If life exists in Enceladus' ocean, the geysers might contain chemical traces of its presence. McKay can't contain his enthusiasm when describing the moon's plumes: He waves his hands overhead tracing the trajectory of an icy eruption. "It's like free samples, take one!" he says.

McKay has already met with Japanese researchers to discuss plans for a joint mission to Enceladus. He wants NASA and Japan to send a probe through the moon's geysers and deploy what amounts to a mechanical catcher's mitt. Coated with a sticky gel, the mitt would collect material from the geysers; the spacecraft would return the samples to Earth. The same technology was used to snag matter from a comet's tail in 2006, so there aren't any new engineering hurdles to overcome. Since Saturn is more than 10 times farther away from us than Mars, a shared origin for life on Enceladus and Earth would be less likely, improving the odds that McKay's second genesis might be found in the depths of that distant ocean.

If Mars and Enceladus and other candidate worlds in our own solar system turn out to be sterile, we now know there are plenty of others that might be friendly to life. NASA's Kepler space telescope has logged more than 1,000 planets around other stars, and astronomers now estimate that our galaxy alone may contain as many as 40 billion Earth-like worlds. If life were found on any of them, the extreme distances would all but guarantee a second genesis. What are the odds that so much cosmic real estate is barren? As the Scottish philosopher Thomas Carlyle remarked more than a century ago, "If they be not inhabited, what a waste of space." ☺

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The Real Landscapes of the Great Flood Myths

In Tibet, a geologist learns how folk stories may record actual catastrophes

BY DAVID R. MONTGOMERY

I CAME TO TIBET IN THE SPRING of 2002 to investigate a geologic mystery: How had the mighty Tsangpo River cut through the rising Himalaya to carve the deepest gorge in the world? Origin questions like this one fascinate me. I'm a geomorphologist—I study landforms and construct scientific narratives to explain the evolutionary processes that created and molded them. For years, I believed that my stories stood apart from myth in that they were forged in the topography of real landscapes—in the shape of hills to the lay of valleys. But that was before I visited the Tsangpo.

From the airport in Lhasa, my colleagues and I drove southeast, up and over an icy pass that descended into a tributary. As we wound our way toward the main river, I was surprised to see a series of flat surfaces perched, like a giant's banquet tables, above the bottom of the valley. Known as terraces, these enormous piles of loose sediment commonly form when a river slices into its bed, leaving older, higher floodplains

behind. But many of the terraces I now beheld were capped in alternating layers of silt and clay. Such fine, orderly strata would never settle out in a turbulent mountain river like the one beside us. What were these quiet-water deposits doing in an alpine valley at the top of the world?

Bouncing in the back of our Land Rover, I kept careful track of the terraces, marking their elevations on topographic maps. I noticed that at some point downriver, they all rose to roughly the same contour and then stayed at that elevation on down the valley, growing progressively taller as the river dropped lower and lower. Days later, when we visited the confluence where this tributary entered the Tsangpo, the terrace tops stood hundreds of feet above the valley floor.

Out of this landscape-scale jigsaw puzzle, a picture took shape: An ancient lake had once submerged the Tsangpo and its tributaries. Rivers emptying into the lake had deposited deltas, stacking sediments into layered terraces that today record the lake's timeworn

shorelines. There was just one missing puzzle piece: What had kept all of that water from draining down the Tsangpo gorge?

At the head of the gorge (which at its deepest depth drops the river almost 20,000 feet below the surrounding peaks), we found the eroded remnants of a glacial moraine—dirt and rocks pushed downhill by flowing ice. Debris appeared on both banks of the Tsangpo, indicating that a glacier advancing down the flanks of a nearby mountain had bulldozed a colossal dam of earth and ice over the river. The barrier had sealed off the valley, and the river had swelled to form a massive lake. But the water-worn form of the moraine told us that the dam hadn't lasted. When it broke, a wall of water raged down the steep, narrow gorge at hundreds of millions of gallons per second—surpassing the discharge of the Amazon.

This discovery was electrifying. In reading the land, we had unearthed a grand geological saga long lost to history. Or so we thought. One day, as we bumped along past a small peak ringed by terraces, one of my graduate students told a story he'd read in a guidebook. The peak, he said, marked the site of a kora—a Tibetan Buddhist pilgrimage—commemorating how the spiritual teacher Padmasambhava, also known as Guru Rimpoche, brought Buddhism to Tibet. According to legend, Guru Rimpoche converted the people from animism through a series of miracles, which included defeating a demon who dwelled in a great lake. How did the guru beat the demon? He drained its lake.

Guru Rimpoche came to the Tsangpo in the eighth century, around the time the ancient lake we had just stumbled upon filled the valley, according to radiocarbon tests of charcoal bits collected from the terraces. I



FLOOD LEGENDS Many cultures have their own versions of a flood story. At left, an artist's rendition of Noah's flood. At right, an illustration of Manabozho, a trickster featured in a Native American flood myth.



WIKIPEDIA (LEFT), R.C. ARMOUR (RIGHT)

The features of a fabled flood often bear a striking resemblance to local geological processes.

pondered these two stories—one cast in culture, the other written on land. Could they be telling different versions of the same affair?



THE LATE GEOLOGIST Dorothy Vitaliano coined the term geomythology in the 1960s to describe oral lore that explains peculiar landforms or references geological cataclysms—earthquakes, fires, floods, volcanic eruptions, diverted waterways, or the sudden emergence or disappearance of islands. Like most geologists, I once dismissed these accounts as imaginative fantasies. Embellished with supernatural details and shrouded in the language of myth, they rung no truer than science-fiction yarns about Martian colonies and cyborg races. There is some evidence, however, that many geomyths are in fact grounded in events that actually happened.

The story of the great flood is one of the oldest and most widely told. A version of this legend appears in so many cultures that some pseudoscientific theorists have invoked its ubiquity as evidence of a global flood. But while flood myths share common elements—catastrophic inundation; a harrowing escape, usually by boat—the nature of the deluge varies from region to region. And the differences are telling. Often, the features of a fabled flood bear a striking resemblance to local geological processes, suggesting that many myths record real catastrophes witnessed in antiquity.

Flood stories from coastal settlements, for instance, such as in Fiji and Tahiti, tell of giant waves that struck from the ocean without warning or rainfall. A prehistoric tale from central Chile depicts two powerful serpents that vie to lift the sea the highest, inciting an earthquake and flooding the shore. In the American Pacific Northwest, native tribes tell of epic battles between Thunderbird and Whale. Again and again, the winged being grabs the sharp-toothed monster out of the water and then drops it, rousing enormous waves that sweep canoes into treetops.

These reports sound a lot like tsunamis. Indeed, thanks to Japanese temple records, we know that a major earthquake struck the Pacific Northwest on Jan. 26, 1700, sending waves as far as Japan. About that time, according to archaeological remains, Native Americans abandoned villages along the western coast of North America, from British Columbia to Oregon. In the myth of Thunderbird and Whale, survivors apparently preserved the memory of this or earlier tsunamis that drove them from their homes.

Similarly, inhabitants of the Arctic and high alpine regions, like the Tibetans of the Tsangpo Valley, have retained flood myths that seem to describe glacial dam breaks. Norse mythology, for example, recounts how Odin, the “allfather” of gods, and his brothers killed the ice giant Ymir, whose blood, made of water, gushed forth in a deluge that drowned men and animals. Connecting this fantastical tale to an historical act is fraught with speculation. But I’d be surprised if Ymir wasn’t born out of an actual ice-dam rupture as glaciers retreated from Scandinavia at the end of the Pleistocene.

A third category of flood stories reflects the experiences of river communities, who speak of perpetual

rains and slowly rising waters. The biblical story of Noah, from the Book of Genesis, is the iconic example. This Hebrew myth has roots in an older Mesopotamian tale recorded, in blocky cuneiform runes, on a fragmented clay tablet excavated from the ruins of an ancient library. The inscription portrays a righteous man who receives a divine warning of an impending flood intended to destroy humanity. He is ordered to build a vessel—an ark—and bring his family and animals aboard to ride out the storm.

There may be geological truth behind this tale, too. It's possible, for instance, that heavy rains swelled the Tigris and Euphrates rivers enough to breach their levees, filling the lowlands like a bathtub. Columbia University oceanographers Bill Ryan and Walter Pitman came up with another hypothesis in the early 1990s. Analyzing sediment cores from the bed of the Black Sea, they discovered that before 5600 B.C., the sea was a large freshwater lake. Then, when glacial ice melting off the poles raised sea levels worldwide, the Mediterranean overtopped a narrow strip of land and decanted into the lake. The inflow “roared and surged at full spate for at least three hundred days,” the researchers write in their book *Noah's Flood*, cascading over the land at 200 times the flow of Niagara Falls.

Ryan and Pitman speculate that this spillage rapidly inundated a broad plain where some of the world's earliest farming communities lived. Perhaps, they offer, traumatized survivors fled to Mesopotamia, bringing with them knowledge of agriculture and irrigation—and a story about a great flood that submerged their world.



WHEN I RETURNED TO THE Tsangpo Valley in 2004 on another research expedition, I told a local farmer that our team had found geological evidence of an ancient flood that drained a lake where her village now stood. Yes, she replied, she knew about the flood. The lamas at the local temple taught that when the lake emptied, it exposed flat, fertile land for her people to farm. She pointed halfway up the valley wall. There,

The lama's quest to understand the world was not so different from mine.

she told me, the falling water had stranded three boats.

My colleagues and I decided to visit the lamas. Their temple sat high above the valley bottom on a lake terrace. In a colorful fresco on the temple wall, Guru Rimpoche hovered resplendently above a lake-filled valley. When we asked about the flood, the head lama listened patiently and then dismissed the event as old news. But he was curious about another geological puzzle: Why, he wondered, could one find water-rounded rocks on nearby mountainsides? Did their presence not prove that an ocean once covered Tibet's tallest peaks?

As a geologist, I know that his theory wouldn't hold up to scientific scrutiny. More likely, the smooth rocks were cobbles, stranded high on the valley wall when ancient rivers discharged into a glacier-dammed lake. Yet the lama's profound interest in and attention to the details of the landscape struck me. Although he lacked the tools and training of a modern scientist, his quest to understand the world was not so different from mine.

I began to see science and mythology as two faces of the same coin. After all, the divide between these fields is a relatively recent development. Historically, they weren't so easily teased apart.

Take the story of Noah. Early natural philosophers' belief in a global flood colored their interpretations of worldly phenomena even as they laid the foundations for modern geology. Saint Augustine, a fourth-century bishop in a Roman province of Africa, warned against readings of the Bible that conflicted with reason and the study of nature. In his view, the earth didn't lie. When he found seashells encased in mountain rock, he took them as confirmation of a global flood. How else could the bodies of marine creatures get locked up in mountaintops?

Nicolaus Steno, a Danish natural philosopher living



THE GURU'S FLOOD A Tibetan myth tells how Guru Rinpoche subdued a demon by draining his lake, inciting a flood that may actually have occurred.

in 17th-century Italy, likewise relied on field observations to uphold the truth of the biblical flood. While dissecting the head of a great white shark, he noticed that its teeth were precisely the size and shape of mysterious triangular objects in rocks known as tongue stones, which today we know are fossilized shark teeth. To explain how these teeth got into rocks, Steno reasoned that after Creation, the earth settled out of a primeval sea in layers, with the oldest layers on bottom and the youngest on top. Now known as Steno's Law of Superposition, this rule became the foundational principle of geology. Steno used it to deduce that earth history involved six stages—one of which was Noah's flood.

Gradually, however, the ties binding biblical narratives and geological science began to unravel. Steno showed that rocks could tell their own stories, thereby guiding, constraining, and ultimately refuting religious doctrine. Subsequent generations of geologists and paleontologists established that the history of our planet, and its flora and fauna, was much too long and complex to map neatly onto a literal interpretation of scripture. By the time Darwin published his controversial ideas on evolution, the geologically literate clergy had largely abandoned faith in a global flood.

Now geomorphology is reweaving empiricism and symbolism, ferreting out kernels of fact buried in fable. Humans have always toiled to make sense of the world and our place in it. And for most of our history as a species, oral traditions were the only way to safeguard knowledge for posterity. In this sense, science can be seen as an extension of folklore—a new way to pass on the same stories. Only with better data. ☺

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26

TWICE A YEAR, the Pantone corporation holds secret meetings in a European capital to decide on a “Color of the Year”—something that fits the mood of the time. This year, for the first time in three years, Pantone also added a brand new color to its palette: minion yellow, after the *Despicable Me* character.

Of course, minion yellow is not a *new* new color. It has undoubtedly been produced and seen before. It is part of white light like every other visible color. But now it has a name, number, and a cartoon cast. Leatrice Eiseman, the executive director of the Pantone Color Institute, says Pantone’s focus is on “what it means when people see [the color].”

Which perks up the ears of many a philosopher. Philosophers have a name for what it feels like to have an experience: qualia. And they have been arguing about qualia for over a century. How should qualia be defined? Do they exist for every experience? How do they play into the division between body and mind?

What’s remarkable about this debate, besides its longevity, is the frequency with which it uses color as the canonical experience—a unique point of intersection between the subjective and the objective, occupying a space that includes both minion yellow and plain old yellow.

But if you haven’t seen *Despicable Me*, is there a difference?

Welcome to “Color.”

—MS

“Blue has become the default color of a living planet, a cosmic oasis, a life-harboring, fragile, and tiny jewel sitting in space.”

CALEB SCHARF

“Life Beyond the Pale Blue Dot” p. 84

Color

BEYOND THE SPECTRUM



The Girl Who Smelled Pink

A mother wonders if we are all born with synesthesia

BY KIRSTEN WEIR

MY TONGUE IS ORANGE!” my 2-year-old daughter shrieked after licking a dollop of clear hand sanitizer. More orange experiences followed. “Mommy, my ear feels orange,” she moaned when an earache struck. “Mitten off! It’s orange,” she whined from inside her snowsuit when a scratchy tag in her new white glove rubbed uncomfortably against her wrist. As her vocabulary blossomed, she started to associate colors with scents. “What’s that brown smell?” (A local coffee roaster.) “What smells pink?” (Dryer exhaust puffing out of a neighbor’s basement vent.)

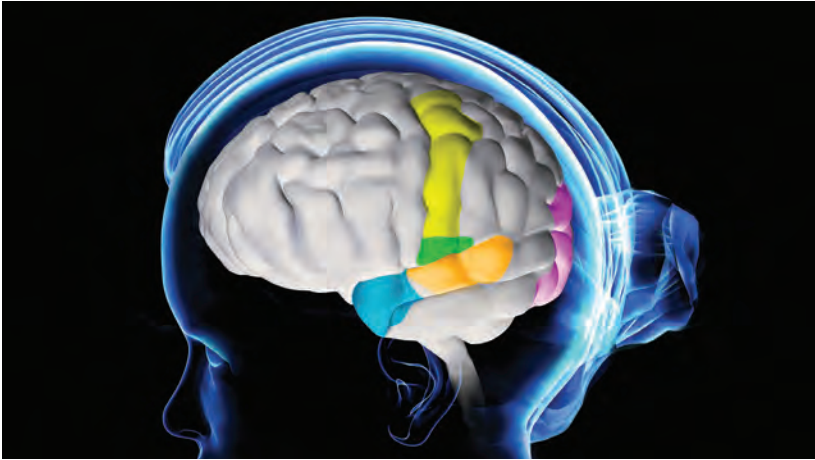
Anyone who has spent time around toddlers knows they say some strange things. But my daughter’s curious way of talking about colors was so emphatic, and so consistent, that I began to wonder if she might be experiencing synesthesia—a kind of cross-wiring of the senses that can evoke flavors from sounds, tastes from words, or colors from smells.

Since 1812, when an Austrian doctor first described

his own propensity to see numbers and letters in their own distinct hues, researchers have documented more than 50 forms of synesthesia.¹ The novelist Vladimir Nabokov wrote that the letter F assumed the green of an alder leaf, while the letter Z took on the dark blue of a thundercloud. The neurologist Richard Cytowic once met a synesthete who could feel with his hands cold, glass columns every time he inhaled spearmint. Another of Cytowic’s subjects reported tasting poached eggs when he heard the name Steve.

Yet despite its extraordinary nature, synesthesia is remarkably common. Studies estimate that up to 5 percent of adults have some form of the condition, including as many as 16 million people in the United States alone. But even if my daughter doesn’t grow up to be part of that statistic, her obsession with color may signify more than just an overly vivid imagination.

Some researchers suspect that we are all born with perceptual abilities like those of synesthetes.² In the absence of synesthesia, the adult brain mostly



A SIXTH SENSE Both adults with synesthesia and infants have more neural pathways between sensory regions of the brain, including areas for touch (yellow), sight (pink), hearing (orange), taste (green), and smell (blue).

processes information about the outside world through separate sensory systems—one for vision, another for touch, and so on. But in the mind of a baby, the senses are less distinct; the environment may exist as a kind of undefined blur. “Babies aren’t seeing mom versus hearing mom versus smelling mom,” says Daphne Maurer, an expert in the development of perception at McMaster University, in Ontario. “They’re just experiencing ‘mom-ness.’” Perhaps my daughter is expressing the weird sensory realm that all very young children inhabit but only synesthetes can still visit later in life.

WE MAY NEVER KNOW exactly how infants perceive the world because they can’t tell us. “But it’s very possible it’s a complete mess to them,” says Nicholas Root, a doctoral student studying synesthesia at the University of California, San Diego. Studies in animal and human infants suggest that when we’re born, the brain regions responsible for handling input from our eyes, skin, and other sensory organs aren’t yet specialized. When babies look at faces, for example, their brains show activity in vision centers as well as areas that process language and sound. Similarly, when babies listen to human speech, the auditory regions activate along with the visual regions.

This cross-activation implies that the sensory areas in the infant brain are knitted together in a cat’s

cradle of neural links. “Soon after birth, you have the most connections you’ll ever have in the brain,” says Jamie Ward, a cognitive neuroscientist at the University of Sussex. As you mature, the useful connections strengthen while the idle ones weaken or disappear. What starts out as a tangled thicket of sensory branches gets pruned into a tidy topiary.

Precisely how the extra crosslinks in babies’ brains affect perception is something of a mystery. But the experiences of synesthetes may offer a clue. Neuroimaging studies show that, like infants, adults with synesthesia have more physical connections between sensory processing areas than do other adults.³ And one type of stimulation can similarly engage multiple sensory areas. In synesthetes who see colors in sounds, for example, spoken words activate a part of the brain associated with color vision.⁴

These observations have led some scientists to conclude that people with synesthesia keep some of the cross-sensory connections they were born with. Other researchers suspect that higher-order brain centers, which typically shush superfluous communication between sensory regions, don’t completely stop the gossip. In either case—and both may be true—the result is the same: The senses never fully disentangle.

Because the brains of babies and synesthetes share common features, it’s possible that an infant’s

The vast majority of people with synesthesia say their worlds are richer for it.

perception may look a lot like an extreme case of synesthesia. Behavioral studies support this theory. In a 2011 paper, psychologist Karen Dobkins and doctoral student Katie Wagner at the University of California, San Diego presented babies with circles and triangles displayed on differently colored backgrounds. The researchers found that at 2 to 3 months, the infants favored certain shape-color pairings, and, like adult synesthetes, their preferences differed from person to person. By 8 months, however, babies didn't seem to care whether a circle was blue or a triangle was yellow.⁵

For some people, early synesthesia-like gifts may endure even longer and continue developing. In a 2013 study, Julia Simner, a psychologist at the University of Sussex, tested more than 600 kids between ages 6 and 7 for signs of grapheme-color synesthesia, in which letters and numbers take on distinct hues. She identified eight children who consistently paired certain colors to about one-third of all Arabic numerals and English letters. A year later, they matched nearly half of these graphemes to a fixed color. And by age 10 and 11, five of the eight children appeared well on their way to becoming full-blown synesthetes—they colored 70 percent of the numbers and letters in a routine way. The other three kids, meanwhile, seemed to have lost at least some of their synesthetic ability.⁶

The possibility that my daughter began life as a synesthete is in one sense delightful. To her, a hummed lullaby might literally have felt like a hug. A tickle to the toes might have invoked a shimmering rainbow before her eyes. On the other hand, this sensory mélange might explain why it's so easy to overstimulate a newborn. "If the parents turn on the light, start to sing in a

loud voice, or bump into the crib, to a baby that might be equivalent to screaming at the top of your lungs," Maurer says.

WHETHER HEART-WARMING OR HAIR-RAISING, an infant's perceptual mash-up likely serves an evolutionary advantage. The abundant sensory connections in a newborn brain may allow babies to adapt to the peculiarities of their particular time, place, and culture. If the senses were hard-wired at birth, "there would be lots of ways that could go amok," Maurer says. Instead, "what's built in is this mechanism of 'use it or lose it.'"

A baby's brain is constantly learning which sensory inputs represent real information and which signals are just "noise in the system," Maurer explains. As newborns, we take in nearly everything because we don't yet know what's important. But as useless connections get silenced or trimmed away, a more efficient brain emerges. Sensory regions become specialized and streamlined, able to tune out neural noise and home in on the messages that matter for our survival.

In the first few months of life, for example, infants can tell the difference between two faces regardless of the subjects' ethnicity. By the time they turn a year old, however, babies can more easily distinguish faces from their own culture than faces from other cultures. Similarly, young infants are pretty good at discriminating a wide variety of speech sounds. But by their first birthdays, they no longer notice differences that are irrelevant to their native language. Children born into Spanish-speaking families, for example, lose the ability to differentiate between "va" and "ba," which are used interchangeably. Babies exposed to English similarly stop being able to contrast two "da" sounds important in Hindi—one made with the tongue at the front of the mouth, the other made with the tongue to the side.

Maurer views these findings as further evidence that a baby's perceptual world exhibits many of the characteristics of synesthesia. In her work with adult synesthetes, she has found that they retain some ability to distinguish between foreign faces and speech sounds as babies do. Although they don't do as well as culture-blind infants, they do a significantly better job than non-synesthetes.

Even in typical adults, the pruning process might not be absolute. Like rope bridges stretched between

$$7 = \text{yellow square}$$

$$9 = \text{blue square}$$



$$5 + 2 = \text{yellow square}$$

$$6 + 3 = \text{teal square}$$

1 PLUS 1 IS BLUE Just as you may struggle to say the ink color of words such as **RED**, synesthetes have trouble naming the color of a square when it differs from the color of the solution to a math equation paired with it.

islands, some of the neural connections between sensory areas that exist in the infant brain may linger into adulthood. And those links might bias us to make certain associations between sensory objects, often without knowing it. “There are remnants of this early wiring in all of us,” Maurer says. “It doesn’t affect our full-blown conscious perception, but it’s there in our behavior.”

Take the perception of color and pitch. Studies show that both children and adults without synesthesia match lower-pitched sounds with darker objects and higher pitches with lighter objects, even though they don’t consciously perceive these sounds as having intrinsic colors, as synesthetes do.⁷ Maurer and Ferrinne Spector, a former graduate student and now a professor of psychology at Edgewood College, in Madison, Wisconsin, have found similar universal biases between colors and scents, textures and letters of the alphabet.

Some of these associations can be explained by experience—green for the letter G, yellow for the scent of a lemon. But other biases may be part of our neural architecture and probably help us learn, Spector says. Mentally linking larger objects with louder sounds, for example, is in line with the way the world works. Elephants sound louder than mice. Having a ready-made intuition about such natural rules could give babies a jumpstart on making sense of their environment.

Still, many patterns are puzzling. In a study of 78 adults without synesthesia, volunteers described the smell of ginger as black, rough, and sharp more often than chance. Lavender, meanwhile, was green or white, liquid, and sticky.⁸ Studies of adults and pre-literate toddlers likewise reveal unconscious pairings between the letters O and I with the color white, and between the letters X and Z with the color black.

These strange sensory unions may be artifacts of the way our brains are wired, Spector speculates. Our tendency to match light colors with high pitches, for instance, may be a side effect of how our brains understand frequency. Or it may simply be a shadow of our infant viewpoint—a lurking reminder that we all started life surrounded by a swirling cloud of sounds and smells, tastes and textures, contours and colors.

IN SEAN DAY’S SENSORY UNIVERSE, beer tastes turquoise. Freshly cut grass smells deep purple with a lavender streak. Notes from a piano look like a cloud of sky blue.

Day is an anthropology instructor at Trident Technical College in South Carolina and the president of the American Synesthesia Association. For as long as he can remember, he has experienced colors in flavors, scents, and sounds. In his spare time, he likes to cook and compose music, and his synesthesia inspires

his recipes and compositions. “I’ll deliberately go after certain color combinations that are vivid and flashy,” he says. “Dark purple with orange is really good—green leafy vegetables are dark purple; raspberries are orange.” Electric sounds and echo effects likewise create flamboyant color fusions.

Some synesthetes find their condition distracting or overwhelming. Try learning math when the color of the answer doesn’t match the colors of the digits you’ve just added together. Or navigating Times Square when every word on every billboard multiplies the colors and shapes flashing before your eyes. But the vast majority of people with synesthesia say their worlds are richer for it. Day, for one, knows he would miss his musical and savory hues if they disappeared. Because one day they did.

In 1999, he was living in Taiwan when the Jiji earthquake struck, killing more than 2,000 people. “There were aftershocks; no water,” he recalls. “Destruction all around.” In the days that followed, his synesthesia mysteriously vanished—a symptom of stress, he thinks. For four months, food seemed drab; music was dull. Then finally, their colors returned. “If they hadn’t come back, it would have been a pity—a loss.”

My daughter will turn 3 in October. She hasn’t described pain or discomfort as “orange” in months. She rarely paints scents in the language of color. When I press her to characterize an aroma, she looks at me with confusion. If she did experience some kind of synesthesia in her first two years of life, the ability seems to be slipping away.

I can’t help but feel wistful for the vibrant Kodachrome world she might have lived in and might now be leaving behind. I long to see what she saw when her ear throbbed orange, when she inhaled a deep breath of pink-tinged air. It’s comforting, though, to think that the ghosts of those colorful moments may still reside deep in her brain, as they may in mine. One spring day, when the lilacs are in full bloom, we may walk outside and together smell the green sticky air—for a brief moment, inhaling the world again through the kaleidoscopic mind of a baby. ☺

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COLOR | FOOD

The Colors We Eat

Food color does more than guide us—it changes the experience of taste

BY TOM VANDERBILT

PHOTO-ILLUSTRATIONS BY MATHERY STUDIO



WHEN IT COMES TO FOOD, color is money. Food companies scan their products on the line with custom colorimeters to ensure mathematically consistent hues.

Fruits and vegetables are shipped in chemically “modified” atmospheres, because “better stem and fruit color gives better prices,” according to the website of the delivery company TransFresh. Color is judged by a legion of standards all along the food chain. The hue of orange juice, for example, is carefully calibrated by the United States Department of Agriculture’s Orange Juice Color Standards (Grade-A orange juice from concentrate has to be “not as good as OJ 5 but much better than OJ 6.”) There are few worse fates, in the eyes of federal regulators, than for a berry to be “undercolored.”

Oranges and berries are just the beginning. The color matching business Munsell sells color standards for French fries, tomatoes, pumpkins, olives, molasses, honey, and cherries. Art Schmechling, a manager with Munsell, tells me a product like the maraschino cherry actually has two color standards: One for the cherry after it is bleached to a pale yellow, which is done so the cherry can be properly dyed its trademark iridescent red; and another for that red.

The attention to color is not just for show: For all the talk of the tongue and palate, our eyes are arguably the most important gustatory organ. As Charles Spence, who heads the Crossmodal Research Laboratory at Oxford University, points out, more than half of our cortical real estate is dedicated to processing vision—just a percent or two is given over to taste faculties (making us rather unique among mammals). The result is not just that color flavors our expectations: It actually changes how we taste food.

IN A 1980 STUDY, subjects were blindfolded and asked to tell whether the beverage they were drinking was flavored orange.¹ Only one in five could. But when they were allowed to see what they were drinking, each of them identified the orange flavor. And when a lime-flavored drink was colored orange, nearly half of respondents thought it was flavored orange—none did when it was green.

It’s not just the color of the drink that matters. Test subjects thought coffee in a white mug tasted less

sweet than in a transparent or blue mug,² and that 7up had a more lemon-limey taste when more yellow was added to the packaging.³ Even the color of the plate might change our sense of taste: Subjects reported strawberry mousse tasted better on a white round plate than on a black square plate.⁴

The eyes can deceive even the expert tongue. A study at Cornell University, for example, found that trained experts had trouble distinguishing the fat content of milk when they could not see it; the “whiteness” of milk was a far more important cue than whatever sensations came from actually having it in one’s mouth. “There is nowhere that is safe from expectation,” argues Spence.

In another well-known study by professor of oenology Wendy Parr and her colleagues, wine experts were asked to describe the odors in two glasses of wine, a chardonnay white and a pinot noir red.⁵ Unbeknownst to them, a flavorless red food coloring had been added to the white wine. When they sampled the colored white wine in *opaque* glasses, they were more accurate. In *clear* glasses, however, they began straying into descriptors more common to red wine; their considerable knowledge of red wine descriptors was triggered by the mere sight of red. Their knowledge was, in a sense, backfiring.

Food companies, which regularly do taste testing internally, know the confusion that color can create. Their trained sensory panelists evaluate new foods under red lighting, so that their powers of discrimination are not thrown off by traditional color-flavor expectations. As Jeannine Delwiche, a sensory scientist at Mead Johnson Nutrition (and before that at PepsiCo) notes, at the early stages of a food product’s development, “the color often isn’t set.” Changes in the way the food is eventually processed may change its appearance. “The assumption is you can address that separately,” she says. “Meanwhile you want to know how the flavor’s doing.” The red light, she says, compels the panelists to focus more on other attributes, like texture and flavor.

PRECISELY WHAT IS HAPPENING when someone misidentifies the flavor of a beverage with an unexpected color? Is it that participants simply cannot fully discern what that flavor is, and so rely on visual cues

to help inform their decision? Or does color actually change the experience of the taste?

The key to this question is the effect of color on expectation. “The primary taste cortex is one of the first stops after the tongue,” says Spence. But “even activity there is modulated by your expectations.” Where the thinking used to be, notes Spence, that “all this information comes from outside through our eyes, ears, and tongue and works its way up through the cortical hierarchy, at each stage being condensed, it turns out that there are more pathways going from the inside out.”

The brain acts like a prediction engine: If bright red fruits usually taste sweeter, the next time you eat a fruit that looks bright red a top-down “back projection” might be, as Spence suggests, “constraining the activity earlier in the neural system closer to the outside, to your eye or tongue.”

A 2014 article in the journal *Neuropsychologia* puts it this way: “expectations bias sensory representations both prior to and during evidence accumulation.” Imaging studies, it notes, “have detected anticipatory signals or ‘baseline shifts’ in sensory regions that are selective for expected stimuli.”⁶ One of the simplest baseline shifts when it comes to taste is that the brain’s gustatory system “codes” flavor information faster when that flavor matches expectations (color being a major part of that expectation).⁷ In rats, at least—our fellow omnivores—the mere *association* with a taste previously experienced seems to stimulate similar “neural ensembles” in the gustatory cortex as does actually experiencing the taste.⁸

And so, gazing upon a glass of deep red juice, which we are told is made from strawberries, we have a learned association with that flavor and its expected sweetness. A “template” of sweet strawberry taste is activated. Or in the language of the *Neuropsychologia* study, a “feedforward prediction error signal” issues from the “lowest-level stimulus template.” If the tongue senses a reduced sweetness, a back-and-forth communication between lower and higher order parts of the brain can decide in favor of the reigning idea of a sweet strawberry juice anyway.

We taste first with the eyes, just as the old saying goes. And the path from color to taste can go in both directions. As an article in the *Journal of Dairy Science* notes, consumers want cheddar cheese that looks good

(the USDA standard is for “medium yellow-orange with a uniform bright color, and an attractive sheen”).⁹ But if something is not right with the flavor, the “attention of consumers can be drawn to the cheese color.” It may now *look* wrong because it *tastes* wrong. In fact, in imaging studies in which subjects’ taste expectations were violated, areas of the visual cortex were suppressed, as if the brain was saying “wait, the eyes are not to be believed here.”¹⁰

Charles Gilbert, a neurobiologist at Rockefeller University, notes that, even when we are unaware of it, “we are constantly implementing an interaction between top-down influences and input coming from the sensory periphery.” He notes demonstrations (like the McGurk effect) in which subjects watch someone saying different phonemes, even as the audio actually stays the same. The visual guide is enough to make them perceive the different phonemes. “What you hear

There are few worse fates, in the eyes of federal regulators, than for a berry to be “undercolored.”





We are all born liking sweet things, but we are not born knowing what sweet things *look* like.

depends on what you see,” says Gilbert. “We are only now beginning to learn what kind of information is conveyed in a top-down fashion and how top-down influences are manifested at different cortical levels, but I’ll bet that all levels are involved in some way.”

IN HIS BOOK *An Anthropologist on Mars*, Oliver Sacks tells the story of “Mr. I,” a painter who lost the ability to distinguish colors after a car crash. While he *knew* the color of things from memory, he no longer saw them. “Tomato juice is black,” he wrote. Over time, these new associations took hold. When he ate, he closed his eyes, “but this did not help very much,” wrote Sacks, “for the mental image of a tomato was as black as its appearance.” In desperation, he began to eat only black and white foods—black olives, yogurt—because these at least looked as they should.

The episode illustrates the flip side of the visual influence over taste: We can use vision to learn to like new tastes. There is little evidence that color-flavor relationships are hard-wired. We are all born liking sweet things, but we are not born knowing what sweet things *look* like.

The brain, says Spence, “picks up the statistics of the environment,” and we learn, for example, “that fruits go from green and sour and unripe to red and ripe and full of energy.” We do not have to taste a green strawberry to know we will not like its taste.

Sacks’ story hints at how quickly these associations can be changed. As Spence notes, several decades ago, it was a truism in the food industry that you couldn’t sell blue foods, given their rarity in nature. Yet now, shelves bristle with “cool blue” Gatorades and “blue raspberry” Icees. Those associations, he says, were taught—and it helps when the flavor is novel, or indeed invented. Candy and beverages seem particularly amenable to color experimentation, suggests Delwiche. “They are like the evening wear of the food world—not what you wear to the office.” But strange colors have also crept into food marketed to children, where novelty is prized, and learned associations less rigid. Heinz sold many bottles of green, orange, and yes, blue, ketchup in the 2000s, before the novelty ran dry.

If we can learn to like new colors of food, color can also help us learn to like new foods. Tim Geistlinger, vice president of research and development at Beyond

Meat, a company making plant-based protein products, notes that consumers are not ready for chlorophyll-tinged hamburgers. “There’s no meat that’s green unless it’s going bad.” So his job, turning green into brown, while technically complex, has a simple end goal: Looking just like the (cooked or raw) meat it is aiming to replace. “It’s got to be very recognizable, or people won’t buy it. That’s their first due diligence.”

Don’t like that wine? Try it under a different kind of lighting. Want that drink to taste sweeter? Make its color brighter. Want your tea to feel colder? Put it into a glass container. Seeing really is believing.

LIKE AN INVISIBLE CONDUCTOR, the brain deftly arranges and synthesizes information coming in from the different senses. As this “multisensory integration” typically feels so seamless, actually glimpsing it at work feels disconcerting, a ripple in the Matrix. Take the red pill, and you find out that vision casts a dominant view over every sense (though it too can be affected, as in a demonstration in which a single flash of light, accompanied by two “beeps,” suddenly looks like two flashes).

In a famous 1964 experiment, the scientists Irvin Rock and Jack Victor had people look at small square objects that had been experimentally manipulated to appear like rectangles. They had others touch the objects with their eyes closed. A third group did both. They were then asked to draw what they experienced. As you might expect, the lookers drew rectangles, while the feelers drew squares. But those who could look *and* feel drew rectangles.¹¹ Vision, argue the philosophers Dustin Stokes and Stephen Biggs, has an unparalleled, “asymmetric” power over other senses, not least because we seem to rely on *mental* imagery—“visual cortical processing”—to know what things feel like: “We often invoke visual imagery to learn about certain tactile stimuli, but we rarely, if ever, invoke tactile imagery to learn about visual stimuli.”¹²

Taste seems so inviolable because it takes place *inside* of us; like a secret memory, only we can taste what we can taste—how could it betray us? But before food gets to us, our eyes have already seasoned it. ☯

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Life Beyond the Pale Blue Dot

Our own oasis of life in the cosmos is blue, but will others be?

BY CALEB SCHARF

AT A DISTANCE of 3.7 billion miles from the sun, on an otherwise ordinary February day in 1990, the Voyager 1 probe turned to point its camera platform away from its headlong rush into the cosmic void. A narrow-angle optic switched on and snapped a sequence of brief shots.

One of the sensor's tiny pixels, spanning about the length of a dozen bacteria lined up end to end, registered an increased charge. There, among the sun's lens flare, diffracted light, and electronic noise, sat an extra point of light. It was the smallest of small blips, an inconsequential mote in the emptiness of space, and it had a pale blue hue.

This mote was *us*, our world, Earth—a shockingly abrupt summation of 4 billion years of complex and chaotic history. The image taken that day was the ultimate selfless selfie. It provided an existential perspective that is unique among the species on our planet: Only we humans have seen ourselves from billions of miles away. Carl Sagan would later immortalize the image with the title, the “Pale Blue Dot.”

The Pale Blue Dot was the latest in a long history of association of the color blue with our home in the universe, and with life itself. Two decades before Voyager, as Apollo 8 circled the moon, astronauts recorded the now-famous “Earthrise”—a stunning color photograph of a bright blue-white hemisphere suspended above a gray lunar landscape. Four years later, the Apollo 17 mission captured a beguiling whole-Earth image that became “The Blue Marble.”

These space-age portraits drive home the fact that we evolved on a blue planet. Some people, like Wallace Nichols, the scientist and author of *Blue Mind*, have suggested that we have a primal, near irrational, desire for water and its blue oceans and lakes. This thesis is supported by a recent global survey suggesting that blue is our favorite color. In the United Kingdom alone, a world-beating 33 percent of respondents ranked blue above anything else, with red a runner-up at about 15 percent.

Blue has made it into our flags and emblems, too. NASA, the European Space Agency (ESA), the Search

for Extraterrestrial Intelligence (SETI), and the Planetary Society are represented by blue backdrops, or abstract blue Earths, or blue symbols. The One Flag in Space initiative advocates a Blue Marble flag, in which a photo of the Earth is shown on a blue backdrop. Just this May, a Swedish design student named Oskar Pernefeldt proposed an International Flag of the Planet Earth that has attracted wide media coverage, consisting of seven interlocking circles on a vivid blue background.

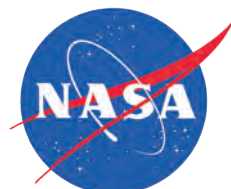
Blue has become the default color of a living planet, a cosmic oasis, a life-harboring, fragile, and tiny jewel sitting in space. But there's a catch: The very science and technology that gave us the Pale Blue Dot in the first place is undermining what we thought blue meant.

AROUND A STAR CALLED Henry Draper 189733, some 63 light-years from Earth, is a giant planet just a little larger than Jupiter. This gas-cloaked world takes about two Earth days to complete an orbit. It lives incredibly close to its stellar parent. As a result, the upper planetary atmosphere is heated to over 1,300 degrees Fahrenheit (or over 700 degrees Celsius). Powerful thermal gradients drive winds to thousands of miles an hour while a hot rain of glassy silicates beats its way through the maelstrom. It is, in other words, a truly beastly place.

By stretching current astronomical instruments to their limit, scientists have been able to make a first, crude measurement of how this planet reflects starlight, and to divine its overall color. Which is a rather serene, deep azure blue, not unlike that of Earth's skies on a summer's day.

Astronomers' best guess is that this world has a moderate cloud deck of condensed, but still scorching, minerals—with a clear atmosphere above it. The clouds reflect most light, but molecular hydrogen in the higher atmosphere preferentially diverts and polarizes blue wavelengths. That upper atmosphere may also contain sodium atoms that absorb red wavelengths. The upshot? The planet is another blue marble, but very unlike Earth.

We don't even have to look as far away as HD 189733b to find blue planets. In fact, Earth isn't the only Pale Blue Dot in its own solar system. If you take a look at Voyager's full family portrait of planets, you'll notice



NASA



European Space Agency



SETI



The Planetary Society



One Flag in Space



International Flag of the Planet Earth

that both Uranus and Neptune could, at a glance, be called pale blue (actually, Neptune is more of a strong azure). In neither case is it water oceans or Earth-like atmospheres producing our favorite color.

The dominant blue in these hulking ice giants is caused by trace amounts of methane lurking in their upper atmospheres. Methane molecules absorb light in various bands of the red and infrared spectrum, leaving the blue reflected light alone. The difference in blue tones between these planets is, however, still a bit of a mystery. Neptune's vigorous atmospheric upheavals, which loft compounds like ammonia and water ice up from interior layers, may be responsible for its deeper shade of blue. Its stratosphere may also contain a greater number of hydrocarbons.

The bottom line is that blue may correspond to sterile, inhospitable places just as much as it may reflect a planet ripe for being inhabited. The Pale Blue Dot turns out to be a lousy signpost for life.

SUPPOSE THAT, INSTEAD OF OBSESSING over colors that indicate the right conditions for life, we look for the colors of life itself? On modern Earth, the dominant light-harvesting mechanisms for life employ a set of pigments we call chlorophylls. These molecules preferentially absorb light in the blue and red, reflecting back greenish tones. As a result, near the surface of Earth's oceans, microscopic photosynthetic organisms can create vast green blushes, mixed with the scattered blue light of pure water. On dry land, plant life can also produce great swathes of green, blending with the inorganic hues of the planet.

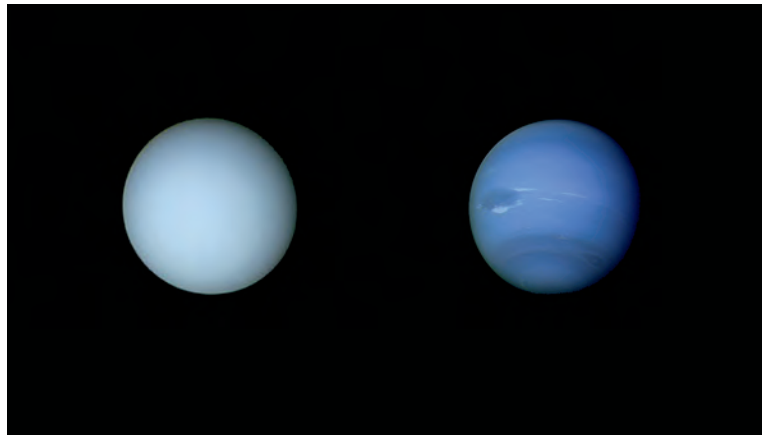
If we could see these signatures in Earthshine—the summed up, one-shot, reflected light of the whole planet—we might be able to tease out the signs of life, and then look for those same signs in distant planets. But evaluating Earthshine is difficult because we seldom have the right spectrographic instruments and telescopes sitting off world. So astronomers have resorted to ingenious methods that measure Earthshine as it reflects from the night side of the moon. It's a technique that was used from the 1920s to the 1960s to evaluate Earth's reflectivity, or albedo, but then largely forgotten.

One modern approach involves lining up the slit of a telescope's spectrograph across different parts of the lunar disk, and undertaking a hair-raising set of geometric calculations to figure out what part of Earth's dayside is illuminating the moon—then considering the complex effects of lunar reflection and scattering. This is not an easy experiment, with photons being further absorbed and scattered as they travel back and forth through Earth's atmosphere. But it can be done, and some of the results suggest that finding the green tint of photosynthetic life from bulk Earthshine is disappointingly hard. This pigmentation seems to contribute little to the total spectrum, although that could depend acutely on exactly which oceans and continents are bouncing light to the

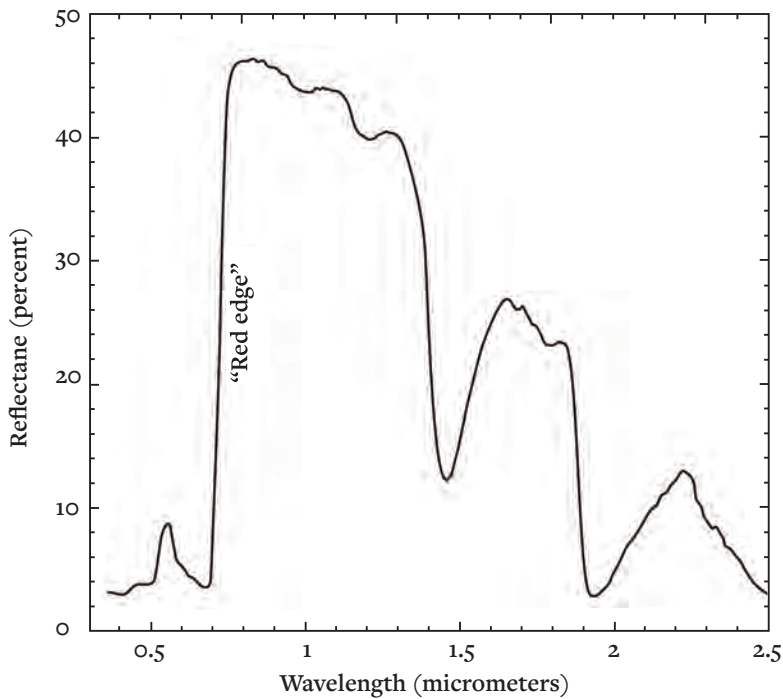
Powerful thermal gradients drive winds to thousands of miles an hour while a hot rain of glassy silicates beats its way through the maelstrom.

moon at a given moment.

What's more, green may not be the right color to look for. Even on Earth, there are a variety of different pigments that can be involved in photosynthesis. So-called "accessory" pigments serve as intermediaries that pass on absorbed photon energy to chlorophylls for final processing. Carotenoid accessory pigments can appear red, orange, or yellow. Microbial species that use both carotenoids and chlorophylls can tweak the mix depending on their environment—cranking up the yellows and oranges in conditions of harsh sunlight or high temperatures, or switching down to browns and greens in cold or wintery conditions. Another class of accessory pigments called phycobilins can be blue or red.



OTHERWORDLY BLUES Uranus (left) and Neptune (right) can also be described as Pale Blue Dots. These photos were taken by Voyager 2, and their colors have been processed to approximate what the human eye would actually see.



THE RED EDGE The reflectivity (in percentage) of terrestrial vegetation as a function of wavelength shows a dramatic rise around 0.7 micrometers, known as the vegetation red edge.

The colors of life can also change over geological time scales. In 2006 the astronomer Bill Sparks and the microbial geneticist Shil DasSarma suggested that a pigment called retinal—a form of vitamin A—might have been widely deployed by ancient photosynthesizing organisms. Retinal is simpler in molecular structure than chlorophyll, and certain species of tough halophilic (salt-loving) archaea use it for photosynthesis today—species that also hold up well against intense UV radiation. Retinal absorbs green light, with maximum absorption at a wavelength of around 568 nanometers, close to the maximum in the energy density of the sun’s spectrum. The result is that retinal membranes used for photosynthesis also reflect nicely in the red and blue, producing a rich purple color. In other words, 3 billion years ago, on an Earth harboring microbial life in a largely oxygen-free atmosphere,

there is a chance that the planetary surface was covered in purple. Should we be scanning the heavens for pale *purple* dots?

Or maybe black is the right color. The overwhelming majority of stars in the Milky Way are smaller, fainter, and colder than the sun. My colleague Nancy Kiang, at NASA’s Goddard Institute for Space Studies in New York City, has argued that, on these worlds, the dim reddish spectrum of starlight could encourage the natural selection of organisms that capture all parts of the visible spectrum: Black wins. The trouble, of course, is that black is hard to find. A distant astronomer trying to detect and decipher a planet’s biological systems through color might be out of luck.

To complicate things even further, we don’t yet have any instrument sensitive enough to peer at the reflected colors due to life on Earth-analog exoplanets

(though we are at least gaining insight into what it would take to do this: huge light-gathering telescopes and optical trickery to remove glaring starlight). Yes, life can be colorful, but looking for it that way is a tricky proposition.

THE TRUTH IS THAT COLORS are a cosmically parochial idea. The electromagnetic spectrum is not inherently divisible into neat pieces, except by limited sensory facilities. Light at different wavelengths is entwined with a vast array of physical processes, from the probabilistic hop and skip of electrons between atomic energy levels, to scattering and diffraction by matter's electromagnetic fields. Wildly disparate processes can produce or consume photons of identical energy, generating almost indistinguishable gross features such as color. And sometimes a single underlying physical process can make utterly dissimilar objects appear the same.

Into this morass steps the phenomenon of life. Physics and chemistry are important for gross planetary color, but not necessarily biology. Naïvely equating the color blue with habitable environments has some serious flaws.

But that doesn't mean that color is useless to the cosmic life hunter. A biosphere clearly brings new *structure* to color, modifying a planetary spectrum in ways that could be pronounced and specific.

A classic example is the famous "vegetation red-edge"—a sharp enhancement of transmission and reflectivity of photons by the cells of plant life here on Earth. At wavelengths longer than about 0.7 micrometers, plants start reflecting approximately 50 percent of the infrared light hitting them—more than a tenfold step up in reflected brightness compared to the shorter wavelengths of visible red.

The origins of the effect are still incompletely understood. It seems that the internal optics of plant cells are largely responsible. At cell walls, water-to-air boundaries result in mirror-like critical angle reflections. Infrared photons bounce between these boundaries, then get efficiently ejected. What plant life gains from this is not entirely clear. It's possible that rejecting near-infrared radiation helps with temperature regulation.

Whatever its origin, the red edge is hugely useful to us, enabling remote sensing satellites to map out

Earth's jungles, grasslands, and crops. However, since a randomly illuminated crescent of a world like the Earth is on average 70 percent ocean, with an average of 70 percent cloud cover, red-edge optics can amount to less than a 10 percent feature in the total planetary spectrum. Get lucky though, and the signal can be much stronger.

Life also brings strong *temporal* structure to color. Seasons impact planetary habitats, and organisms can be triggered to bloom and die. For example, in 2008, iron-rich ash from the Kasatochi Volcano in the North-eastern Pacific caused a huge green growth of plankton, visible from space across 2 million square kilometers of ocean, in mere days. Changing colors on exoplanets could potentially provide a signature of life, even if we did not understand what the colors themselves meant.

Color, then, will no doubt remain an important part of the astrobiologist's toolkit. It just may not be as simple as "spot the blue dot." In this sense we should see the Voyager image as one of great hope. It was merely the opening clause in a dialogue with the universe. It was the day we finally got to watch our deceptively simple colors flying among an armada of new worlds. ☺

CALEB SCHARF is an astrophysicist and the Director of Astrobiology at Columbia University in New York. His latest book is *The Copernicus Complex: Our Cosmic Significance in a Universe of Planets and Probabilities*.

The Nanopainter

BY JEANNE CARSTENSEN

PHOTO BY PETER EARL MCCOLLOUGH



ARTIST KATE NICHOLS PAINTS with nanoparticles. Her artistic journey from 15th-century oil painting to a nanotechnology lab at the University of California, Berkeley, began with her obsession with the Blue Morpho butterfly. The insect's iridescent blue color arises from nano-sized structures in the wing that cause light waves to interfere with each other. Nichols wondered if she might be able to create this kind of “structural color” effect by using nanoparticles to make her own custom paints. Paul Alivisatos, a leading chemist and material scientist, invited her to join his U.C. Berkeley lab as artist-in-residence. With no chemistry background, the “remarkably persistent” Nichols learned the rigorous techniques of nanoparticle synthesis and developed a silver nanoparticle paint she applies to glass surfaces.

Like a Morpho wing, her painted glass changes color depending on the vantage point of the viewer. The paint appears yellow on clear glass but looks bluish green against a black background. Nichols says that after working with the “optical ambivalence” of nanoparticles she doesn’t think about what color something is—but instead its “particular relationship with light.” Like the medieval craftsmen who learned by experimentation to use gold and silver nanoparticles in stained glass to create glorious yellows and ruby reds, or ground their own pigments in search of a more vibrant purple or blue, Nichols is exploring the color possibilities of new nanomaterials for artists today. 🌀



About Your Skin

What you should know about your body's biggest organ

BY STEVE PAULSON

SKIN MAY SEEM LIKE a superficial human attribute, but it's the first thing we notice about anyone we meet. Nina Jablonski came to this realization many years ago when she was teaching a human anatomy class to young medical students in Hong Kong. When faced with dissecting a dead body, they flinched at the thought of cutting into or even touching it. But they lost their inhibitions once they opened up the cadaver. Without skin, the corpse no longer looked human.

Jablonski got hooked on all things related to human skin. As a primatologist and paleobiologist, she wanted to understand why humans—alone among the primates—evolved to become the naked ape, and why skin comes in so many different hues and shades around the world. Once she started investigating the science of skin color, Jablonski was pulled into the sordid history of racism, and she saw how even great thinkers like Kant and Thomas Jefferson believed people with dark skin were innately inferior to light-skinned people like themselves.

As a young girl, Jablonski learned that one of her great-great-grandfathers was a “Moor” from northern Africa, which embarrassed her family but helped explain why, she has written, she had one of the darkest pigmentations of any kid at her school in upstate New York. Later, when she launched her academic career, she discovered that color anxiety permeated her own field of anthropology. Today, she's an anthropologist at Penn State University with a long string of published articles and two books, *Skin: A Natural History* and *Living Color: The Biological and Social Meaning of Skin Color*.

I talked with Jablonski about how the emerging science of skin color could inform today's public discussion about race. She grew animated when commenting on scholars who believe there are biological differences between races, even on the loaded issue of intelligence. In our conversation, Jablonski ranged over various issues—from human evolution to the history of slavery—as she described her fascination with skin.

ILLUSTRATION BY JASU HU



Do you think about your own skin?

I think about it every day. Everyone, including me, looks in the mirror and says, “Hmmm, getting a bit older.” I see it as my autobiography. My skin has seen everything that I have, all of the weather, the sorrow, the happiness, the toil. I love the changes that I see in my skin, and I see it as part of my human story.

What about skin color? Why does this interest you as a scientist?

It is one of the most fundamental ways in which people vary in their appearance. People have also made a big deal about skin color. It’s caused humanity a lot of difficulties because people have associated color with the value of human character and moral values.

Do we know when dark skin first evolved in our ancient ancestors in Africa?

We can make a very good estimate from the fossil record, as well as from studies done by human geneticists. Humans probably evolved naked skin around a million and a half years ago, and at the same time they mostly lost their coat of fur. Today we have a few tufts of hair remaining on various parts of our bodies, but compared to our primate relatives, we are relatively hairless. Basically we’ve turned on the pigment-producing capabilities of our skin cells and allowed this dark pigment called melanin to serve as a natural sunscreen in the place of the hair we lost.

Why did we lose our fur?

We think it occurred because of the need to keep ourselves cool when we were moving around very vigorously in a hot environment. Around 2 million years ago, we see the evolution of the first members of the genus *Homo*. These ancestors were tall, strapping, strong walkers, vigorous runners, and all those activities under equatorial sun generate a lot of heat. Primates, including humans, dissipate heat through the surface of their skin. We can’t really pant like dogs, so we have to lose heat either through radiant heat loss from the surface of our bodies or by sweating. So we

evolved the ability to sweat copiously and lost most of our fur.

So early humans in equatorial Africa developed dark skin as protection against the sun?

That’s right. The sun is great, but it has a lot of injurious rays, especially ultraviolet radiation. Most animals protect themselves from UV radiation with fur. What we did in our lineage was turn on pigmentation genes that allowed us to produce more permanent pigmentation in our skin cells. This was really an important revolution in human history because it allowed us to continue to evolve in equatorial environments and thrive and disperse. It really made it possible for us to continue along the trajectory toward modern humans, *Homo sapiens*, in Africa.

We developed melanin to protect us against the sun. Was skin cancer the main problem?

That probably wasn’t the main problem, although ultraviolet radiation can certainly lead to serious and lethal skin cancer. But this rarely occurs in individuals during their reproductive years, so when we think about the mechanisms of evolution, we have to think about what’s going to be affected during one’s reproductive years. As I was struggling with this problem more than 20 years ago, I realized that one important effect of UV radiation on biological systems is the ability to break down an essential B vitamin called folate, something that we get from green vegetables, citrus fruits, and whole grains. Folate is important for making DNA and new cells. It turns out that ultraviolet radiation has the ability to damage folate and some of the molecules related to folate that are important for our metabolism. The key insight behind our research is that protective melanin pigmentation evolved primarily not to protect us from skin cancer but to preserve our folate so that we could continue to reproduce.

Given all of the advantages of melanin, why doesn’t everyone have dark skin today?

For most of human history, we did. What we see today

For most of human history, everybody had dark skin. What we see today is the product of dispersal of a few human populations out of Africa around 60,000 years ago.

SUNSCREEN After our ancestors lost their fur to keep cool, they developed protective pigmentation that allowed them to thrive in equatorial environments.



is the product of evolutionary events resulting from the dispersal of a few human populations out of Africa around 60,000 to 70,000 years ago. Our species, *Homo sapiens*, originated around 200,000 years ago and underwent tremendous diversification—culturally, technologically, linguistically, artistically—for 130,000 years before a few small populations left Africa to populate the rest of the world. These early ancestors of modern Eurasians dispersed into parts of the world that had more seasonal sunshine and much lower UV levels. It's in these populations that we begin to see real changes in the genetic makeup of pigmentation. As people move into areas with much lower and more seasonal UV, they run into problems if they have too much natural sunscreen. Some UV is essential for making vitamin D in the skin.

What about differences between the sexes? Don't men tend to have darker skin than women?

On average, men are darker than women in every population that has been examined. Sometimes this difference is subtle; sometimes it's greater. Certainly some of it has to do with the physiological needs of the two sexes. Women need to make more vitamin D during their lives, especially when they're pregnant and breastfeeding, to mobilize enough calcium for their offspring. So they are probably lighter because of this. But we also know that in many peoples across the world there has been a preference for one sex or even both sexes to be lighter colored. In Japan and India, it's important for a wife to have lightly pigmented or nearly white skin. Where we actually see systematic preference, there's sexual selection for individuals with lightly pigmented skin.

Wouldn't it work the other way as well—that women would find men with darker skin more attractive?

Yes, in some cases that's probably true. In Japan, we know it's true from sociological studies. In India, however, most groups of men and women select for the lightest possible mates. So we have this interesting phenomenon where not only biological forces but also social forces lead to differences in pigmentation between the sexes or even between groups.

Is skin color still evolving?

Skin color is evolving insofar as we see all sorts of exciting new mixtures of people coming together and having children with new mixtures of skin color genes. If you go into any major city of the world, you see how children are being produced through such felicitous interactions. Not only the pigmentation genes but lots of other genes are getting mixed up. We don't see much natural selection of pigmentation as we did earlier in our history because we mostly protect ourselves from the harshest parts of the environment—from excess sun or cold or dryness. We're pretty good at putting on clothes and living in buildings as a buffer against the exigencies of the environment.

If we're going to talk about skin color, we also have to talk about how we separate people into racial categories. How should we understand race, scientifically?

I think it's important to understand this from a few different perspectives. When we look at genetic diversity, we can see there are no clean breaks between human populations. Individuals have different groups of genes, so we see rough-and-ready kinds of biological groupings, but these blobs of genetic variation overlap and grade into one another. There are no clear demarcation lines. This is one of the reasons, the primary reason, why geneticists have said there are no human races from a biological perspective.

Every population is unique, and there are some geographical patterns in that variation. The most important of these is the African origin of our species. Only a tiny fraction of alleles, and a small fraction of allelic combinations, is restricted to a single geographic region, and even less to a single population. The diversity between members of the same population is also large. There is extensive sharing of alleles across continents and small genomic differences between populations. This is why attempts to identify races in humans have failed.

How would you define race?

The definition of race depends on what kind of a scientist or observer you are. To most biologists studying

racies of plants or animals, a race is a population of organisms that can be visibly distinguished from other such groups. Human races have been defined by combinations of anatomical, behavioral, and cultural criteria, and these definitions have varied through time, through history, and from place to place. To most humans, races are creations of the mind that have social reality and that often have physical traits associated with them.

So race is strictly a social construction?

Yes, but that doesn't make it any less real. When people identify as belonging to a certain group, the biological or philosophical status of the race doesn't really matter. So race is a very durable construct and people have strong racial identities that are often tied up with physical appearance, but also include a lot of cultural aspects.

But it would seem there are some physical differences between races. For instance, people of West African origin dominate the world-class sprinting competitions.

This raises a very interesting question: Would you put West Africans in a separate race? Most people wouldn't because their biological characteristics have so much overlap with people from East Africa, where people have tremendous abilities in long-distance running but not in sprinting. You can see concentrations of people with certain attributes, but these attributes overlap with nearby and even distant populations. So drawing a definite line of demarcation becomes impossible. And if you're looking at a characteristic like sprinting ability, this requires biological ability in a person's skeletal muscles. It also requires tremendous amounts of training, so there's a huge cultural component. You can't have just one or the other.

If our bodies evolved to develop certain differences, such as skin pigment, wouldn't we also expect variations to evolve in our brains in response to local pressures? So wouldn't the social behavior of different racial groups also be shaped by evolution?



For over 2 million years, our brains got larger along with the technology we developed to manipulate the environment and our fellow human beings. Over time this process was based on cultural rather than biological innovations, with most of the biological specialization of the modern human brain established before 70,000 years ago, when humans started leaving Africa and dispersing into Eurasia. We can't rule out the possibility of genetically based specializations of the brain over the last 70,000 years, but this has undoubtedly been very minor.

All modern humans share tremendous abilities to observe and remember and respond with uncanny behavioral flexibility to all kinds of complex problems. The evolution of human skin, by contrast, has really only been affected by cultural evolution in the last 20,000 years, when we see sewn clothing and complex shelters. Before that, skin was the primary interface between our bodies and the physical environment. The tremendous variety of skin colors that we see today owes to local natural selection and also to genetic drift, which restricted the gene pools—and the variation of pigmentation genes—in many small, dispersing populations.

DARKSIDE

In Greek and Roman societies, slaves were not darkly pigmented people, but those considered culturally inferior—a trait assigned to slaves from Africa.

When we look at genetic diversity, there are no clean breaks between human populations. This is why geneticists have said there are no human races from a biological perspective.

What do you make of studies that have linked IQ and race?

The studies are flawed in the way they've been conducted, in the nature of the samples that have been used, in the tests that have been given. The people who have undertaken these studies have gone in with an agenda in mind. This is dangerous, and we know in the history of science that when people come in with an idea they want to prove, this is not science.

There have been studies of relatively small numbers of individuals, with much better controls for educational background, socioeconomic background, and all environmental variables. What these small, careful studies have shown is that there's no difference in intelligence between the so-called races and that all differences that develop are due to cultural differences. Some of these may be due to differences in diet. Most have to do with differences in learning patterns that result from a child's cultural framework. In other words, we are all born basically with equal potential and what happens after birth is what really determines our so-called intelligence.

One of the most disturbing historical developments is how blackness became stigmatized around the world. Do we know when people of darker skin color started to be seen as socially inferior?

We do. In the earliest recorded interactions between people of different skin color—in ancient Egypt between 4,000 and 7,000 years ago—we see a history of felicitous trading interactions between peoples along the Nile, darkly pigmented and lightly pigmented people trading with one another and having mutual respect for each other's cultures. In the earliest recorded history of interactions between peoples of different color, we don't see any prejudicial interaction going on, but simply an acknowledgment of difference.

Some of those ancient societies had slaves, but those slaves were not necessarily dark skinned.

Absolutely. What we see in Greek and Roman societies is that slaves came in all colors. They didn't share the Greek or Roman culture, so they were considered to be culturally inferior. In Rome, slaves were taken in huge

numbers from Eastern Europe to man the agricultural plantations and the mines of the Roman Empire. Slavery was not just for darkly pigmented people. People from Africa were taken as slaves fairly late in the game. Sadly, they became the biggest slave market for a variety of reasons. They could be harvested in large numbers from equatorial Africa through various trading networks. People were also beginning to assign negative personality traits and moral values to their color.

We live in a strange world where many light-skinned people want to be darker and a lot of darkly pigmented people want to look lighter.

When did this prejudice become widespread?

This becomes really potent in Europe in the 16th and 17th centuries and then in a significant way in the 18th century. It's mostly associated with the growth of the trans-Atlantic slave trade. It becomes very important in the history of colonial mercantilism. A workforce was needed to develop colonial lands, and for a long time European traders tried to use European colonists and convicts to meet this need. This was insufficient for the tremendous demand and so, "Well, let's get some slaves." It's very important that you create slaves as an inferior class as people. You dehumanize them by saying they are inherently immoral, inherently incapable of developing true human qualities. They are sub-human. This makes the whole slave trade much more palatable.

There were some influential thinkers who played up these racial differences. Linnaeus, the 18th-century scientist who developed modern taxonomy, separated people into four human races and attributed various temperaments to each. The philosopher Kant wrote

about the different races of humanity and claimed that white Europeans were the most talented race. These people helped lay the foundations for the modern world.

Linnaeus was read by Kant, and many people read Kant, including Thomas Jefferson and other thinkers important in the formation of our country. Kant had a tremendous influence on them. They had their own emotionally based opinions about race that they wrote as fact, which complemented the biblical misinterpretations of color. This becomes the most toxic combination in human history. You have blackness associated with sub-human status, on a lower rung of human creation that's less able to generate a complex civilization. This turns out to be a very potent combination and sadly, one that we're still stuck with because so much of modern thinking in the United States derives from the late 18th and early 19th century, when these ideas were widely circulated and the trans-Atlantic slave trade was going strong.

Pale skin is clearly not as prized as it once was. How do you see the politics of skin color in today's world?

We live in a strange world where many light-skinned people want to be darker—or at least tanned to look healthy and like they've just enjoyed a vacation on the Riviera. A lot of darkly pigmented people want to look lighter because lightness is associated with higher status. So we have a paradoxical situation where many light people want to be darker and many dark people want to be lighter. Humans are motivated by diverse sets of ideas. They usually aspire to an appearance that confers higher status. Once we recognize that it's a pretty stupid thing to do, we can adjust our cultural sights and say, "Hey, let's just live with the skin color that we have. Let's protect it, let's cherish it, let's make sure that we are healthy with it." ☺

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27

“THE FINDING SUGGESTS that these galaxies ... are very likely enveloped by something very massive.” So reflected Jin Koda, astronomy professor at Stony Brook University, on the discovery this June of more than 800 dark galaxies in the (appropriately named) Coma Cluster. Many are located in a part of the cluster subject to tidal forces that should destroy them, if they were made entirely of visible matter.

So something else—not visible—must be bulking up their mass and protecting them. The nature of this dark matter is one of the most pressing questions in modern cosmology.

While the cosmological version is the most famous, it is far from the only dark matter story in science. There are silent neurons, missing fossils, and nighttime animal migration; death and conception; inscrutable algorithms both genetic and man-made. Seeing, it turns out, isn’t the only path to believing.

Welcome to “Dark Matter.”

—MS

“Today we know that a large population of cortical neurons are ‘silent.’ They spike surprisingly rarely, and some do not spike at all.”

KELLY CLANCY

“Here’s Why Your Brain Seems Mostly Dormant” p. 102

Dark Matter

ALL THAT YOU CAN'T SEE



Here's Why Your Brain Seems Mostly Dormant

The brilliant compromise between efficiency and ability in your head

BY KELLY CLANCY

YOU'VE PROBABLY HEARD the myth that the average person uses only 10 percent of their brain. It's a seductive lie because it suggests that we could be more than we are. Sci-fi movies like *Limitless* and *Lucy*, whose protagonists gain super-human abilities by accessing latent mental capacities, have exploited the myth. Neuroscientists, on the other hand, have long loathed it. Eighty years of studies confirm that every part of the brain is active throughout the course of a day. Save those who have suffered serious brain injury, we use all of our brains, all of the time.

But, like many legends, the 10 percent myth also carries a grain of truth. In the last 20 years, scientists have discovered that our cortex follows a strangely familiar pattern: A small minority of neurons output the vast majority of activity. It's not that we don't use 90 percent of our brain, but that many neurons remain eerily quiet even during use. The story behind this silence is more profound than the boosted IQs and temporary clairvoyance from the movies. It speaks to the basic principles of how our minds represent reality in the first place.

NEURONS COMMUNICATE with electrical impulses called spikes. In the 1930s, scientists began to record spikes from individual neurons using small metal electrodes inserted into the brain. They observed neurons

with activity rates of tens to hundreds of spikes per second, with each spike lasting a few milliseconds.¹ The brain seemed to be buzzing with communication. Then in a 1968 review of microelectrode technology, the biomedical engineer David Robinson brought an important discrepancy to light. As electrodes are lowered into the brain, they should detect activity from any cell they come close to. In a typical recording, this would theoretically amount to about 200 cells. Yet researchers were lucky to record from five cells per electrode insertion. Where were the rest of the neurons?

Many brushed these concerns aside—the low discovery rate might be due to tissue damage from the electrode, or because the recordings were made while the animal subjects were anesthetized. But Robinson's insight was vindicated 30 years later as researchers began to make painstaking recordings from the inside of cells.¹⁻³ They found that the majority of neurons in the cortex spike much less than the commonly reported 10-100 spikes per second, and that these high rates describe only the most active 3 to 20 percent of cells. It turns out that scientists had long failed to record from the majority of neurons in the brain, simply because they lacked the methods to detect them.

Today we know that a large population of cortical neurons are “silent.” They spike surprisingly rarely, and some do not spike at all. Since researchers can only take very limited recordings from inside human

brains (for example, from patients in preparation for brain surgery), they have estimated activity rates based on the brain's glucose consumption. The human brain, which accounts for less than 2 percent of the body's mass, uses 20 percent of its calorie budget, or three bananas worth of energy a day. That's remarkably low, given that spikes require a lot of energy. Considering the energetic cost of a single spike and the number of neurons in the brain, the average neuron must spike less than once per second.⁴ Yet the cells typically recorded in human patients fire tens to hundreds of times per second, indicating a small minority of neurons eats up the bulk of energy allocated to the brain. The remaining neurons may fire a few times per minute or less. This energy budget puts limits on how much of the cortex can be engaged at once: In total, no more than 1 percent of neurons can be active. This may explain why our attention is so limited in scope—our brains can only allocate so many spikes to any given perception.

Why does the brain keep around a huge number of relatively inactive cells? The question is a hard one because while we know that spikes translate into our perception of the world, we're still far from knowing how.⁵ This translation is referred to as the neural code, and neuroscientists have been trying to crack it for the past 100 years.

There are two extremes of neural coding: Perceptions might be represented through the activity of ensembles of neurons, or they might be encoded by single neurons. The first strategy, called the dense code, would result in a huge storage capacity: Given N neurons in the brain, it could encode 2^N items—an astronomical figure far greater than the number of atoms in the universe, and more than one could experience in many lifetimes. But it would also require high activity rates and a prohibitive energy budget, because many neurons would need to be active at the same time. The second strategy—called the grandmother code because it implies the existence of a cell that only spikes for your grandmother—is much simpler. Every object in experience would be represented by a neuron in the same way each key on a keyboard represents a single letter. This scheme is spike-efficient because, since the vast majority of known objects are not involved in a given thought or experience, most

A small population of neurons fire hundreds or thousands of times more often than others.

neurons would be dormant most of the time. But the brain would only be able to represent as many concepts as it had neurons.

Theoretical neuroscientists struck on a beautiful compromise between these ideas in the late '90s.^{6,7} In this strategy, dubbed the sparse code, perceptions are encoded by the activity of several neurons at once, as with the dense code. But the sparse code puts a limit on how many neurons can be involved in coding a particular stimulus, similar to the grandmother code. It combines a large storage capacity with low activity levels and a conservative energy budget.

Sparse coding is considered one of the great triumphs of theoretical neuroscience, as its predictions are in stunning agreement with real data. In a 1996 paper, the neuroscientists Bruno Olshausen and David Field trained an artificial neural network to “learn” images. Their network was constrained to a sparse code by limiting the number of neurons active at any given time, and requiring that the information each neuron encoded be maximally independent from that encoded by other neurons. Under these constraints, the artificial neurons extracted information from images in the exact way that real neurons in the visual cortex do: by spiking for local edges with a particular form. In the brain, neuroscientists believe these edges first reassemble into shapes and textures, then eventually into the perceptions of specific concepts like faces, bowties, and boats. The visual world gets ripped apart into its primary elements before meaning is layered on as information rises through increasingly specialized brain regions.

The sparse coding strategy explains why some neurons spike extremely rarely: They encode very specific information. But it doesn't explain why a small population of neurons fire hundreds or thousands of

times more often than others. This can partially, but not fully, be explained by the diversity of cell types—some neuron classes simply spike more than others. But even among excitatory cells, the most common neuron class, there is a dramatic activity imbalance. This disparity might represent two separate coding strategies: A small, active population might make a rapid “best guess” for enabling more immediate responses, while the quiet population refines this into a specific perception. Think of all the times you thought you caught an ominous figure out of the corner of your eye, only to realize it was a coat rack.

The quiet neurons might be doing more than refining perceptions. Though they spike infrequently, we know from intracellular recordings that they still receive inputs from other neurons, which causes their membrane voltages to fluctuate. The sum of these fluctuations and spikes constitute what’s commonly known as brain waves. Over the past 15 years scientists have begun to amass evidence that these brain waves play an active role in information processing, shunting some neural inputs while enhancing others, for example, or altering the timing of spikes. This suggests that spikes are not the sole information-carrying signal in the brain, and that, in turn, the “inactive” neurons are doing much more than it seems.

In addition to shaping the output of high-spiking neurons, these quiet neurons could be a kind of “reserve pool” for learning and recovery. A mouse that loses one whisker becomes more sensitive to his remaining whiskers, because neurons in the touch-related cortical region rewire to receive inputs from the spared whiskers. When scientists recorded neural activity before and after trimming a mouse whisker, they found that it was the less active neurons that became more sensitive to spared whiskers.⁸

If this is true, we really do have latent mental capabilities, as suggested by the 10 percent myth. They are more prosaically referred to as learning. ☺

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The Reinvention of Black

*As the means of creating the color black have changed,
so have the subjects it represents*

BY MARK PELOW

SUDDENLY BLACK WAS EVERYWHERE. It caked the flesh of miners and ironworkers; it streaked the walls and windows of industrial towns; it thickened the smoky air above. Proprietors donned black clothing to indicate their status and respectability. New black dyes and pigments created in factories and chemical laboratories entered painters' studios, enabling a new expression for the new themes of the industrial age: factory work and revolt, technology and warfare, urbanity and pollution, and a rejection of the old status quo. A new class of citizen, later to be dubbed the "proletariat," began to appear in illustrations under darkened smokestacks. The industrial revolution had found its color.

Black is technically an absence: the visual experience of a lack of light. A perfect black dye absorbs all of the light that impinges on it, leaving nothing behind. This ideal is remarkably difficult to manufacture. The industrialization of the 18th and 19th centuries made it easier, providing chemists and paint-makers with a growing palette of black—and altering the subjects

that the color would come to represent. "These things are intimately connected," says science writer Philip Ball, author of *Bright Earth: The Invention of Color*. The reinvention of black, in other words, went far beyond the color.

"BIDEFORD BLACK IS an extraordinary material," says Onya McCausland, a doctoral candidate in fine art at University College London. She is talking about a black pigment found in the Carboniferous formation that runs from Wales to Devon in England. Mined from the 18th to the 20th centuries, it was considered one of the best coal-based black pigments available. "Its texture is soft and velvety," McCausland says. "It produces a very dense, bluish-black. If I want the black to be really immersive and dense, I'd use Bideford black."

Bideford black was one of many carbon-based black pigments used from the 16th through the 19th centuries in Europe. Charcoal was the inexpensive mainstay, though it produced a gritty paint that was difficult to apply. Bone black (ground from burnt bones) gave

FREDERIK DE WILDE: NANOBLOCK-SQR #1 (2014) / CARROLL/FLETCHER
AND THE ARTIST. CARROLL/FLETCHER.COM. PHOTO BY ROBIN REEVE

ARTWORK BY FREDERIK DE WILDE

a warm brownish black, while lamp black (burnt vegetable oils) and vine black (charred grapevines or other vegetable products) gave cooler shades. Black derived from ground ivory was perhaps the richest of the lot.

This dark arsenal of dyes supported an evolving but particular set of subjects and themes. For centuries, black was a color of death and evil. The Egyptian jackal-headed god Anubis, who guided souls to the afterlife, almost always appeared as a black figure, his skin matching the blackened flesh of mummified bodies. When the devil began to appear in European art, in the 11th century, he too was usually a nightmarish black.

Black also developed a second identity around this time representing the asceticism favored by monks, as noted by the French historian Michel Pastoureau. By the 15th century, black garb had become a fixture of regal courts in Europe, connoting power and privilege. Soon after, the growing middle class also adopted black garments to represent their growing wealth, as well as their piety.

Seeking to reflect the wealth around them, 16th- and 17th-century artists used this broad palette of blacks to distinguish the different tones and textures of their sitters' sumptuous clothes. "In the late Middle Ages, black became the color of distinction," says Ball.

The arrival of the industrial revolution in the 18th century sparked advances in mining technology that boosted the output of coal-based pigments including Bideford black, while simultaneously driving up demand. Bideford black was ideal for polishing up the cast iron stoves that swept into kitchens during the period, for example, and it also fuelled local lime kilns.

Coal could also be baked in hot, airless ovens to drive off water and gasses to make coke, a high-carbon fuel useful for cooking, heating, and smelting ores. By the early 19th century, the purified coal-gas generated in this process—containing hydrogen and hydrocarbons—was being burned to light factories and streets. And when chemists began to investigate the sticky black waste left behind after coking or gasification, they found a rich source of organic molecules that would come to overshadow coal itself as a direct source of pigment.

In the 1840s, August Hofmann extracted aniline (a benzene ring connected to a nitrogen-containing amine group) from coal tar. Then in 1856, William

Perkin, a student of Hofmann's, oxidized aniline to create a deep purple dye, subsequently called mauve. This marked the birth of a completely new industry: synthetic dyes. By 1860, other researchers had found that oxidizing aniline under different conditions, using sulfuric acid and potassium dichromate, created a new black pigment: aniline black. The reaction fuses together 11 aniline molecules to make a complex chain of benzene rings connected by nitrogen atoms. Mixed in paint or ink, it produces a neutral, matte black also known as Pigment Black 1.

This compound—and many other synthetic organic blacks—would be produced on an enormous scale for printing and dying cloth. They also opened up new possibilities for black ink, which had traditionally been made with lamp black or iron gall. Soluble synthetic organic dyes were much more versatile, and could be mixed with different solvents to create just the right consistency of ink for applications as diverse as ballpoint pens, felt-tip pens, and spray paints.

Around the middle of the century, paint-makers began to offer a synthetic inorganic black pigment known as Mars black. It was made by reacting iron sulfate with an alkali such as lime or caustic soda—all chemicals that were in widespread use at the time—to make iron oxide. Mars black had a much smaller particle size than its natural equivalent. This made it handle well on the brush, and gave better coverage on the canvas. And it had a greater tinting strength than even ivory black, making it probably the most opaque black available at the time.

Mars black also dried much faster than carbon blacks. That is because linseed oil, the favored medium in oil painting, dries not by losing water, but through a series of chemical transformations. Its fatty acids react with oxygen from the air and then join together to form polymers. In most colored oil paints, metal salts in the pigments catalyzed this reaction. Sometimes drying agents, such as lead white, were added to speed up the process. But that was not possible with black, as it would wash out the dark hue—and since most black pigments were made of carbon, rather than metal salts, that meant that the black areas of oil paintings dried slowly and unevenly. The result is that blacks are often the most cracked areas of old paintings.

Spanish surrealist Salvador Dalí used Mars black,



FROM ABOVE

Michelangelo Merisi da Caravaggio used ivory black to convey asceticism, piety, and inspiration in his 1605-6 painting, *St Jerome Writing*.

“Creating the blackest black is a reaction born out of necessity.”



INTO NOTHING

Black acrylic paints form deep ridges in Pierre Soulages' *Painting 2009*, currently on display at the Lyon Museum of Fine Arts. The effect recalls ripples on a moonlit lake—or the enormous gear-wheels of an infernal machine.

Black, which seems to obscure and remove color and life, invited a new inner life.

and said of Jacques Blockx, who developed one of the earliest commercial Mars black oil paints, “This man, who never painted, will contribute more to the painters of tomorrow than what we will have accomplished, all the modern painters together.”

IN THE 20TH CENTURY, a flood of new black paints would inspire a new set of artistic styles that took on modern subjects and themes. “Black was increasingly connected with industry, technology, and the urban environment,” says Erma Hermens, who leads the Technical Art History Group at the University of Glasgow. “Black becomes a statement.” Black also helped artists to delineate a new period in the history of art. “It was saying that the time of classical painting was past,” says Ball, “that we’re using modern materials in a modern way.”

The starting pistol for this movement was *Black Square* by Polish-Russian artist Kazimir Malevich, first exhibited in 1915. A very early example of abstract painting, it is simply a square of canvas covered in black paint. Malevich called his style “Suprematist.” Relying on simple shapes and a limited palette, it marked an absolute rejection of the depiction of objects in favor of pure expression. Tellingly, the painting was mounted high in the corner of the room, where Russian Orthodox icons would traditionally have been placed—a rejection of religion in favor of the secular. “It symbolized the collapse of traditional values and social structure,” says Belgian artist Frederik De Wilde—processes that had been hastened by the industrial revolution and its creation of new socioeconomic classes.

Malevich grew up in Tsarist Russia, and trained in a series of art schools in Kiev and Moscow. In 1913 he designed the set and costumes for *Victory over the Sun*, an avant-garde opera that saw “futurist strongmen” rip the sun from the sky, ending its decadent reign and freeing the future from time itself.

These themes—decrying the status quo, and looking ahead to a new world—were common in the Russian avant-garde of the time, and they fed into the growing demands for societal change that resulted in the Russian revolutions of 1917. Malevich would join the People’s Commissariat for Enlightenment in 1918, but by the 1930s his work had been labeled anti-Soviet and degenerate. After he died in 1935, his coffin was

adorned with a black square.

Malevich’s work inspired abstract artists such as Robert Motherwell, Ad Reinhardt, Jackson Pollock, and Mark Rothko, who all made heavy use of black in their work. Whereas Malevich used a spectrum of carbon blacks in his paintings, from ivory black to lamp black, his successors wanted to reflect the rapid technological changes in society through the materials they used, and went looking for new black paints. As Pollock said in 1951: “It seems to me that the modern painter cannot express his age, the airplane, the atom bomb, the radio, in the old forms of the Renaissance or any other past culture. Each age finds its own technique.”

Pollock repurposed enamel paints that were intended for painting cars or interior decorating for his art. Developed in the 1930s, enamel paints typically used synthetic iron oxide or mass-produced carbon black pigments suspended in polyesters known as alkyds, which readily cross-polymerize in air and dry to a hard, glossy finish. They gave Pollock’s “drip paintings” a sheen that emphasized their explosive power, and a durability that continues to please conservators. His liberation from the materials of the past was echoed by the physical freedom he enjoyed while creating his paintings, striding around canvases laid on the floor like a sculptor working around a lump of stone. He rarely planned what his paintings would represent—instead, it was an act of instinctual expression. The results evoke moods that range from joy to chaos.

In the early 1950s Pollock created a series of works that relied almost entirely on black, often pouring globs of thick enamel paint onto the canvas. The paintings were a reaction against his earlier, more colorful abstracts. Seemingly stung by some critics’ claims that these earlier pictures were merely decorative, Pollock set out to produce determinedly difficult works: This would disabuse “the kids who think it’s simple to splash a Pollock out,” he explained in a 1951 letter.

This stance was shared by Ad Reinhardt, who produced a series of all-black paintings that were first exhibited in 1963. One, called *Abstract Painting*, is a huge black square composed of nine smaller squares, each of subtly different blacks: The squares at the corners have a red tinge, while the others have a hint of blue or green. Reinhardt described it as “a free, unmanipulated, unmanipulatable, useless, unmarketable,

Black opens up a mental field all of its own.

irreducible, unphotographable, unreproducible, inexpressible icon.”

Pollock’s and Reinhardt’s rejection of the usual literal forms of representational painting was, in a sense, strengthened by the rejection of color itself. Black enabled a pure abstraction, and amplified the turning away from the aesthetic values of the Renaissance and Enlightenment that had been displaced by the same industrial technologies creating the new pigments of the modern era.

The displacement of literal representation opened room for a new meaning of the color: negation, contemplation, and spirituality. In the words of the French artist Pierre Soulages, black “opens up a mental field all of its own.” He began his epic journey into blackness in 1947, when he started creating abstract expressionist works using a dark walnut stain to make bold slashes across canvas. By the 1950s he was working in oils, thickly smeared onto surfaces using a palette knife. And in 1979, he began a new series of works in a style he dubbed “Outrenoir”—roughly translated as “beyond black”—with canvases completely saturated in black.

Transcendence and negation also inspired the American painter Mark Rothko, who produced a series of black paintings in the 1960s. For Rothko, the negation of color and light represented “doorways to the unknown,”

and invited spiritual contemplation. In the words of the Tate Gallery, the paintings introduce “an element of duration and physical self-awareness into the process of perception.” Black, which seems to obscure and remove color and life, invited a new inner life. Some of Rothko’s black paintings were commissioned for a Catholic church in Houston, today known as the Rothko Chapel, making their spiritual dimension explicit.

The new industrial black pigments had another attractive feature that was altogether more prosaic: They were cheap. This was a key factor for abstract artists who wanted to cover large canvases. Industrial quantities of mass-produced paint let them work on an industrial scale. “They painted as though they were painting industrial structures,” says Ball.

Motherwell, for example, painted more than 100 paintings in his series *Elegies to the Spanish Republic*, many of which measured more than 9 feet across. Featuring large black ovals on a pale background, he called the series a “funeral song” inspired by the Spanish Civil War. This war was, itself, a conflict only conceivable in the industrial age, taking the lives of 700,000 people in three years and sparking the first-ever air-raid bombings of civilians. For Motherwell, the contrast between the dark ovals (rendered in black acrylic paints, which blended pigment with polymers of acrylic esters) and

their background represented a contrast between life and death, while the ovals were reminiscent of the testicles of dead bulls displayed after a bullfight.

TO DESCRIBE *NANOBLCK-SQR #1* as a black square seems not only obvious, but a gross understatement. Created by De Wilde, this meter-wide artwork is an all-encompassing void of utter black. As Spinal Tap's lead guitarist Nigel Tufnel once said: "It's like, how much more black could this be? The answer is none. None more black."

The surface of *NanoBlck-Sqr #1* is coated with a forest of carbon nanotubes that trap more than 99.99 percent of the light that falls on them. Exhibited in London earlier this year (see p. 114), its complete lack of discernable features produces a sense of limitless depth—viewers have an urge to reach right into the space it creates. "It's like a visible black hole—that's a very powerful effect," says Narayan Khandekar, the director of the Straus Center for Conservation and Technical Studies at the Harvard Art Museums in Massachusetts.

The artwork continues the intersection of science and aesthetics that has so characterized the history of the color black. As an art student, De Wilde was frustrated by the lack of innovation in painting and sculpture. He believed that using the most advanced materials in his art would offer a way to represent science and innovation's broader influence on society. De Wilde cites the French artist Yves Klein as a key inspiration. In 1955, Klein collaborated with a Parisian chemical manufacturer to create a new shade of blue—similar to ultramarine—dubbed International Klein Blue. The secret was not to invent a novel pigment, but to combine it with a polyvinyl acetate resin that gave full reign to the pigment's intense color.

In the mid-2000s, De Wilde realized that he might be able to control the behavior of reflected light by tailoring pigments at the nanoscale. So he started searching for scientific collaborators. "If you look at the history of nanotechnology, you arrive at Rice University in Texas," says De Wilde. Rice was home to Robert Curl and Richard Smalley, who shared the 1996 Nobel Prize in Chemistry with Harold Kroto of the University of Sussex for their discovery of nano-sized spherical shells of carbon atoms (C_{60}).

In 2010, De Wilde began collaborating with chemist Pulickel Ajayan at Rice, and soon produced *Hostage pt.1*, a black square not much bigger than a postage stamp that was billed as the blackest painting ever made. "With my black squares, I'm anticipating the creation of a new society," says De Wilde. "It's very related to the artworks of Malevich." But while De Wilde may have been inspired by Malevich, his techniques were beyond anything available during Malevich's time: He made his blacks by manipulating light on scales smaller than a single wavelength.

De Wilde created the work by first sputtering charged iron ions onto a silicon wafer. When the wafer was transferred to a chemical vapor deposition furnace, the iron acted as a catalyst that helped to knit together carbon atoms from a feedstock of acetylene gas into nanotubes. "It's a very delicate process, and it doesn't work every time," says De Wilde. "But when it does, you can see the material literally growing like a black forest."

De Wilde went on to apply a carbon nanotube-based optical coating technology developed at NASA to cover a set of 3-D printed titanium structures. The result is a series of objects collectively called *M1Ne II*, which look like futuristic birds' nests about 20 centimeters across. The structures hearken back to the birth of the industrial revolution by reflecting data about seven coal mines around Limburg in Belgium. This data includes the depths of the shafts, the amount of air pumped into them, the energy produced by their coal, and the relative locations of the mines. "In part it symbolizes the cohesion of the coal miners—they had to rely on each other to survive," says De Wilde.

The series neatly connects the various identities and histories of the color. But it also reflects a basic desire of the artist, says De Wilde: "Creating the blackest black is a reaction born out of necessity." ☺

MARK PELOW is a science journalist based in Cambridge, U.K.



What's 250 Million Light-Years Big, Almost Empty, and Full of Answers?

Astronomers are using new tools in their search for cosmic voids

BY MATTHEW R. FRANCIS

THE DARKEST HOLE IN THE UNIVERSE lies near the constellation Boötes, the plowman of the northern sky. This region, called a void, is 250 million light-years across and is almost entirely bereft of matter. If you centered a region of the same size on the Milky Way, you'd find thousands of galaxies. The Boötes void has only 60. Looking in all directions from its center, the cosmos would appear dark and empty.

If galaxies are cities, then the edges of a void are the suburbs, and the center is the deepest wilderness. But an atlas isn't complete if it includes only cities and roads; it also needs the empty spaces in between. Scientists are increasingly entering the deep, dark wilderness of the void to complete their atlas, and in doing so are learning about other, greater dark presences in our universe.

Dark matter, for example, makes up 80 percent of the matter in our universe, but neither emits nor absorbs light. Because its gravitational force gathers

together atoms to make galaxies and clusters of galaxies, though, the stars, gas, and dust that constitute the visible stuff of the cosmos reflect the underlying dark matter distribution. Where galaxies are thickest, dark matter is densest. The reverse is also true: In a region empty (or nearly so) of galaxies, dark matter should be sparse.

"Voids are vast, shallow troughs in the dark matter [distribution]," explains Joseph Clampitt, a post-doctoral researcher at the University of Pennsylvania. "Galaxies sit at the center of narrow, towering peaks." If you use height as a stand-in for density, "a typical galaxy has the same height and footprint as the Empire State Building [and] a medium-size void would be a 3-foot-deep hole three times the size of Manhattan." Find the voids, fill out your dark matter map.

Voids can also tell scientists about another darkness, called dark energy. It drives the acceleration of the expansion of the universe, and therefore the size and number of voids. Peter Melchior, a cosmologist at

ILLUSTRATION BY SERGE BLOCH

the Center for Cosmology and Astro-Particle Physics at Ohio State University, says that a measurement of the distribution of void sizes and profile shapes would help pin down this mysterious force. “It would give us information about how strongly dark energy works, because [dark energy] would affect the growth of [void] size over time.”

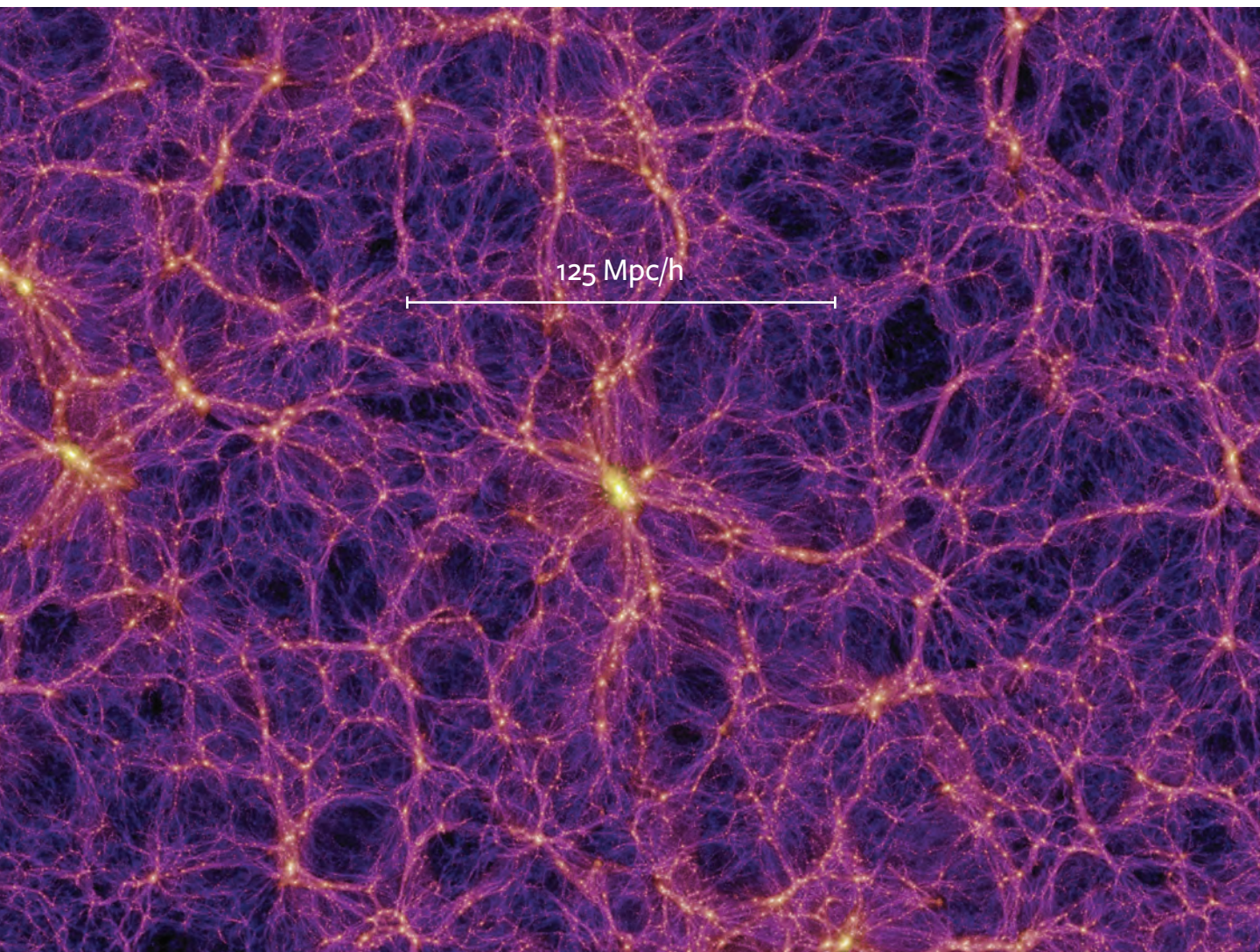
As empty as they are, then, voids are full of promise. The only problem is, how can you find an emptiness in the vast fullness of space?

EVEN THE ENORMOUS BOÖTES VOID evaded detection until 1981, when it was discovered by Robert Kirshner and colleagues. While we inhabit a three-dimensional universe, our view of the sky is two-dimensional because the vastness of the cosmos stymies our depth perception. A void is both large and mostly empty, but galaxies in both the foreground and background obscure it from our view. Only by measuring that third

dimension with precision instruments can we grasp how incredibly huge and empty these regions are.

Since the discovery of the Boötes void, astronomers have found a number of similar empty patches using similar methods. There’s even one near the Milky Way, creatively named the Local Void. Voids are ubiquitous, and come in a range of sizes and shapes. But it’s not enough to know voids exist: Scientists want to know how many there are, how large they are, and how they are distributed in space and time.

To accomplish this, scientists are turning to gravity. All forms of matter and energy exert a gravitational force, which in turn affects the path of light, as predicted by Einstein’s general theory of relativity. “The gravitational deflection of light by mass is similar to the familiar effects of a glass lens or prism,” says Clampitt—although it is much harder to observe. Where matter is dense, light is affected strongly, producing striking multiple distorted images of distant



objects; that effect is known as strong gravitational lensing. Where matter is rarified, the result is a “weak lensing” that is more subtle: twisting light, magnifying background galaxies slightly, and other small tweaks that require careful observation to detect.

These different lensing behaviors can be used to find voids. As Clampitt explains, a galaxy or galaxy cluster will produce a gravitational lensing signature “that is tangential or barrel-shaped,” while voids “imprint a radial or pincushion pattern.” Although individual voids produce too weak a gravitational signature to detect reliably, Melchior and his collaborators proved this year that the gravitational signature of many voids together can be detected. They took 901 known cosmic voids from the vast Sloan Digital Sky Survey (SDSS) and “stacked” them, averaging the light passing through them to extract their general gravitational properties. Starting from voids that were already identified, the team compared the voids’ lensing signals to what is expected from theoretical models, to see if the voids were truly as empty as expected. They were—so patches of the cosmos with very few galaxies also have very little dark matter. That’s an expected but pleasant confirmation of cosmological theory.

At the University of Pennsylvania, Clampitt took a complementary approach that was not restricted to voids that had already been identified. With University of Pennsylvania astrophysicist Bhuvnesh Jain, he directly searched the SDSS catalog for the weak gravitational lensing signature expected from voids, without first relying on galaxy distributions. This turned up around 20,000 possible voids, which the researchers now plan to check against galaxy distribution data.

The use of gravitational lensing to find voids is novel, says Asantha Cooray, a cosmologist at the University of California, Irvine. “Before these two papers weak lensing has been mainly used to measure mass concentrations like galaxy clusters and groups. The measurements provide lensing-based estimates of the void size ... [and] confirm there are indeed large regions in the

Only by measuring that third dimension can we grasp how incredibly huge and empty these regions are.

universe that are devoid of galaxies,” he explains. Additionally, these papers confirm a major aspect of the theory of galaxy formation: Dark matter forms knots and filaments, with large empty spaces in between.

THE CENTER OF THE BOÖTES VOID is relatively close by: about 700 million light-years away from Earth. However, many voids are much farther away than that, scattered across the sky. SDSS and its successor, the Baryon Oscillation Spectroscopic Survey (BOSS), which are based at the Apache Point Observatory in New Mexico, cover one patch of the northern hemisphere sky chosen largely to look away from the thickest part of the Milky Way. Other surveys, including several currently in the planning stage, will cover more of the sky, specifically looking at weak gravitational lensing and void lensing.

Voids, then, will be an important part of the future of astronomy—and, for that matter, of the universe itself. That’s because, in the far future, the cosmos will be more void than not, thanks to the actions of dark energy. The cosmic web will shred, leaving only wisps in the deep darkness of intergalactic space. Trillions of years in the future, matter, not voids, will be the exception. ☺

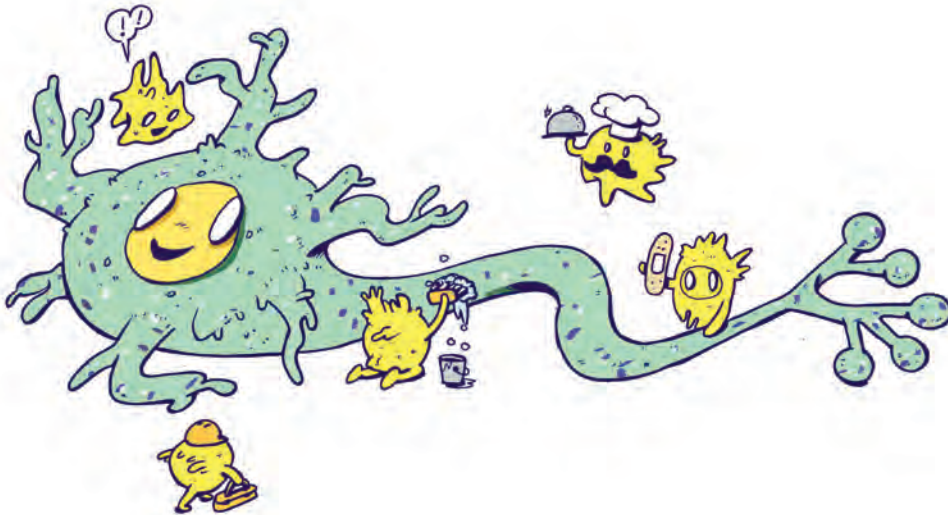
MATTHEW R. FRANCIS is a physicist, science writer, public speaker, and educator.

THE COSMIC WEB In this simulation of the structure of the universe, every bright point represents a galaxy cluster, and the empty spaces are voids.

The Neuron's Secret Partner

Glial cells are the brain's architects, doctors, police, janitors, and gardeners

BY FERRIS JABR



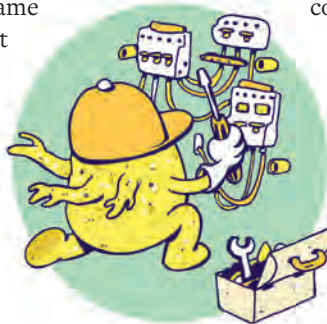
WHEN WE SPEAK of brain cells we usually mean neurons: those gregarious, energetic darlings of cell biology that intertwine their many branches in complex webs and constantly crackle with their own electric chatter. But neurons make up only half the cells in the brain. The rest, known as neuroglia or simply glia, have long lived in the neuron's shadow.

French physiologist Henri Dutrochet first documented glia in 1824, though he had no idea what they were—he simply noted globules between the nerves of mollusks. In 1856, German biologist Rudolf Virchow gave those blobs the name “neuroglia,” describing them as “a sort of putty in which the nervous elements are embedded.” In the following decades, scientists learned that this putty was in fact made of individual cells—at least six major types, we now know—that

formed intricate structural networks with both neurons and blood vessels. Yet they still regarded glia (which is Greek for “glue”) as mere fluff ‘n stuff, the brain’s packing peanuts, an inert plasma holding everything else in place.

By the early 1900s, that notion had begun to erode. Many leading neuroscientists proposed that glia were in fact much more active than previously realized: Perhaps they were feeding neurons, or helping them communicate, or repairing them after injury. From the 1960s onward, thanks in large part to a suite of sophisticated laboratory tools, neuroscientists confirmed that glia are the brain’s architects, doctors, police, janitors, and gardeners.

In the last five years, researchers have finally brought glia into the limelight as the highly dynamic, incomparably versatile, and indispensable partners of the neuron. Here are five recently discovered roles glia play in the brain:



ILLUSTRATIONS BY JACKIE FERRENTINO

Wiring

Neurons are not always born where they are meant to reside. In the developing brain, so-called radial glial cells form a widespread lattice of cables along which neurons crawl like inchworms to their permanent homes. When this scaffolding is no longer required, radial glia transform into other kinds of glia, such as starburst-shaped astrocytes and octopus-like oligodendrocytes, or even into neurons. Scientists recently discovered that a specific subset of radial glial cells are fated to become neurons in the upper-most region of the cerebral cortex, the brain's wrinkly outer layer responsible for our most sophisticated mental talents. Because the cerebral cortex of the human brain is so large and dense for a mammal our size, these glial cells likely played a key role in our evolution. A series of studies in the last three years have also confirmed that some glial cells excrete molecules that promote the formation of new connections between neurons, while others engulf and digest weak and underused synapses, changing the brain's microcircuitry throughout life.



Clearing Clutter

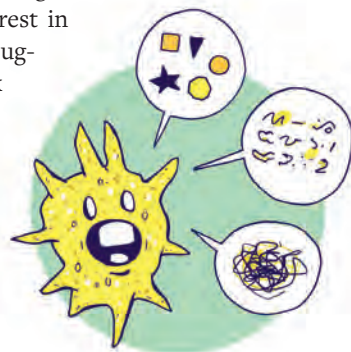
Every organ in the body needs a clean-up crew: a means of clearing away superfluous fluid, dead cells, and lingering cellular debris that could impede business as usual. The brain is no exception. Scientists have known for years that finely branched glial cells called microglia play a major role on the brain's waste management team. Microglia roam about scavenging harmful tangles of proteins, the remains of dead cells, and bits of unneeded DNA. But a study published just last year indicated that microglia are essential for eliminating clumps of amyloid beta and other protein clusters associated with Alzheimer's and related neurodegenerative disorders. Microglia are not the only members of the glia tribe that help take out the trash, though. Three years ago, Jeffrey Iliff, then of the University of Rochester Medical Center, and his colleagues injected fluorescent molecules into the fluid surrounding the brains of live mice. The

molecules traveled through a previously unrecognized network of channels formed by glia known as astrocytes, which flank arteries and veins. Perhaps these glial ducts, Iliff and his team surmised, act as a drainage system for the brain. When they introduced amyloid beta into the rodents' brains it was indeed cleansed away via the astrocyte aqueduct.

Helping Neurons Talk

The oligodendrocyte precursor cell (OPC) is one of the most unique and active types of glia. OPCs eventually mature into adult oligodendrocytes that wrap their many tentacles around neuronal branches, sheathing them like rubber insulating electrical wire. Scientists discovered more than a decade ago that OPCs form synapses with neurons and change their own behavior based on the electrical signals they receive from those neurons. They are the only glial cells to do this.

Now, emerging evidence indicates that the communication between OPCs and neurons goes both ways. The surfaces of OPCs are studied with a distinct protein known as NG2, and in a study published last fall, Dominik Sakry and Angela Neitz of Johannes Gutenberg University Mainz showed that the electrical impulses OPCs receive from neurons sometimes trigger enzymes to cleave NG2 from the cell membrane, allowing the protein to drift away and contact nearby neurons. When the cleaved fragments of NG2 bind to neurons, they make the cells more responsive to neurotransmitters such as glutamate, which are essential players in neuronal communication. When Sakry and Neitz eliminated either NG2 or its associated enzymes from mice, the animals' ability to pick up sensory information was impaired: They were slower than typical mice to realize that a repeated startling sound was innocuous, and they showed less interest in new smells. That suggests the cross-talk between neurons and OPCs is not mere idle chatter, but rather an essential dialogue that underlies behavior.



Helping You Breathe

The glia known as astrocytes wrap tightly around blood vessels feeding neurons, which puts them in an excellent position to monitor blood contents and adjust circulation as needed. Alexander Gourine of University College London and his colleagues studied how astrocytes in a rat brain might respond to fluctuating blood levels of oxygen and carbon dioxide. First, they genetically engineered the astrocytes of living rats to glow when the cells revved up their internal calcium signals, which help orchestrate activities within the cell. Then they exposed the astrocytes to differing pH levels. Only astrocytes in the medulla oblongata, a part of the brain stem that controls breathing and heart rate, responded. When those astrocytes detected a drop in blood pH, which would correspond to elevated levels of carbon dioxide, they increased their internal calcium signaling and began to secrete adenosine triphosphate (ATP)—a molecule used to store energy and perform a wide range of cellular tasks. The ATP stimulated surrounding neurons to fire, which increased the breathing rate in live rats, eventually bringing more oxygen to the brain. Raising the pH, which would correlate with oxygenated blood, had the opposite effect. This suggests that glia are crucial for every breath you take.



route out of a maze and to learn that a certain sound signaled an imminent electric shock. Here's the thing: The scientists did not infuse the mice with neurons, but rather melded the mice brains with human glial cells. There are likely several reasons for this glial-fueled boost in brainpower. Several months after the surgery, many immature glial cells had matured into human astrocytes and essentially taken over the mice's forebrains. Human

astrocytes are larger and more powerful than their rodent counterparts: They have about 10 times more branching tendrils and their internal waves of calcium ions travel three times faster. By absorbing and releasing neurotransmitters, and thereby modifying the availability of these molecules, astrocytes change how frequently and forcefully neurons fire. In mice with human astrocytes, neurons sent stronger signals and were more likely to fire in the first place, leaving them with super-charged forebrains. One can only imagine what our glia can do with a forebrain full of human neurons, or how different we'd be without them. 🌀

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

Making You Smart

In Daniel Keyes's 1958 short story *Flowers for Algernon*, scientists perform experimental brain surgery on a man named Charlie Gordon to dramatically increase his intelligence. First, though, as so often happens in medical research, they test out the procedure on a mouse—the eponymous Algernon. A few years ago, scientists did something spookily similar (to a mouse, that is, not a human). Steven Goldman and Maiken Nedergaard of the University of Rochester Medical Center and their colleagues injected immature human brain cells into the heads of infant mice. A few months later, those part-human mice performed much better on tests of memory and intelligence than mice with typical brains. They were quicker to find the escape



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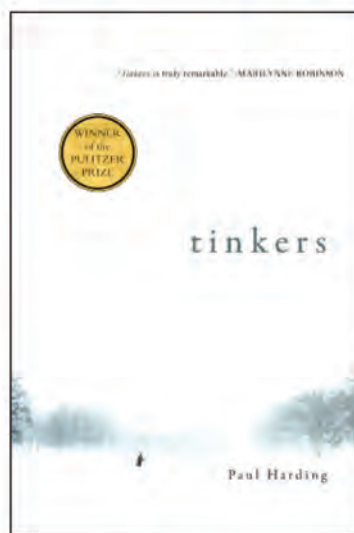
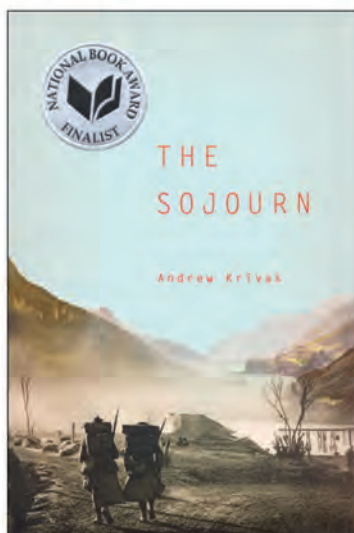
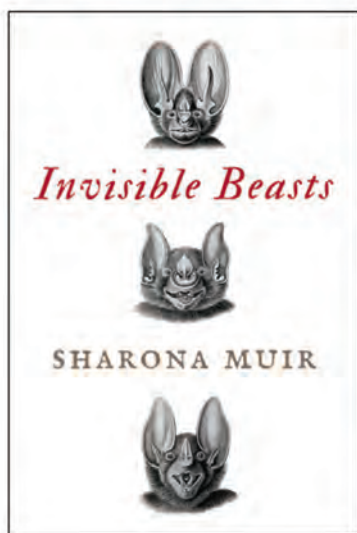
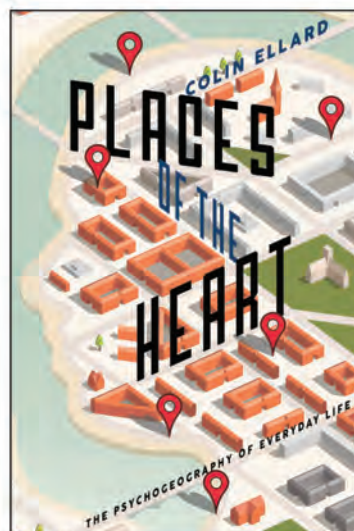
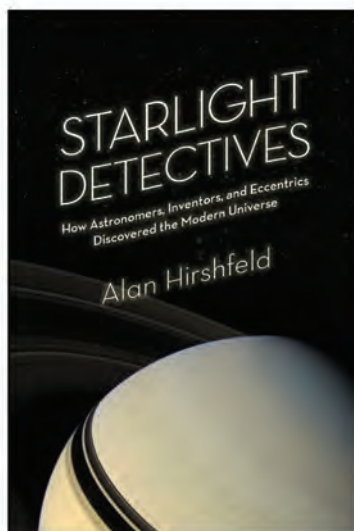
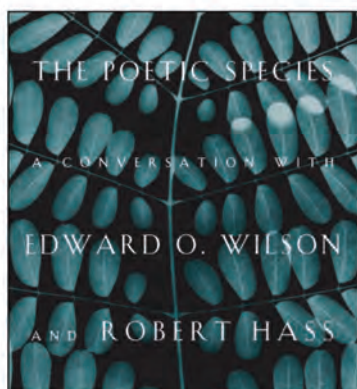
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01 | FALL 2013

- 01 **HUMAN UNIQUENESS**
What makes you so special
- 02 **UNCERTAINTY**
Inside our indeterminate world
- 03 **IN TRANSIT**
The elements of motion

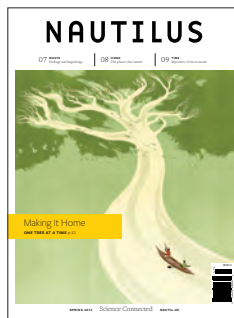


02 | WINTER 2014

- 04 **THE UNLIKELY**
Chasing the odds
- 05 **FAME**
The evolution of celebrity
- 06 **SECRET CODES**
Stories hidden and revealed

Issue Index

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03 | SPRING 2014

- 07 **WASTE**
Endings and beginnings
- 08 **HOME**
The places that matter
- 09 **TIME**
Mysteries of the moment



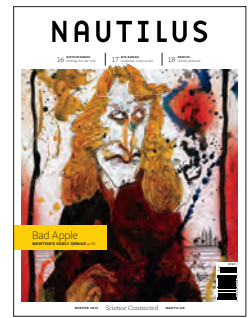
04 | SUMMER 2014

- 10 **MERGERS & ACQUISITIONS**
How nature comes together
- 11 **LIGHT**
Fields of vision
- 12 **FEEDBACK**
What goes around comes around



05 | FALL 2014

- 13 **SYMMETRY**
Structure takes wing
- 14 **MUTATION**
Engines of change
- 15 **TURBULENCE**
Out of order



06 | WINTER 2015

- 16 **NOTHINGNESS**
Peering into the void
- 17 **BIG BANGS**
Suddenly, a new world
- 18 **GENIUS**
Off the pedestal



07 | MAR/APR 2015

- 19 **ILLUSIONS**
Real enough
- 20 **CREATIVITY**
Swimming in possibility
- 21 **INFORMATION**
The anatomy of everything



08 | MAY/JUNE 2015

- 22 **SLOW**
Another time
- 23 **DOMINOES**
One thing leads to another
- 24 **ERROR**
Something wrong?



09 | JULY/AUGUST 2015

- 25 **WATER**
Beneath the surface
- 26 **COLOR**
Beyond the spectrum
- 27 **DARK MATTER**
All that you can't see



10 | SEPT/OCT 2015

- 28 **2050**
- 29 **SCALING**



THE LAST WORD

Jeff VanderMeer

The author of the Nebula Award-winning Area X: The Southern Reach Trilogy reflects on the themes in Nautilus

INTERVIEW BY LEN SMALL



ON WATER

I grew up in Fiji where my dad was an entomologist studying rhinoceros beetles. We would go by boat to islands for him to conduct his research, and my mom would do biological illustrations of sea turtles. Living through hurricanes in Fiji shows you the force of water. Then we moved to north Florida where you have humidity every day and the mold and fungus that come with it. There's these little shrimp-like

creatures—not sea life—that come wriggling out of puddles in the driveway, microcosms of freshwater tidal pools. There's nothing in this humid climate that is not full of life and at the same time decaying and dying. That had a huge impact on my fiction because it became subconscious, this overheated hothouse of humid decay.

ON DARK MATTER

When I read about dark matter, physics gets more surreal. Which I like because it ties into my own view of the absurdity of the universe. When we look closely at the universe, things we don't know peek through. So I think of dark matter as this unknowable thing,

peeking through, and I see the characters in *The Southern Reach* residing somewhere in that realm. At the same time, the term dark matter begins to hint at a kind of antagonist. You wonder what's behind something, and my characters' paranoia is the feeling there's something underneath. So reading about the theoretical aspect of physics helped me create a sense of the unknowable.

When we look closely at the universe, things we don't know peek through.

ON COLOR

Maybe because my mom is a painter, color is very important to me. I manipulate moods by use of color. For *The Southern Reach Trilogy*, I actually had a book for every possible word for green, every possible word for blue. I wanted to get across the feeling you have when the sun hits the water at a certain angle. I wanted to get across the beauty of the natural landscape in a way that wasn't clichéd. A lot of that was deploying color and how it reacts in shadow and light. However, in my previous books, which had a lot to do with fungal technology, I was trying to use color to describe not the five senses we have but alien experiences. And that's kind of an impossible thing to do! ☹️

ILLUSTRATION BY ANDY FRIEDMAN

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