NAUTILUS

Space Is Out to Lunch

PHYSICS' STRANGE NEW REALITIES p.26

$12

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"There are unique times in history when events and advancements in technology converge to elicit a quantum leap in medical care. That time is now for cancer. Our knowledge in the science of genomics, proteomics, immunology and immunotherapy has advanced and converged at an unprecedented speed, making now the right time to accelerate the deployment and to orchestrate the precise combinations of immunotherapy for the benefit of millions of cancer patients. The Cancer MoonShot 2020 Program, the National Immunotherapy Coalition and the QUILT Trial are designed to do just that - to rapidly deploy new immunotherapies by bringing together a diverse group of visionary leaders and stakeholders at the FDA, NCI, Pharma, and Payers. By connecting this actionable information to clinicians at the point of care across the country, we will bring to patients a dramatic improvement in cancer care."

Patrick Soon-Shiong, M.D.
Founder & Chief Executive Officer
NantWorks & The Chan Soon-Shiong Institute of Molecular Medicine

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Glitch in the Matrix

WHOA. DÉJÀ VU." The line from the 1999 film *The Matrix* is prompted by a passing cat, followed by another cat that looked just like it. Nothing earth-shattering, except for the fact that "déjà vu is usually a glitch in the Matrix"—a small imperfection in a reality that is faked, generated by computers to keep the human race enslaved.

While the film's metaphor might be mostly a social one, real-life physics has had its own glitch in the Matrix. The Einstein-Podolsky-Rosen paradox, formulated in 1935, pointed out that the then-emerging discipline of quantum mechanics required some distant particles be able to communicate instantly with each other. Since this contradicted general relativity, the paradox's namesakes argued that quantum mechanics was either erroneous or incomplete.

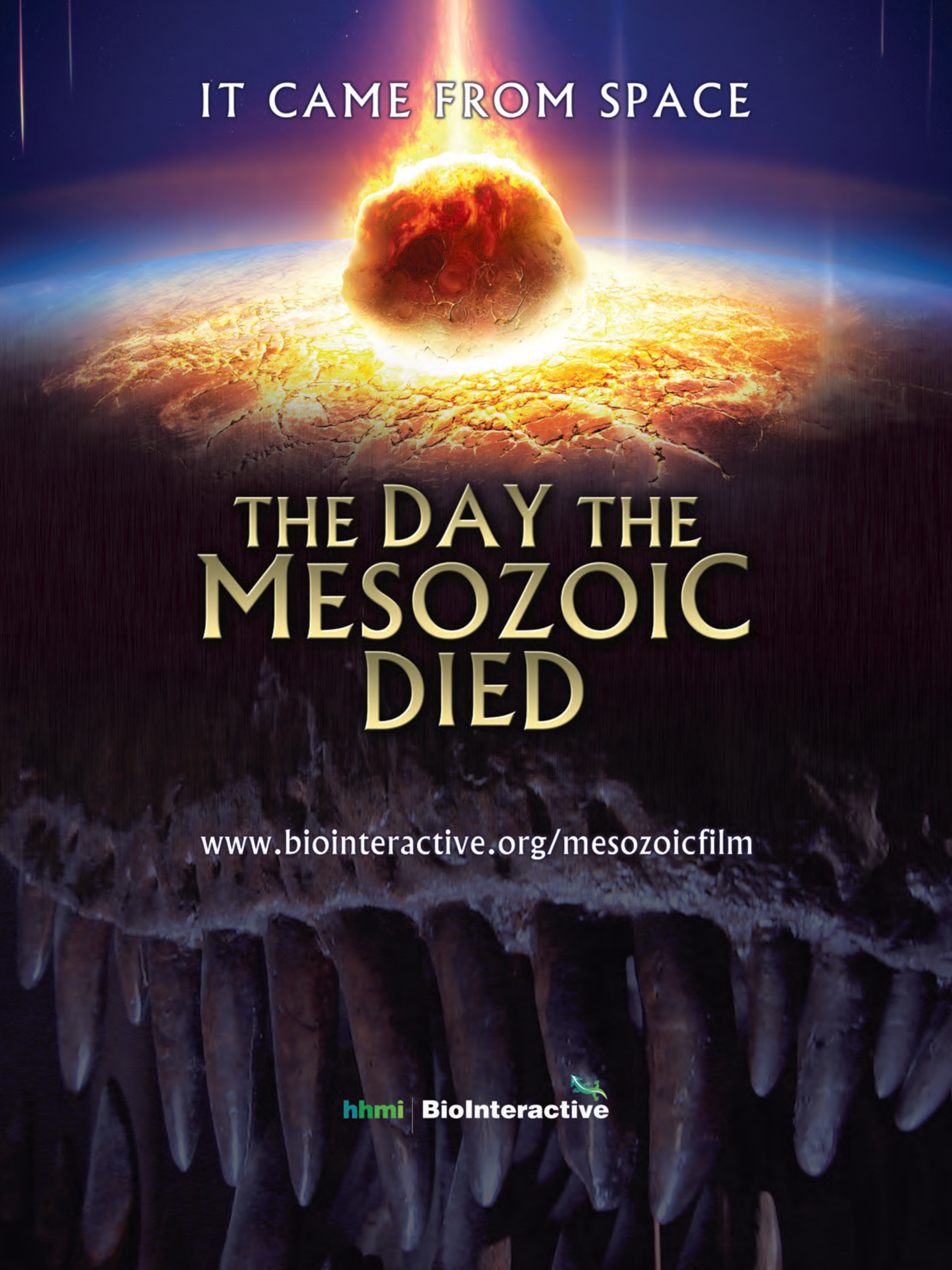
But in the 1970s, experiments began to verify this prohibited communication. So-called "local realism" began to die: We could no longer "point" at some phenomena, because they didn't happen in any particular place.

As George Musser explains in this issue's cover story, nonlocality has been increasingly embraced by modern physicists. Unified theories cast a skeptical eye at the very idea of space. In most of the universes they describe, it doesn't exist at all. And in our own, it may be a Matrix-like illusion, produced by objects rather than containing them. It's not that you're able eat that slice of pie because it's close enough to your mouth—it's the other way around.

Which leave us in an awkward spot, so to speak. The "truth" of *The Matrix* universe is relatively straightforward: A different but familiar real space undergirds fake space. It's just full of robots and stuff. In our real world, there is no safety net. There may be no Morpheus to welcome us to the real world, because there may be no place where the greeting might happen—no real places, at all, at least in the way we're used to thinking about them.

Welcome to the January/February 2016 *Nautilus* print edition.

—*Michael Segal*
Editor in Chief


IT CAME FROM SPACE
THE DAY THE
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—Tom Vanderbilt, p. 44

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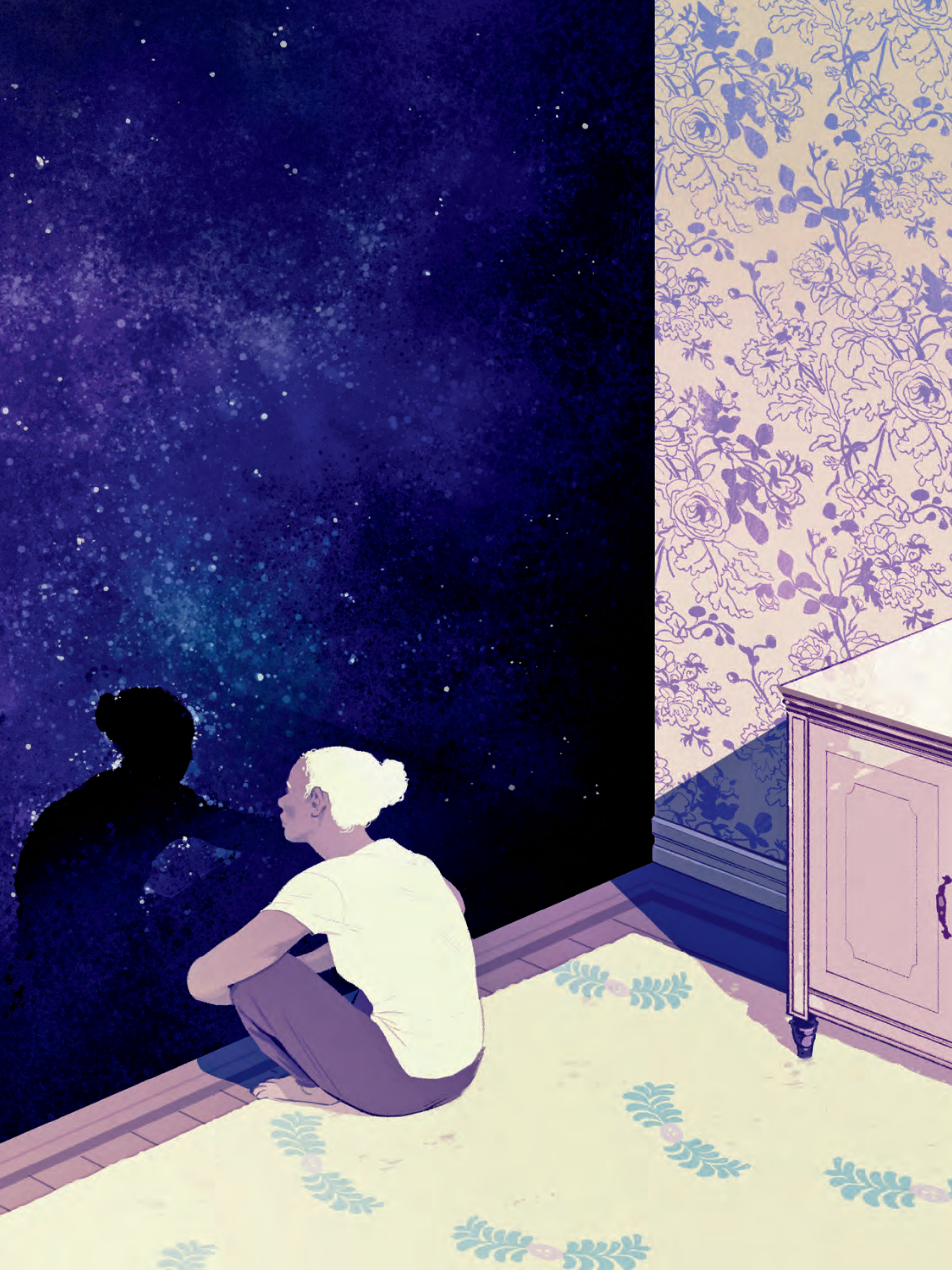

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Attraction

"It's worth considering whether pigeons might experience aspects of love that we don't."

—Brandon Keim, p. 106

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NAUTILUS

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Letters

Reader responses to the November/December 2015 print edition.

"THE STRANGE PERSISTENCE OF FIRST LANGUAGES"

Fascinating. I think a lot of Americans, born and bred in English only, struggle to understand language concepts, as opposed to language as mere utility. It's easy to claim frustration or disinterest over growing immigrant populations who preserve their native tongue in public forums—but only because we've never beheld the threat of losing access to (or being abruptly dislocated from) our entire culture.
—Aaron B.

"BLOWING OFF THE GRID"

This sounds great—but what about all the manure from the livestock. Isn't there a way of deriving some energy from this source? Farm animals in Canada are a great source of pollution to the water table here.
—Brian

"HOW THE WESTERN DIET HAS DERAILED OUR EVOLUTION"

We are really only beginning to understand our biome, and that what we eat has an impact upon us. But our famed antibiotics are equally dangerous to us—indiscriminate use, like eating a diet of fast food, impacts our autoimmune system in ways that research is only now beginning to flesh out.
—Anechidna

"WHEN DESTRUCTIVE BEHAVIOR MAKES BIOLOGICAL SENSE"

It strikes me that the inverse of this may explain the delayed development of today's millennials. Their well-off, stable, Boomer parents have the exact opposite impact on their millennial children as unstable families. Instead of maturing at an accelerated pace, their children actually mature much more slowly, so much so that there is dramatic difference from even their immediately preceding generational cohort.
—Haggie

"IS FACEBOOK LURING YOU INTO BEING DEPRESSED?"

Facebook and Twitter are not some creepy, evil entities that force their harmful will upon us. I am so tired of this false dichotomy, that many people have slipped, comfortably, into: big bad Facebook vs. "us," its unsuspecting, innocent victims.
—Tatyana Tarnopolsky

Of course Facebook and Twitter can make you depressed. These social media sites intentionally and psychologically manipulate your mind and emotions to make you feel depressed, happy, stressed, sad, etc.—basically mind control.
—taisen43255

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

Preludes

OLFACTION

To Find Love, You May Need Your Nose

People who can't smell struggle to bond with others

WHAT ARE THE INGREDIENTS of a good relationship? Trust? Communication? Listening skills?

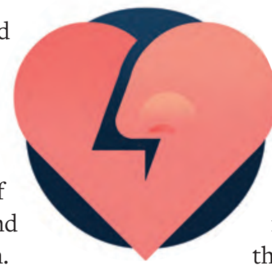
How about a sense of smell? When researchers in the United Kingdom surveyed almost 500 people with anosmia (the loss of a sense of smell), more than 50 percent said they felt isolated and blamed their relationship troubles on their affliction.

"I worry I will never be able to share again properly in my social and sexual life—I feel like I am an observer," lamented one anosmic. "So much of sexual closeness is wrapped up in smell: It's how you know who you are with when the lights are off," said another.

Data back up their claims. A 2012 study on 32 patients co-led by Thomas Hummel at the Dresden University of Technology found that anosmic men had had one-fifth as many sexual relationships as able-nosed controls. While anosmic women didn't experience this drop, they tended to be more insecure about their partners. "Anosmic people feel socially insecure, especially about their body odor, and tend to withdraw from social interactions," Hummel says.

Smell is important for forming social bonds, says Pamela Dalton, a psychologist at the Monell Chemical Senses Center in Philadelphia. When a new mom smells her baby, for example, the scent activates brain regions associated with nurturing behavior. Smells might similarly trigger brain activity involved in affection, compassion, or romantic love. Dalton thinks this may explain why many anosmic patients can have a hard time bonding with their partners.

A healthy olfactory sense may also be crucial for communicating and understanding emotions. In experiments, volunteers who smelled sweat samples from people who were experiencing certain feelings, such as fear or disgust, experienced those same emotions themselves. Psychologists suspect that such "emotional contagion" is at the root of empathy. If it's disabled, we may have a harder time relating to others.



Smell is important for forming social bonds.

Research into the social function of scent is still in its infancy, and some scientists are hesitant to draw conclusions about its power.

Still, many anosmics are convinced that smell shapes our interactions in ways we may not consciously perceive. "You will know it only when you lose it," says Duncan Boak, founder of Fifth Sense, a charity for those with smell and taste disorders. Boak lost his sense of smell to a brain injury. One of his greatest wishes is to smell the skin and hair of his partner.

—Ankur Paliwal

ILLUSTRATIONS BY ROBIN DAVEY

EXTRATERRESTRIAL LIFE

Look Down to See Up

How Earth's subsurface might help us find life on Mars

GREG WANGER, AN ASTROBOLOGIST with NASA, has been thousands of feet underground so many times that he often forgets he's not on the surface. "I try to put it out of my head," he says, which isn't hard when he's using Wi-Fi or ordering Domino's pizza. But it's not always easy when you find a rock the size of a fist at your feet.

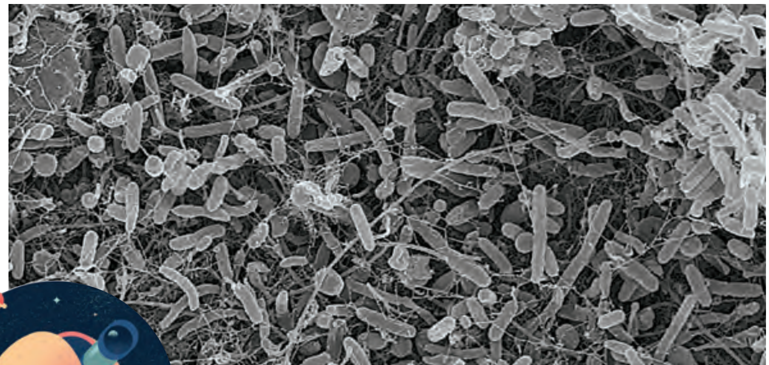
In these moments, he takes in the 1-mile thick bedrock above him. He's near the western edge of South Dakota in the now defunct Homestake Mine, founded in 1876, when gold prospectors flooded west, settling the frontier. In a way, his work is helping to explore a new frontier. Deep underground, Wanger is collecting bacteria that he will observe using a new spectrometer called SHERLOC, which will eventually find its way to Mars.

Wanger suspects that if there is life on other planets in our solar system, it won't be concentrated and visible to the naked eye like "a big tree or a thick biofilm." Instead, it will be diffuse and microscopic, very much like life underground on Earth. This theory is not new, but the technology that Wanger is helping develop is.

SHERLOC, which stands for Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals, can detect organic compounds. Typically, spectrometers cause both bacteria and their mineral background to fluoresce, an effect Wanger says is akin to "looking at a candle held up to the sun." SHERLOC produces more contrast, causing carbon forms to stand out like objects on a clear day.

Wanger is developing software for SHERLOC, and a method of grinding down minerals to create a flat surface for the instrument to scan. The NASA Mars 2020 rover will be equipped with a shoebox-sized version of the spectrometer (the current one is about half the size of a pool table). Wanger is confident that the rover will detect carbon forms, but he's skeptical we'll find life during this expedition. "As for finding life on Mars: I would love it if we did but I think that we will have to look to its subsurface to improve our chances."

—*Regan Penaluna*



ABOVE: This micrograph shows a biofilm collected along a tunnel wall in a South African gold mine. The gooey bacterial slime is about 1 centimeter thick.

GREG WANGER

TAXONOMY

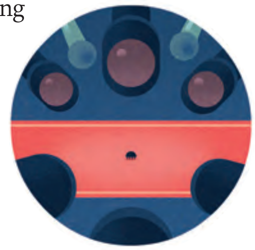
Meet the World's Most Notorious Taxonomist

Popular culture draws attention to science

IN 2005, QUENTIN WHEELER named a trio of newly discovered slime-mold beetles after George W. Bush, Donald Rumsfeld, and Dick Cheney. The taxonomist believed the names could increase public interest in the discovery and classification of new species, and help combat the quickening pace of extinction.

He knew he was onto something when, having received a call from the White House, it was Bush on the other end, thanking him for the honor. Wheeler began attributing all sorts of provocative names to his bugs, including Darth Vader, Stephen Colbert, Roy and Barbara Orbison, Pocahontas, Hernan Cortez, and the Aztecs—he has even named six species after himself.

Nautilus spoke with Wheeler about his work.



I think future generations will be appalled with us.

What's exciting about taxonomy?

It is the one field with the audacity to create a living inventory of every living thing on the entire planet and reconstruct the history of the diversity of life. If that isn't real science, I don't know what is. It infuriates me that taxonomy is marginalized as a bookkeeping activity.

Do taxonomists do experiments?

We have observed, discovered, and named hundreds of millions of specimens over the years, and the claim "All insects have six legs" seems to be true. And yet, if I found one tomorrow that has eight legs or four legs, I've falsified that claim. There is no more rigorous science than an all-or-nothing claim about the world.

Why is taxonomy important today?

I think future generations will be appalled with us, that it was so easy to explore biodiversity and where we came from, and we chose not to because we were doing parlor tricks with DNA at the time everything was going extinct. Taxonomy is more important than ever. It's really a matter of now or never that we learn about these species.

How will modern genetics change taxonomy?

Right now, there are people looking to replace the Linnean tradition with a DNA-based system, where species get assigned DNA barcodes instead of names. Yes, this could be easier, but I'd still argue that it's the wrong way to go: It meets the needs of taxonomic information, but it ignores taxonomy as a science—as a cosmology. I'd argue that we don't only need to know the numbers of species, but their unique properties, too.

—*Susie Neilson*

KENSY COOPERRIDER

ONE QUESTION

What's the most surprising role that space plays in your research?

Rafael Nunez

Cognitive scientist at the University of California, San Diego

Humans don't deal with just one space, but construe and manage multiple spaces—often in mutually incompatible ways! Sometimes these are centered on the body: "The bike is *behind* me." Sometimes they are external, organized cardinally: "She lives *North* from campus." Or they're topographical: "The route is *downhill* from here." Amazingly, we recruit these construals of space to ground a whole range of abstract concepts—from everyday ones, like "The week *ahead* looks great," to technical ones, like "f(x) gets *closer* to L." It's these multiple spaces that make entire domains of human imagination and abstraction possible.

NEUROLOGY

I Need Some Space

The discomfort we feel when someone stands too close is rooted deep in our neurobiology

THE AMERICAN ANTHROPOLOGIST EDWARD Hall first defined the concept of personal space in the mid-1900s as the invisible area around your body that you regard as psychologically your own. He noticed that the size of this space varies widely from culture to culture: Southern Europeans and Latin Americans, for example, embody *Seinfeld*'s "close talker," while Northern Europeans and North Americans are more stand-offish. For Hall, personal space was a form of social communication, helping to separate insiders from outsiders.

More recently, neurological studies suggest that personal space has deeper evolutionary roots. In research published in 2009, scientists at the California Institute of Technology concluded that the brain constructs personal space in the amygdala, a region associated with the fear response. In one experiment, they asked a woman known as SM, whose amygdala had been destroyed, to rate her comfort level as an experimenter approached her. Although she understood the concept of personal space and knew that standing too close to others could make them uncomfortable, she didn't feel that her own space was being invaded.

"SM demonstrated a striking lack of discomfort at close distances," the researchers wrote. "Even when nose-to-nose with direct eye contact," she insisted she was "perfectly comfortable."

Other research links personal space to the brainstem, which, in coordination with the amygdala, directs reflexive reactions to threats. In a 2013 study, neuroscientists at University College London recorded subjects' "hand blink reflex," a defensive response to an electrical stimulus applied to a nerve in the wrist. When subjects placed their hands at arm's length and then began to move them toward their faces, the strength of this reflex stayed fairly consistent. But around 20 to 40 centimeters away, it intensified and continued to grow larger as subjects' hands got closer, pointing to a clear boundary to the space they needed to feel safe.

This boundary shifted according to subjects' disposition: People who scored higher on an anxiety test tended to react more strongly when their hands were farther away. This suggests that higher-order brain areas, such as those involved in emotion and spatial processing, help regulate the "fight-or-flight" response, thus determining the unique size and shape of each individual's personal defensive space.

—*Claire Cameron*

Personal space is a form of social communication.

ONE QUESTION

What kind of attraction is most important in your research?

John Dennehy

Evolutionary ecologist at Queens College, CUNY

Viruses latch onto bacterial cells in order to enter them and reproduce the next generation of viruses, and in doing so, kill their hosts. In defense, bacteria have evolved all sorts of strategies to subvert virus infections. But this is a curious love/hate relationship. Viruses often carry antibiotic resistance, metabolic, and virulence genes that give their hosts an edge in competition with other bacteria. The pair is locked into a spiral of adaptation and counter-adaptation, eternally antagonistic—but also inseparable.

ZHILI LIANG

HOW CLIMATE CHANGE COULD STARVE THE MONKEYS

My sister the scientist makes a startling discovery in an Ugandan jungle

BY JULIA ROTHMAN

One day in 2007 I met my sister, Jessica Rothman, for lunch at a New York diner near Hunter College where she is a primate nutritionist. Over salads she told me about a special gift:

"LEAF DATA FROM KIBALE FROM 30 YEARS AGO!"

she practically shouted as I chewed my lettuce. Starting in the late 1970s, she explained, ecologists working in Uganda's Kibale National Park had done some of the first nutritional analyses of local leaves—a dietary staple of the very monkeys she studies. For decades, the unpublished data lay buried in a filing cabinet at Duke University. She'd only recently learned of its existence, and—to her delight—one of its authors had dug it up for her.

My sister's house at the field station

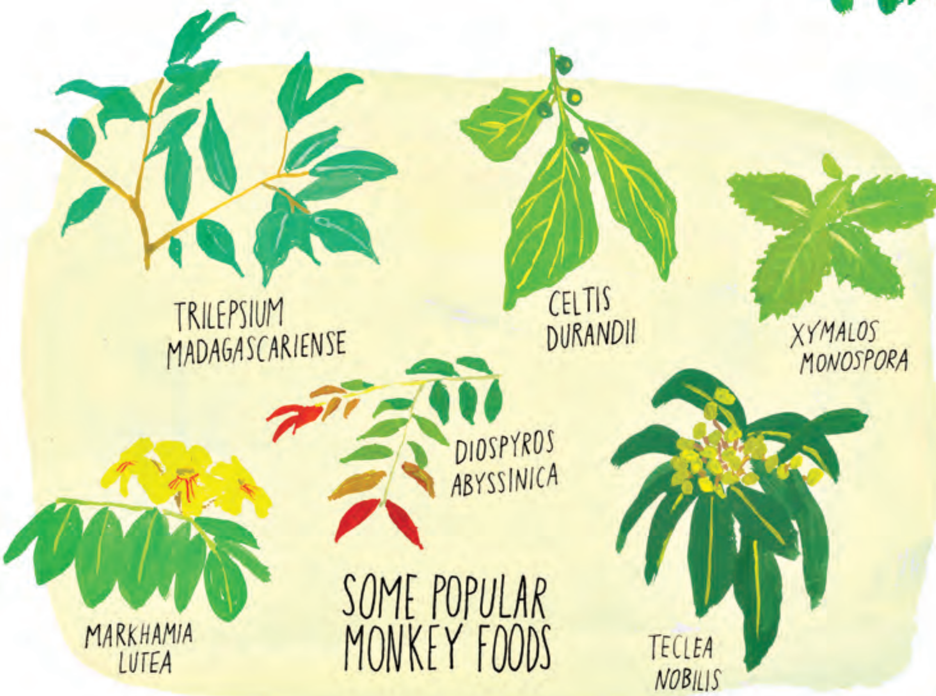
Like many field scientists, my sister leads a double life. For most of our adult lives, I saw her as a devoted professor who spent so many nights and weekends in the laboratory that she never bothered to fully furnish her tiny Queens apartment. I knew about her parallel work in Uganda through stories and pictures: mountain gorillas chomping wood, mango flies hatching under her skin, her concrete-block hut raided by baboons. But I couldn't quite get my mind around that other world and was always too scared to visit even though she begged me to come.

Jessica lives in the forest for months at a time, observing primate groups and collecting their foods and feces. She wants to know how nutrition influences a community's structure, size, and social dynamics.

And now, with the historic leaf data in hand, she can begin to probe the effects of climate change

"SO WE CAN BETTER PROTECT ENDANGERED SPECIES,"

she explains.

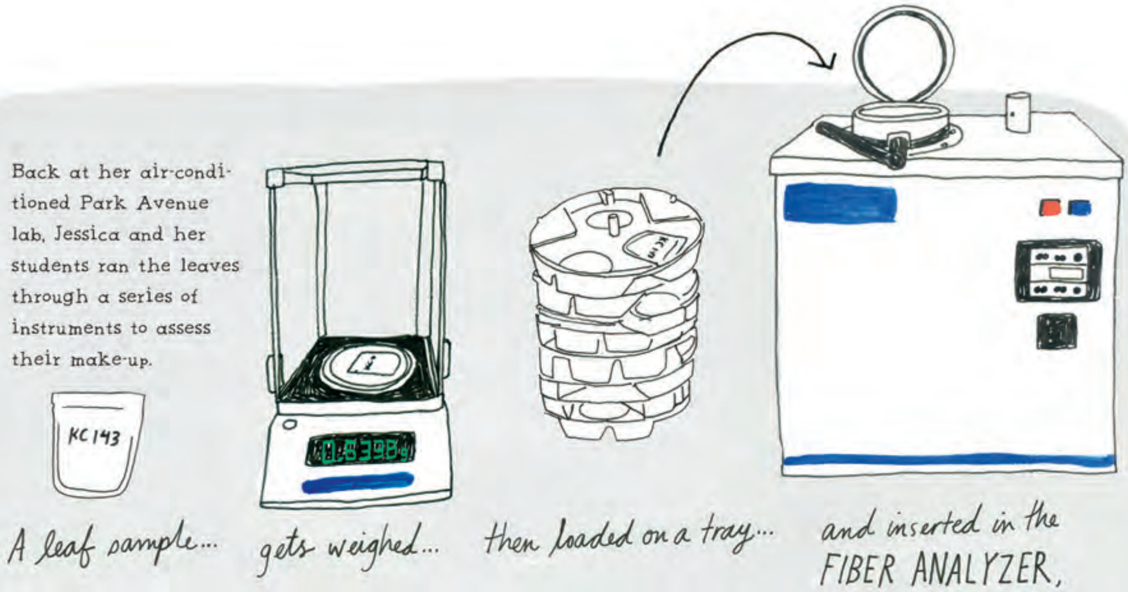


Greenhouse experiments suggest that as carbon dioxide increases and temperatures rise, plants will gain fiber and lose protein, making them less nutritious to primates. According to population surveys, habitats with low-protein, high-fiber foliage tend to have fewer monkeys. So you'd expect monkey populations to shrink as the planet warms.

To test this theory, my sister's team used an old hand-drawn map to locate the same trees that had been sampled between the 1970s and 1990s. They identified each tree by its tag—a code etched into the bottom of a rusty tin can.

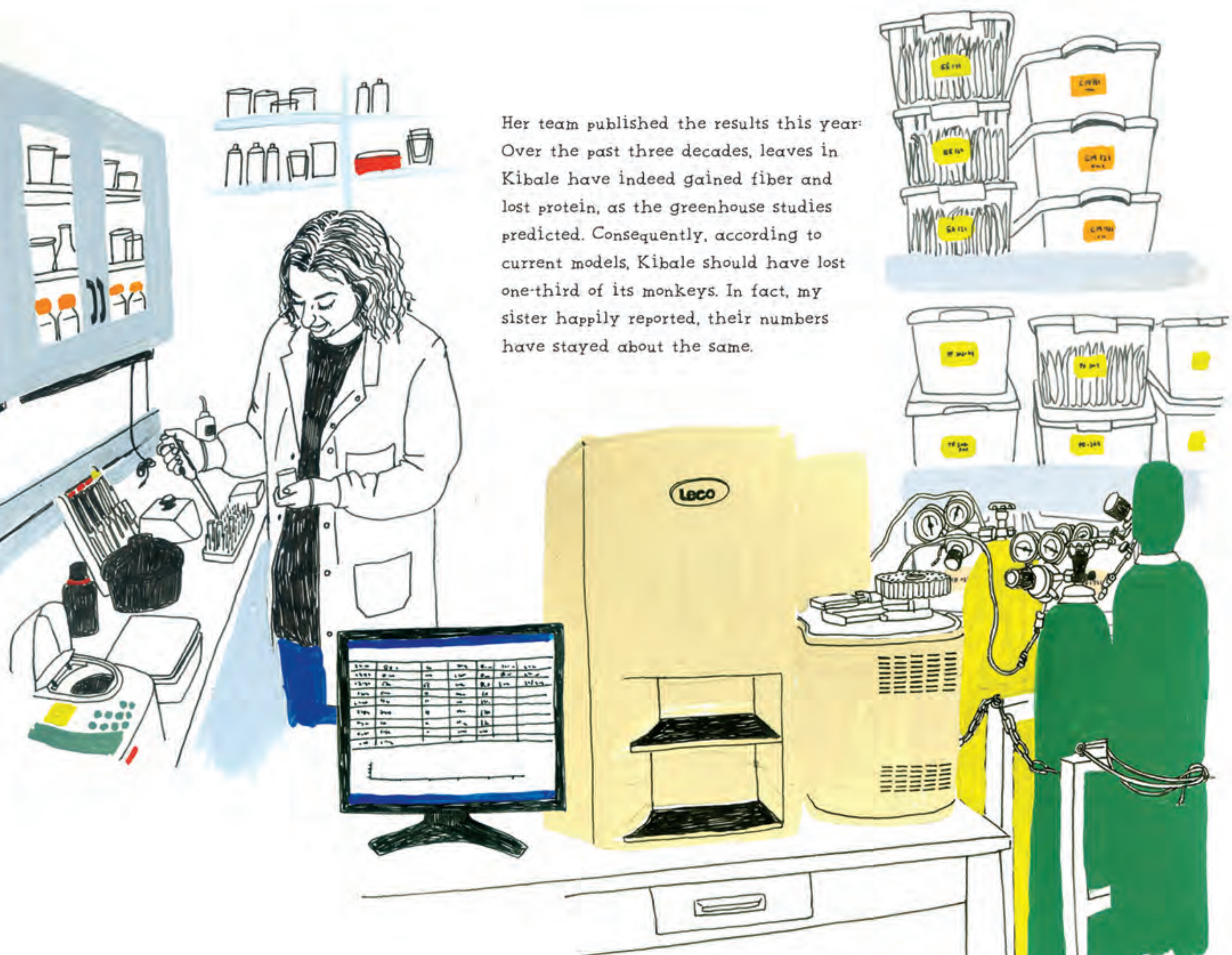

They dried the samples in the sun, ground them up, and packed them in my sister's suitcases.
leaf grinder
bagged samples

Back at her air-conditioned Park Avenue lab, Jessica and her students ran the leaves through a series of instruments to assess their make-up.



Weighing the output tells you the percent of fiber in the leaf. (Another process measures protein.)

Her team published the results this year: Over the past three decades, leaves in Kibale have indeed gained fiber and lost protein, as the greenhouse studies predicted. Consequently, according to current models, Kibale should have lost one-third of its monkeys. In fact, my sister happily reported, their numbers have stayed about the same.



"BUT WHY?"

she wonders. Maybe the monkeys simply changed their diets to compensate. Maybe the models are wrong. Or maybe it just takes time for a population to respond. These are the kinds of mysteries that lure her into the rainforest, again and again, despite the long plane rides, the sporadic electricity, and the bouts of malaria.

Two years ago, I finally worked up the courage to visit Jessica at her field station in Kibale, and I saw her transform before my eyes. I watched in awe as she navigated the jungle trails as confidently as she had navigated our childhood neighborhood, or directed a flock of field assistants who buzzed around her, clipboards and sampling equipment in tow. She even spoke with a local accent. One afternoon, we sat together among the trees, watching monkeys and listening to the sounds of the forest.

Occasionally I looked over at her, reminding myself that this impressive scientist was still just my sister—just Jess.

JULIA ROTHMAN is an illustrator and author who lives and works in Brooklyn, New York. Her latest book is *Nature Anatomy*.


O'BRIEN

Let's Rethink Space

Does space exist without objects, or is it made by them?

BY GEORGE MUSSER

SPACE IS BRUTALLY EGALITARIAN. When you become separated from your lover, the two of you retain no tighter a physical connection than do two lumps of coal. In this way, space serves as the organizing principle of the natural world—the glue that binds the universe together, as the English physicist Julian Barbour has put it. Physical objects do not interact willy-nilly; their behavior is dictated by how they are related to one another, which depends on where they lie in space at a given time. This structuring role is easiest to see in the classical laws of mechanical motion, but also occurs in field theories. The value and rate of change of a field at different points in space fully determine what the field does, and points in the field interact only with their immediate neighbors.

This kind of behavior reflects what scientists call "locality," which means that everything has a place. You can always point to an object and say, "Here it is." The world we experience possesses all the qualities of locality. We have a strong sense of place and of the relations among places. Locality grounds our sense of self, our confidence that our thoughts and feelings are our own. With all due respect to John Donne, every man *is* an island, entire of himself. We are insulated from one another by seas of space, and we should be grateful for it.

But locality isn't what it used to be. Quantum mechanics predicts that two particles can become blood brothers. For want of a mechanism to couple them, the particle should be completely autonomous—yet to touch one is to touch the other, as if distance meant nothing to them. The scientific method of divide and conquer fails for them. The particles have joint properties that escape you if you view them one at a time; you must measure the particles together.

Our world is crisscrossed by a web of these seemingly mystical relationships. And in the past 20 years, I've witnessed a remarkable evolution in attitudes among physicists toward locality. In my career as a

ILLUSTRATIONS BY TIM O'BRIEN

science writer and editor, I have had the privilege of talking to scientists from a wide range of communities—people who study everything from subatomic particles to black holes to the grand structure of the cosmos. Over and over, I heard some variant of: "Well, it's weird, and I wouldn't have believed it if I hadn't seen if for myself, but it looks like the world has just got to be nonlocal."

To make sense of nonlocality, the first step is to invert our usual understanding of space. Physicists and philosophers can *define* space as the fact that the natural world has a very specific structure to it. Instead of saying that space brings order to the world, you can say that the world is ordered and space is a convenient notion for describing that order. We perceive that things affect one another in a certain way and, from that, we assign them locations in space. This structure has two important aspects. First, the influences that act on us are hierarchical. Some things affect us more than other things do, and from this variation we infer their distance. A weak effect means far apart; a strong effect implies proximity. The philosopher David Albert calls this definition of distance "interactive distance." "What it means that the lion is close to me is that it might hurt me," he says. This is the opposite of our usual mode of thinking. Rather than cry, "Watch out, the lion is close, it might pounce!" we exclaim, "Uh-oh, the lion might pounce on me; I guess it must be close."

The second aspect of the spatial structure is that diverse influences are mutually consistent. If a rhinoceros is also able to hurt me, it must be close, too. And if both a lion and a rhino are able to hurt me, then the lion and rhino should also be able to hurt each other. (Indeed, my survival depends on it.) From this patterning of influences, we extract space. If the threat posed by predators couldn't be expressed in terms of spatial distance, space would cease to be meaningful. A less morbid example is triangulation. The signal bars on your mobile phone indicate the strength of the phone's connection to a cell tower and therefore your distance from that tower. In an emergency, the phone company can locate your phone by measuring your signal at several towers and using triangulation or the related technique of trilateration. The fact that the measurements converge on a single location is what it means for you to *have* a location.

The nice thing about defining space in terms of structure is that it sidesteps some of the long-running disputes over the nature of space. The ancient atomists (as well as Isaac Newton) conceived of space as a thing in its own right, whereas Aristotle (as well as Gottfried Leibniz and Ernst Mach) conceived it an abstraction that describes how the contents of the universe are packed together. Either way, though, space reflects a structure that the natural world possesses. If the atomists were right and space has an independent existence, it must be highly ordered, like a neatly woven fabric, so that it can serve the functions that physics demands of it. If space is merely an abstraction, then the contents of the universe must fit together in just the right way to give meaning to the abstraction.

On the face of it, we haven't gained anything by giving primacy to organization; we've merely traded one mystery for another, because now we've got to explain the organization. But this could be an opportunity, because now we can imagine what the universe would be like if it *weren't* ordered in the requisite way. Then it might not be spatial anymore. Instead of thinking of space as an absolute necessity, we can regard it as one of the possible states of the universe, just as ice is one of the possible states of water. The ice analogy isn't bad, actually. Water is solid over a narrower range of conditions than it is gaseous. Likewise, space may be the exception, not the rule; most proposed unified theories of physics suggest that the vast majority of the universe's possible states are nonspatial. "Where space-time exists is very nongeneric," says Moshe Rozali, a string theorist at the University of British Columbia. "It requires some special conditions." In the twilight between order and disorder, space and spacelessness, perhaps we can find a comprehensible explanation for the nonlocal phenomena that physicists have puzzled over.

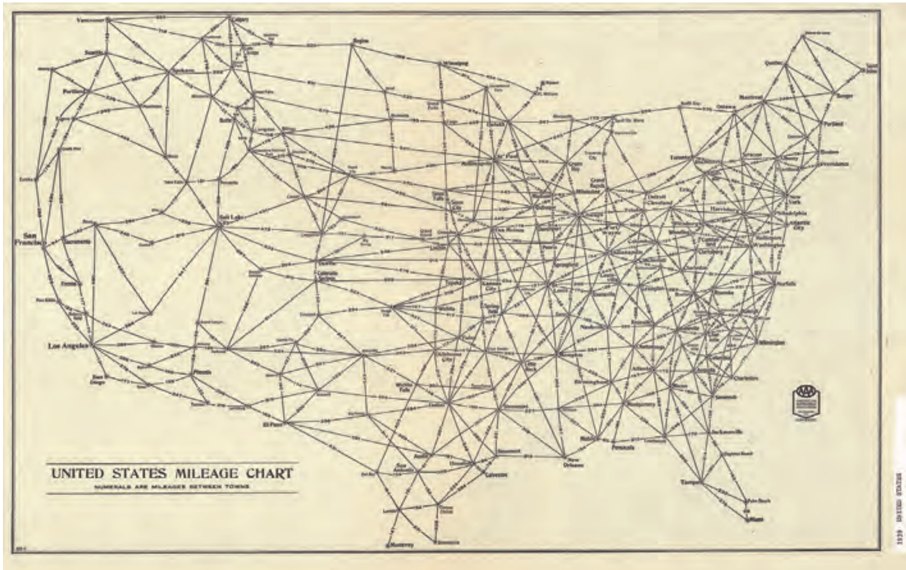
YOU DON'T NEED a complex system of moving, interacting parts to appreciate the organizing power of space. Consider the geography of a country. You can think of the cities as laid out on a map or you can express their mutual spatial relations with a mileage chart, like those found in paper road maps and atlases—one of those rectangular or triangular grids giving the distances between pairs of cities. What's interesting is that the chart contains hidden patterns within it, just as jigsaw puzzle pieces look unrelated when you dump them out of the box but show their affinity as you fit them together.

Suppose you have 20 cities. The chart contains 400 numbers. To fill in the data, a map company such as AAA hires drivers to travel from city to city and jot down the odometer mileage or take GPS readings. In terms of real information content, the chart is highly redundant. The distances obey very specific rules that mathematicians call "distance axioms." To begin with, the 20 numbers running along the diagonal are zero—the distance from each city to itself. Of the remaining numbers, half are repeats, since distances are symmetrical: A car driving from Dallas to Salt Lake City covers basically the same ground as a car going the other way. Indeed, most map companies leave off this redundant information and show only the remaining triangle of numbers.

Even the 190 quantities in that triangle are not fully independent of one another, because you can boil them down to 60 values representing each city's coordinates—latitude, longitude, and altitude—as well as an additional value for Earth's radius when cities are far enough apart that the planet's curvature becomes a factor. Finally, you can lose several more numbers because the conventions used for the coordinate system (such as taking the prime meridian to be zero degrees longitude) don't matter for the purposes of driving distances. That knocks out another six quantities. So now you're down to 55. The 400 numbers you started with are just various arithmetic combinations of 55 numbers. That may not be obvious from looking

	Atlanta	Boston	Chicago	Cleveland	Dallas	Denver	Detroit	Las Vegas	Los Angeles	Miami	Minneapolis	New Orleans	New York City	Orlando	Phoenix	St. Louis	Salt Lake City	San Francisco	Seattle
Boston	1106 16:18																		
Chicago	719 10:34	987 14:24																	
Cleveland	709 10:21	639 9:14	346 5:11																
Dallas	783 11:27	1772 25:40	967 13:56	1194 17:17															
Denver	1404 20:14	1975 28:28	1005 14:28	1334 19:19	879 12:50														
Detroit	721 10:26	814 11:53	282 4:17	176 2:47	1194 17:09	1270 18:11													
Las Vegas	2040 29:12	2718 39:11	1748 25:11	2077 30:02	1316 18:56	747 10:57	2012 28:54												
Los Angeles	2218 31:43	2988 42:55	2016 28:55	2345 33:46	1437 20:28	1016 14:41	2281 32:36	270 3:52											
Miami	664 9:47	1505 22:08	1391 20:26	1243 18:09	1363 19:43	2073 30:04	1390 20:16	2676 38:31	2741 39:12										
Minneapolis	1128 16:10	1402 20:24	408 5:57	761 11:14	988 14:15	915 13:06	697 10:07	1657 23:49	1926 27:33	1797 26:00									
New Orleans	468 6:55	1526 22:19	926 13:19	1065 15:33	520 7:43	1396 20:23	1064 15:26	1833 26:31	1898 27:11	866 12:32	1295 18:37								
New York City	883 12:57	218 3:40	790 11:41	463 6:53	1549 22:21	1779 25:45	614 9:06	2521 36:28	2790 40:12	1290 18:49	1206 17:40	1303 18:56							
Orlando	438 6:26	1298 19:06	1163 17:07	1035 15:09	1136 16:26	1846 26:47	1163 16:59	2449 35:15	2514 35:56	240 3:51	1570 22:43	639 9:15	1083 15:50						
Phoenix	1846 26:32	2700 38:45	1803 25:56	2067 29:42	1065 15:19	909 12:59	2036 29:31	291 4:30	372 5:17	2369 34:02	1791 25:33	1527 22:01	2466 35:43	2142 30:46					
St. Louis	554 8:02	1193 17:13	297 4:21	560 8:12	629 9:25	850 12:17	530 7:39	1596 22:59	1825 26:03	1223 17:52	535 8:21	675 9:51	959 14:15	996 14:35	1502 21:34				
Salt Lake City	1921 27:28	2369 33:55	1399 20:00	1728 24:43	1404 20:10	524 7:54	1664 23:42	419 6:03	688 9:46	2590 37:19	1309 18:38	1921 27:44	2173 31:13	2359 34:04	651 9:56	1366 19:31			
San Francisco	2488 36:00	3103 44:26	2133 30:26	2462 35:17	1815 25:58	1268 18:03	2397 34:09	570 8:27	380 5:33	3119 44:41	2042 29:04	2277 32:40	2906 41:43	2891 41:21	750 10:45	2099 29:56	735 10:25		
Seattle	2696 38:29	3057 43:54	2063 29:31	2417 34:48	2199 31:29	1331 19:00	2352 33:40	1257 17:54	1142 16:29	3365 48:20	1657 23:42	2717 39:02	2862 41:14	3138 45:02	1512 21:40	2142 30:32	840 12:01	815 11:58	
Washington, DC	638 9:18	443 7:00	697 10:35	367 5:53	1330 19:13	1680 24:31	520 7:57	2427 35:14	2675 38:14	1056 15:12	1112 16:35	1084 15:54	228 3:41	849 12:19	2352 33:42	839 12:27	2080 30:04	2813 40:37	2768 40:08

DATA COMPRESSION The 400 possible distances among all pairings of 20 cities are boiled down to 190 numbers in this distance chart. The list can be further reduced to just 55 numbers. This kind of compression is characteristic of spatial ordering.



THERE AND BACK Placing intercity distances on this 1939 map enforces certain distance axioms, like the requirement that the shortest distance from New York to Boston be the same as the shortest distance from Boston to New York.

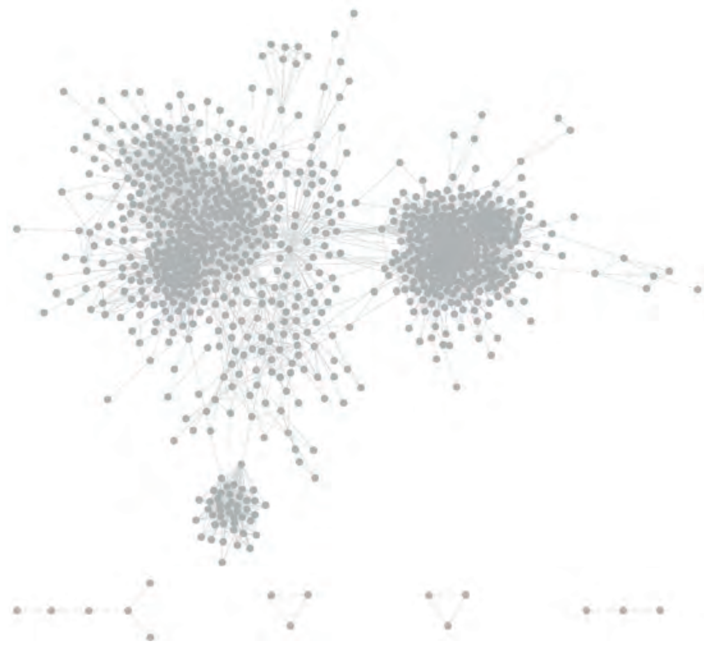
at the chart, but you know it has to be true because you could reverse the process. You could start with the cities' coordinates, mark their locations on a map, and use trigonometry to calculate the intercity distances.

So the chart is highly ordered. This is what it means for the cities to be situated within space. Spatial coordinates are a highly economical way of capturing the possible mutual relations among things. In the above example, we had 20 cities and 400 intercity distances that reduce to 55 unique numbers. The more things you have, the more impressive the savings are. For 100 cities, the chart contains 10,000 intercity distances, reducing to 295 numbers. For all the world's cities, or all its towns, or all its geographical features of any type, the raw distance data would consume a hard drive even though the positions of those features can be concisely expressed on a single map. "That's what space is," Barbour says. "It's data compression on a massive scale."

The reason the compression is so powerful is locality. Locality means that the whole is the sum of its spatial parts, and in this context, that means every journey is a series of smaller steps. You can build up long distances from shorter intermediate ones, so you don't need to specify each and every pair of directions. For instance, the chart might tell you it's 900 miles from Dallas to Denver and 500 miles from Denver to Salt Lake City, so you don't need to be told it's at most 1,400 miles from Dallas to Salt Lake.

Suppose this weren't the case—suppose the data in the chart weren't so highly ordered. If I fill in a chart with 400 random numbers and ask you to mark their locations on a map, you'll almost certainly fail. For instance, the chart might tell you it's 900 miles from Dallas to Denver, 500 miles from Denver to Salt Lake City, and 8,000 miles from Dallas to Salt Lake. Now, that doesn't make much sense, does it? These data put Salt Lake City in two different places, depending on whether you drive straight from Dallas or stop off in Denver. The situation is like an April Fool's joke in which your friend mixes together pieces from different jigsaw puzzles and gives them to you to assemble. You'll struggle to fit the pieces together until it dawns on you that your supposed friend is a cruel prankster.

Under such circumstances, position becomes



SOCIAL SPACE This map of a network of Facebook friends represents a kind of social proximity, which may or may not correspond to spatial proximity.

meaningless. *Space* becomes meaningless. It's not a useful way to describe the relations among places anymore. But that doesn't mean the relative arrangement of cities is incomprehensible. Even if you can't place the cities on a map, you can fall back on the full mileage chart. In other words, you can use what philosophers call the "unmediated" distances, the ones that directly link pairs of cities and can't be reduced to a series of shorter hops. This isn't an entirely hypothetical situation. When I first drove in Boston, I had to learn to distrust my spatial awareness, because it kept getting me lost. In that maze of one-way streets and amoeba-shaped "squares," you routinely have to go west to go east, or get in the left lane to turn right. It does you no good to know where places are located from a bird's-eye view; instead, you need to robotically follow directions for where and how to turn. To a driver, Boston is a nonspatial city.

IT'S REALLY NOT SO STRANGE that networks of relations can burst out of space. This is the case, after all, for human relationships. Our social lives are too tangled to be laid out on a spatial map. Not that people don't try. Family trees translate genetic and conjugal closeness into spatial closeness, and online social networks have spawned similar attempts. The Wolfram Alpha website, for example, used to be able to map out your Facebook friends network, using dots to symbolize your friends and lines to connect those who have friended each other. Spatial distance on the map represents social proximity as judged by the number of friends people have in common. Typically, your friends cluster into distinct social circles: family, classmates, workmates, ultimate Frisbee teammates, fellow Radiohead groupies, and so on. If these people go to the same party, they might congregate in different corners of the room, and the figurative distance between them translates into literal distance.

When I first generated a Facebook graph, I noticed a stray link between my physics colleagues and my music friends, revealing that a theorist I'd worked with shared my passion for Cuban dance music. Finding unexpected connections is half the fun of these graphs, but does expose the limitations of the spatial

That's what space is. It's data compression on a massive scale.

metaphor. There's no consistent way to assign that theorist a location on my graph. Like Salt Lake City in the above example, he occupies two different places, corresponding to two social circles. And the failure deepens when you consider everything these graphs leave off. Two Facebook "friends" may have never met or spoken, yet the diagram links them as if they were BFFs. One person might have an unrequited crush on the other, and still a line connects them. To capture these other dimensions of human relationships, you can festoon family trees with symbols: thick line for a close bond, zigzags for hostility, and so on. Such diagrams, known as genograms, are popular among psychologists, social workers, and people struggling to follow *Game of Thrones*. The symbols compensate for the failure of the spatial metaphor.

In some cases, people organize themselves so that their social network becomes radically streamlined, and these situations let us see how space might emerge from spacelessness. A structure can form where none existed before. That can happen in two ways: Build up or cut back. People might start as atomized individuals who begin interacting, like your grandmother who finally got on Facebook and signs up all her friends. Or they might start with a mess of existing relations and prune them, like a social butterfly who friended everyone he met, realizes he doesn't know who half of them are, and does a friends purge.

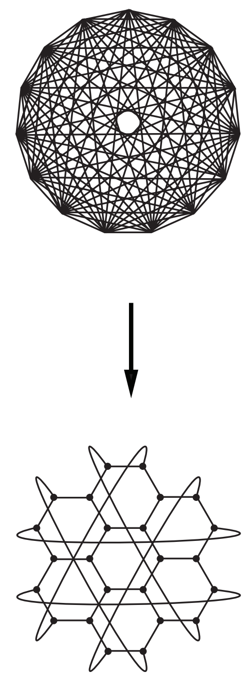
The army, for example, restricts socializing across ranks, on the assumption that familiarity might breed contempt. Consequently, difference in rank is analogous to spatial separation: A private is distant from a colonel in much the same way that Dallas is distant from Salt Lake City. Information flows up and down the chain of command just as a person driving from Dallas to Salt Lake City must pass through intermediate points. Because of this structure, a military hierarchical chart is a fair representation of social relations in the military.

The army's structure is imposed by military discipline, but in other cases the order develops spontaneously from within. A classic example is the market economy. We routinely speak of "the economy" as though it were a conscious being rather than millions of people making rash decisions with their money. And in a sense it is, because collective arrangements transcend the people who create them. In isolation, individuals don't put price tags on goods, because they have no one to buy from or sell to. Price becomes important when people come together and trade. Depending on their haggling skills, the price varies from person to person and place to place. Some plucky entrepreneur takes advantage of these variations to buy low and sell high; in so doing, that person helps to even out the supply and therefore harmonize the prices.

This kind of self-organizing happens all the time in physics. For instance, a single water molecule has no temperature. Temperature becomes meaningful when molecules collide and exchange energy. If you mix cold and hot water, the cold warms up, the hot cools off, until they equalize. Before equilibrium, the water is characterized by two temperatures; afterward, by a single value. From complexity comes simplicity. The complexity remains latent, though. You can tell it's there whenever the temperature fluctuates or water undergoes a transformation such as boiling in a teakettle. Physicists commonly use these deviations from standard behavior as windows into the microscopic composition of materials.

The same might go for space, too. The basic building blocks of nature might be capable of a tangle of relationships that would fill a celebrity gossip rag. Through some organizing mechanism or simply the play of averages, those relationships become regimented, so that they can be laid out on a spatial grid and interact only in strictly prescribed ways. A mind-bogglingly complex network of interactions reduces to a few numbers that we call "the position" and "the time." The underlying complexity never goes away, though. In situations such as black holes, the system can become disordered and events can cease to have a position or a time. And even when the system is spatial, it contains a vast amount of latent complexity. The universe we see playing out in space may be just the surface level, where we float like little boats while leviathans stir in the deep.

THE CONCEPT OF SPACE as a network goes back to the 1960s and the brainstorms of such innovative (and iconoclastic) theorists as John Wheeler, David Bohm, Roger Penrose, and David Finkelstein. Wheeler, for one,



QUANTUM GRAPHITY MODEL OF SPACE In a high-energy network (above), every point is connected to every other point. In a low-energy network (below), every point is connected only to a few others, which become its nearest neighbors in the structure of space.

FOTINI MARKOPOULOU

imagined taking a bucket of "dust" or "rings"—primitive grains of matter that do not exist within space, but simply *exist*—and stringing them together to form space. Physicists have been trying to make the idea work for decades. Today one of its strongest champions is Fotini Markopoulou, who pictures the stringing-together process as a graph akin to those Facebook diagrams. She and her colleagues call their approach "quantum graphity"—cutesy, but any effort to inject a sense of humor into physics jargon has got to be a good thing.

Quantum graphity doesn't specify what the Wheelerian grains actually are—that's a job for a full-up theory of quantum gravity such as loop quantum gravity or string theory. Quantum graphity is a theory-in-miniature that focuses narrowly on what you might build with those grains. Indeed, Markopoulou and her colleagues' philosophy is that the detailed composition shouldn't matter; the principles of organization should be universal. After all, physicists have found that similar rules govern a huge diversity of complex systems, from earthquakes to ecosystems to economies. On the downside, quantum graphity is so bare-bones that it faces the problem of meshing with known physics. "Fotini tries to jump straight in, but it's very ambitious and dangerous, because you have no connection to existing theories," says Claus Kiefer of the University of Cologne.

The links between the elementary grains are as simple as can be. Two grains are either connected to each other or not, like Facebook users who can either be friends or not—just an on-or-off relationship. The resulting network looks like a string-art craft project in which you hammer nails (representing the grains) into a sheet of wood and stretch threads (the links) among some of them. Despite the simplicity of its construction, the network can take on a huge variety of shapes, ranging from skeletal outlines to elaborate mandalas.

To breathe life into the network—to give it the capacity to transform and evolve—Markopoulou and her colleagues suppose that the links switch on or off depending on the amount of available energy. This process is ad hoc, but again the goal is not to create a bulletproof theory, but to reconnoiter possibilities for how to construct space. Each link represents a certain amount of energy. Chains of links contain less energy than an equivalent number of isolated links, so the total energy of a network depends not only on the sheer number of links, but also on how they're put together. The more intricate the pattern is, the more energy it embodies.

The energy maxes out in a fully interconnected network, where every grain is linked to every other grain. In such a network, the principle of locality doesn't hold; you can go from any grain to any other grain in one hop, without passing through any intermediate points. The network lacks the hierarchy of relations—near versus far, small versus big—which is characteristic of space. You can't subdivide it into separate chunks; it's an indivisible whole. "This thing has no notion of locality … ," Markopoulou has explained. "If you just put out your hand, you reach everybody in the whole universe."

To see why the high-energy network is not spatial, try assigning locations to the grains. Every grain has to be equidistant (a single hop) from every other. For the first three grains, that's no problem: Arrange them in an equilateral triangle. Four can be stacked in a pyramid. But where does a fifth go? There's nowhere equidistant to the first four points, at least not within ordinary, three-dimensional space. You need a *four*-dimensional pyramid. In fact, each additional grain requires a whole new dimension of space. Before long, you enter an ultra-higher-dimensional realm beyond our capacity to visualize. And most of that vast venue is wasted: The network is only one hop wide in any direction and does a good impression of a balled-up spider's web. So although you might still talk of the network as existing within space, it's not the kind of space we want: three dimensions that extend as far as we can see in every direction and provide an economical description of the relations among objects.

Lower-energy patterns are a different story. They're just what we want. Each grain connects to just a few others, forming a regular grid like a honeycomb or woven fabric. The notion of distance regains meaning: Some grains are close together, the rest far apart. The network is nice and roomy. The principle of locality holds: For an influence to go from one place to another, it can't hop straight there, but must work its way through the network. The passage of the signal takes time, which would explain why the speed of objects through space is limited (by the speed of light).

In short, spacelessness and space are just two different phases of the same network of grains. One can metamorphose into the other; a crumpled wad can unfurl into a flat expanse. Theorists have proposed a couple of ways this might happen. The reshaping could be a process that occurs in time. The network starts off as sizzlingly hot—a highly interconnected pattern containing an enormous amount of energy. Then it cools off and crystallizes like a tray of water freezing to ice, as links dissolve and reorganize to create a tidy arrangement. The trick is to explain the cooling. Things don't just cool down on their own; something must drain them of heat. "Where did the energy go?" wonders Markopoulou. "You need a freezer. You need to cool the universe." She and her colleagues speculate that the energy could go into the creation of matter. The primordial grains could coalesce into elementary particles, so that matter emerges hand in hand with space.

Alternatively, the transition may not be a process that unfolds in time, but a structuring that arises at the quantum level. The network can exist in multiple conditions at once, a limbo known as superposition. Although most of those conditions are nonspatial, they can fuse together into something that *is* spatial. The best-developed account of superposition of space goes by the somewhat unwieldy name of "causal dynamical triangulations." Its inventors have shown that nonspatial geometries neutralize one another, as long as events are highly ordered, with a distinction between cause and effect built in from the outset. The effect is analogous to the wisdom of crowds, those remarkable cases in which you pose a question to a group and no one person has the right answer, yet pooling everyone's guesses *does* give the right answer. The classic example is the jelly-bean experiment: If you ask a

Spacelessness and space are just two different phases of the same network of grains.

group of people how many jelly beans there are in a jar, the average of their estimates will be better than any single person's estimate. The group has a collective intelligence beyond that of its members.

STRING THEORISTS HAVE EXPLORED ideas similar to Markopoulou's quantum graphity. In the 1990s they pioneered "matrix models," so called because the equations are based on grids, or matrices, of numbers much like the mileage charts. A matrix in the mathematical sense has nothing to do with the virtual-reality "matrix" of the movie *The Matrix*, yet the premise is eerily similar: The world we experience is a kind of simulation generated by a deeper level of reality. The best-known matrix model was developed by a quartet of theorists, Tom Banks, Willy Fischler, Steve Shenker, and Leonard Susskind. Their model, like quantum graphity, supposes that the universe is a cat's cradle of interconnections among grains of primitive matter. Under the right conditions, extraneous connections rupture and the grains snap into a regular spatial grid. "You start with a bunch of Tinkertoy parts with no particular structure to them," says Susskind, who is a physics professor at Stanford University. "You shake it up and it emerges into a lattice or structure of some sort."

String theory outgrew its name long ago. It postulates not just one-dimensional strings, but also two-dimensional membranes and higher-dimensional analogues—as theorists call them, 1-branes, 2-branes, 3-branes, 4-branes, and so on. Some branes, designated by D, can act as the endpoints of strings. At the bottom of this pecking order is the humble D0-brane, a type of particle. Being a true geometric point lacking size or any other spatial attribute, the D0-brane is the perfect building block for space. Confirming this intuition, theorists calculate that the D0-brane has the right properties to serve as the graviton, the particle that has been hypothesized for decades to convey the force of gravity.

Matrix models take this particle as fundamental and construct the universe entirely from lots of them. Every particle can interact with every particle, and their interactions are not simply on or off, but can vary in strength and in quality. The more energy you inject into a pair of particles, the tighter their bond will become. The namesake matrix of numbers quantifies this web of interactions. For example, if you read down to the eighth row and then across to the 12th column, the number there will tell you how strongly particle number eight interacts with particle number 12. To express not just the raw strength but also the quality of the connection, you need several such matrices.

Each matrix is a square, and running diagonally from the top left corner to the bottom right is a special set of numbers—where the eighth row meets the eighth column, the 12th row meets the 12th column, and so on. These tell you how much each particle interacts with *itself*. Self-interactions are a core feature of matrix models. The particles are subatomic narcissists, the physics equivalent of Facebook users who always "Like" their own posts. Their self-interactions have a carefree, unrestrained quality; you can dial their strength up or down without having to pump in energy.

Whereas the workings of quantum graphity are somewhat ad hoc, the laws governing D0-branes are dictated by considerations of symmetry. The mathematical balance of the equations is the organizing principle of this model. Symmetry ensures that the off-diagonal values in the matrix are yoked to the diagonal values—in other words, that the branes' mutual interactions depend on their self-interactions. Particles that self-interact by comparable amounts forge a bond, whereas particles with differing levels of self-interaction remain aloof. Put simply, like attracts like. Consequently, the branes agglomerate into separate clusters like the social circles in your Facebook network. These clusters constitute the ordinary subatomic particles of physics. Each cluster can be compactly described by a few numbers—namely, the strength and quality of its constituents' self-interactions.

That's how space arises in matrix models. The D0-branes don't live or move within space. Mathematically they all sit on top of one another at a single point. But because they're so selective about their interactions, they produce our experience of living within space. What we call "position" is simply the set of numbers that uniquely identifies a given cluster. It's like pigeonholing your friends as "physics lovers," "Radiohead groupies," or "Cuban-style dancers."

That's just the start. You can take all our familiar spatial notions—movement, size, locality—and explain them in terms of brane dynamics. Movement: Things shift their position because the D0-branes' self-interactions are varying. It's like saying the Cuban dancers suddenly all get interested in Dominican music. They "move" as a group to a new passion. Such movement may sound metaphorical, but in matrix models it's the origin of physical movement. Size: The self-interactions of the branes in an object are not exactly equal, but have a slight spread, so that the object spans a range of positions. Locality: Clusters at separate locations are independent because their self-interactions differ, which suppresses their mutual interactions according to the logic of symmetry. This is like saying that Cuban dancers and Radiohead groupies never have much to say to each other. "Things that are 'separated' are not really separated," Susskind explains. "There's just a cancellation of the things that are connecting them."

If all the branes did was reproduce space, that'd be gratifying, but boring. Our goal is to go *beyond* space. Branes can do that. They can behave in ways that are too complicated to represent with a handful of spatial coordinates. For instance, the mutual interactions among clusters are never fully suppressed, because quantum effects keep tickling them back to life. Therefore, spatially separated clusters are not fully independent; they feel the gentle tug of other clusters. This is how matrix models explain the force of gravity. In a sense, the models evoke Newton's picture of gravity as a nonlocal force that leaps from one thing to another. The interactions that produce it aren't transmitted through space, but are direct, unmediated, nonlocal links.

Another departure from spatiality occurs inside clusters. The internal group dynamics are intense and every brane is interacting with every other. The branes scramble one another's self-interactions, and the matrix values representing those interactions lose the qualities of spatial coordinates. Ordinarily, coordinates are independent numbers: You can measure the latitude of a city separately from its longitude. But you can't do that for branes within a cluster. If you measure the latitude of a brane first, then its longitude, you might get a different result than if you measured the longitude, then the latitude. This kind of ordering effect is known mathematically as "noncommutativity." In effect, the particle seems to be located in two different places, like Salt Lake City in my cities example. "The position in, say, the 'x' direction and the position in the 'y' direction can't simultaneously be measured," says Emil Martinec, a string theorist at the University of Chicago. "This is certainly not the behavior we expect for a collection of discrete particles—we expect to be able to localize them precisely in all spatial dimensions." The degree of ambiguity is a measure of just how nonlocal and non-spatial the system is.

Indeed, the cluster doesn't really have an "inside"—there is no volume of space where the D0-branes bustle around. Arguably there aren't even any D0-branes anymore, either, because they surrender their individuality and become assimilated into the collective. If you look at a cluster from the outside, what you see isn't the outer surface of a material thing, but the end of space; and if you poke your hand into the cluster, you will not reach into its interior, for the cluster has no interior. Instead, your hand will become assimilated, too (which can't be good for it). If you wisely refrain from touching the cluster and instead throw particles into it, you will notice that the cluster's storage capacity depends on its area rather than on its interior volume—again, for the simple reason that it doesn't actually have an interior volume. Space has no meaning at this level.

MATRIX MODELS DO HAVE some peculiarities, but they establish a remarkable principle: A bunch of particles obeying quantum physics can organize themselves so that you'd swear they live and move within space, even if space wasn't in the original specification of the system. And it turns out that this principle is very general. Not just a swarm of D0-branes but almost any quantum system contains spatial dimensions folded inside it like a figure in a pop-up book. Most such systems don't bootstrap space from utter spacelessness, as matrix models do, but prime the pump with a low-dimensional space in order to generate a higher-dimensional one.

The AdS/CFT duality is such a system. It starts with a three-dimensional space and generates a nine-dimensional one. One reason string theorists like this scenario so much is that it neatly explains the holographic principle, the idea that the universe can sustain much less complexity than the principle of locality would lead you to expect. The complexity is reduced by just the amount you'd expect if one of the dimensions of space were illusory. In the AdS/CFT scenario, that's because the dimension in question *is* illusory. It can be collapsed down like an accordion because it was never really there. ("Illusory" is perhaps the wrong word. "Derived" or "constructed" would be better, if less poetic. The dimension may not exist at the lowest level, but it is still very real to anything larger than a brane.)

The disposable dimension reflects a particular aspect of order in the underlying quantum system. In fact, the requisite order is familiar to us from everyday life—specifically, the fact that big things and small things live as if in worlds apart. Our planet trundles around its orbit oblivious to human affairs, just as we spare little thought for the bacteria that lodge in our skin. Conversely, we have only a vague awareness of riding on a giant ball of rock, and bacteria know nothing of our daily struggles. Nature is stratified by scale.

Sound waves are an especially simple example of this stratification. Sounds of long and short wavelengths are oblivious to each other; if you sound a deep bass note and a high treble pitch simultaneously, each ripples through the room as though it were the only sound in the world. Their mutual independence is analogous to the autonomy of spatially separated objects. Suppose you play two piano keys, middle C and the adjoining D key. The C key creates a sound wave with a wavelength of 1 meter 32 centimeters, and D produces one with a wavelength 14 centimeters shorter. These waves overlap in the three dimensions of space through which they propagate, yet they're independent of each other, as if they were located in different places. In a sense, you can think of the sound waves as residing 14 centimeters apart within a fourth spatial dimension.

The farther apart the keys are on a piano keyboard, the farther apart they are within this imaginary dimension; a given distance along the keyboard translates into a given distance within the dimension. You don't see this dimension as such; to you, it's an abstraction that captures the acoustical independence of sound waves. But it's a remarkably fitting abstraction. Musicians call the difference between pitches a musical "interval," which has connotations of distance, as if our brains really do think of the differences between pitches as spatial separation. AdS/CFT duality takes this abstraction literally and suggests that one of the dimensions of the space we occupy represents the energy or, equivalently, the size of waves within the underlying system.

Raman Sundrum, a particle theorist at the University of Maryland, has a dramatic way of putting it. (In fact, it's so dramatic that you'd be tempted to dismiss it as fanciful if it weren't backed up by rigorous mathematics.) Suppose you're an artist painting the National Mall, with an ice-cream stand in the foreground and the Washington Monument in the background. To evoke a sense of distance on the flat canvas, you draw these two objects at different scales. Something like that is happening for real in the AdS/CFT scenario. The universe looks three-dimensional, but could really be a two-dimensional canvas, and what we perceive as distance along the third dimension is ultimately a difference in scale. "The depth dimension could be recreated in the way that artists have to do it: by just drawing the Washington Monument really small and drawing something in the foreground really big," Sundrum says. A faraway object is actually sitting right next to you; it looks small because it really *is* small. You can't touch it not because it's distant but because it's so tiny that your fingers lack the finesse to manipulate it. When things grow or shrink, we perceive that as movement toward or away from us.

Things of different sizes aren't strictly independent; they interact with things of comparable size, and the effects can cascade from one scale to the next. Consider the proverb of the nail: For want of a nail, the shoe was lost; for want of a shoe, the horse was lost; then the knight, the battle, and the kingdom. A nail shortage in a single blacksmith shop didn't immediately cause the monarch's downfall; it exerted its influence indirectly, via systems of intermediate scales. Sound waves of different pitches can also behave like this. A Chinese gong begins rumbling at a low pitch and gradually vibrates at successively higher pitches. The necessity of propagating through scale explains why spatial locality holds in the emergent dimension. What happens in one place doesn't jump to another without passing through the points in between.

It's not automatic that the underlying quantum system would possess this kind of hierarchical order. Just as a painting must be composed in just the right way to produce the sense of depth, so must the system have a certain degree of internal coherence to give rise to space. What ensures this cohesion is entanglement among the system's particles or fields. To produce space as we know it, those particles or fields must be entangled by scale: each particle with its neighbor, each pair of particles with another pair, each group with another group. Other patterns lead to different geometries or systems that can't be thought of as spatial at all. If the system is less than fully entangled, then the emergent space is disjointed, and an inhabitant of the universe would be trapped inside one region, unable to venture elsewhere. "Quantum entanglement is the thing that is responsible for connecting up the spacetime into one piece," says Mark Van Raamsdonk, a theorist at the University of British Columbia. When we first encountered entanglement, it seemed to transcend space. Today, physicists think it might be what *creates* space.

IT'S ASTOUNDING TO THINK that space, thought for so long to be the rock-bottom foundation of physical reality, could perch atop an even deeper layer. Ironically, the main criticism I hear of quantum graphity, matrix models, and AdS/CFT isn't that they're too weird, but that they're not weird enough. All these models still work within the basic framework of quantum physics and general relativity, and much of the structure that is supposed to arise spontaneously is actually preprogrammed into the rules.

Notably, these models presuppose time; they don't incorporate Leibniz's and Mach's suggestion that time should emerge as surely as space does. Some researchers don't see this as a failing, but as a profound truth about nature—that time must be fundamental even if space isn't. After all, physics does need to have *some* foundational structure, something that everything else is built on, and time is as good a candidate as any. Indeed, how could you even talk about emergence as a temporal process if you don't presume time? "As soon as you say time is emergent, you run off the rails," Martinec says. "What are the rules? What do I do?" The Caltech physicist Sean Carroll has put it succinctly: "Space is totally overrated, whereas time is underappreciated … I think that time is going to last … Space, on the other hand—totally bogus. Space is just an approximation that we find useful in certain circumstances."

Yet this separation of time and space runs counter to Einstein's great insight that the two are fundamentally inseparable. If one is emergent, surely the other must be. Many physicists do think that time emerges and have been looking for ways to think of emergence without presupposing time. The key is the existence of a boundary. If the universe has a boundary located out in deep space, the emergent dimension is spatial, but if it has a boundary in the past or future, the emergent dimension is temporal. In fact, as far as astronomers can tell, our universe has temporal rather than spatial boundaries. In the past, there's the big bang; in the future, eternally accelerating expansion, which also serves as a type of boundary. An observer sitting on that boundary in the distant past or far future would know all there is to know about the intervening moments. Yesterday, today, and tomorrow would collapse into one.

By this logic, theories that presume time are still incomplete, merely stepping stones to a complete account of how space and time emerge from deeper physics. Theorists will need an even more radical approach.

GEORGE MUSSER is a writer on physics and cosmology and the author of *The Complete Idiot's Guide to String Theory* and *Spooky Action at a Distance*. He was a senior editor at *Scientific American* for 14 years and has won the American Institute of Physics Science Writing Award, among others.

ILLUSTRATION BY **REBECCA MOCK**

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TRY IMAGINING A UNIVERSE without color, or time. Unusual, but possible to visualize. Now try imagining a universe without space. What does it look like? Just a dot? No—even a dot is a kind of space.

Without space, we seem not to be able to start. But some physicists say space doesn't really exist.

We organize our memories spatially, too, moving through them as we do the rooms of a house. Losing our sense of space can stop our thinking in its tracks. We see evidence of that in solitary confinement, and in certain brain disorders.

Space is a quiet subtext, until we lose it. Then, there's little room to think about much else.

Welcome to "Space."

—MS

"We are descendants of explorers. We're going to change. We're going to make the future different from the past."

DAVID BRIN
"2015 Was the Best Year Ever in Space" p.52

Space

EVERY WHERE

These Tricks Make Virtual Reality Feel Real

Realistic digital spaces need delusions as much as they need detail

BY TOM VANDERBILT

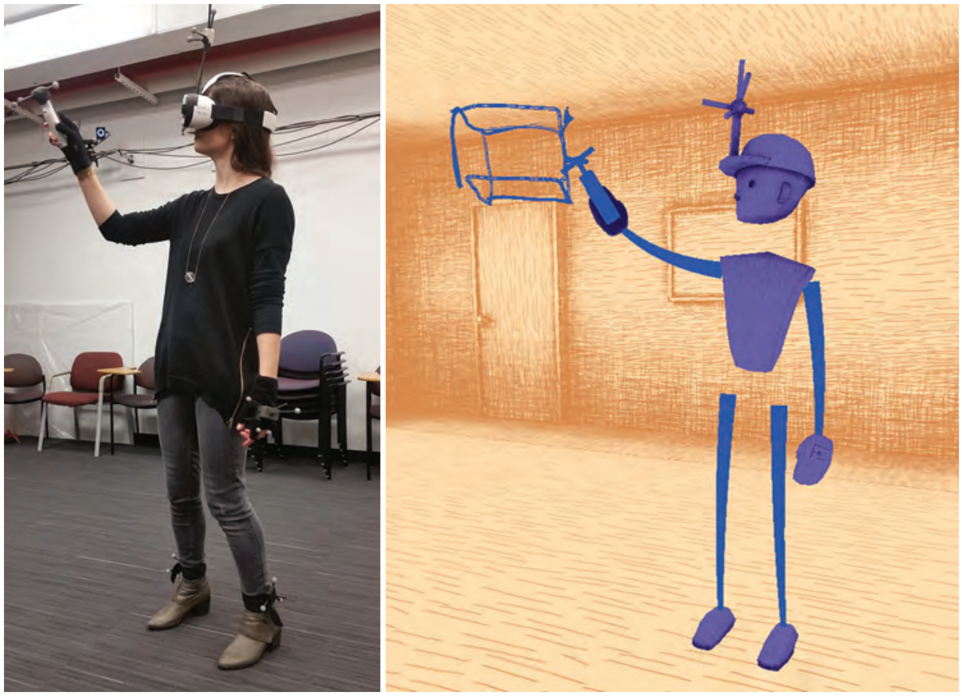
I **AM STANDING A FEW FEET AWAY** from a conference table, about to test something called a "Holojam." It is made of head-mounted displays, motion capture cameras and many lines of code. Affixed to the edges of the table, as well as to my hands and ankles, are little plastic balls, which are used to track things in the virtual environment. Like QR codes, they help the software interpret the table as a table.

Ken Perlin, who directs the Media Research Lab at New York University, describes it to me as the "first community-created collaborative 4-D spacetime sculpture." Then he flips the switch. The space I am standing in is a kind of forest clearing at night, with a bright moon illuminating tall trees. As I move my head, the view subtly warps. "To give you freedom of movement," he says, "we had to make everything more cartooney. The moon and the trees are like billboards, not 3-D. We decided it was more important to have immediacy and presence than high fidelity."

But isn't fidelity what makes a virtual reality feel real? I want wind to whistle past as I walk in full Doppler splendor. Sunlight should gently dapple on the grainy surface of a wood table, and objects should possess the heft and feel that they really do. Many in the field buy into this kind of supremacy of detail. Others, though, believe it's a fetishization that obscures how effective virtual reality isn't just about verisimilitude. As with the way we experience reality itself, it's also about the way we lie to ourselves.

PERLIN KNOWS ABOUT the verisimilitude angle. Early in his career, he worked on the movie *Tron*, now known for its seminal use of computer-generated animation. Dissatisfied with the digital sterility of visual effects, he began investigating ways to create "controlled random processes," which led to more realistic depictions of

ILLUSTRATION BY KARAN SINGH



UNLIKELY AVATAR
Ken Perlin's Holojam virtual reality system lets users interact with each other through cartoon-ish avatars.

things like smoke and fire. Today his influential textural effect is called "Perlin noise."

But Perlin is skeptical of the merits of an indefinite push toward more visual detail. While the emphasis in commercial and gaming virtual reality has been on boosting graphical resolution, there is not necessarily a one-to-one correlation between pixel density and realism. "People who are myopic," says Perlin, "don't think they're living in a fantasy world." The human foveal region itself, says Perlin, maxes out at around 60 pixels per linear degree—smaller than that, he says, "and you're falling between the cells." The mistake of many recent computer games, Perlin argues, is to confuse realism with believability.

This, in essence, describes what many academic researchers see as the current, game-driven state of virtual reality. "It's never going to be real, any more than a movie is real," Perlin argues. Evan Suma, a research assistant professor at the University of Southern California's Institute for Creative Technologies (Palmer Luckey, the founder of Oculus, is an alum), says he worries that virtual reality, once the novelty has subsided, may reach a plateau; because, as he says, most of the experiences being created, while graphically sophisticated, are "couch-locked." "A lot of the magic for me is lost when you're just sitting down and moving."

When we walk, by contrast, we get more spatial cues from the environment, and we are able to pay more attention: It's a cognitively richer experience. Research shows, for example, that children who walk to school can create more robust maps of their routes than those who are driven.[1] "Much of our sense of reality has to do with proprioception," Perlin argues. "Even if my hand were invisible," he says, reaching for a pen on the table, "I would have no problem picking this up, thanks to that notion of body sense, of balance, of the sensation at the bottom of the feet." To know space is to move one's self through space.

It is now easy enough, using motion capture, treadmills, and other technologies, to create canned versions of walk-through virtual environments. But how,

PHOTOGRAPHY: SEBASTIAN HERSCHER
HOLOJAM ARTWORK: DAVID LOBSER

absent creating some sprawling, Borgesian one-to-one mapping of the actual world, do you create a virtual space that can be realistically walked through and yet is many times larger than one's living room?

You delude yourself, of course. Scientists are exploiting the natural inaccuracies in people's own proprioception, via a technique called "redirected walking," to create the perception of space where none exists. Frank Steinicke, a professor of Human-Computer Interaction at the Department of Informatics at the University of Hamburg, is one of its pioneers (he is also recognized, unofficially at least, to have spent the most time of anyone on the planet—24 hours, with short breaks—in an immersive environment, wearing an Oculus Rift head-mounted display). With redirected walking, Steinicke tells me, users can sense they are exploring the twisting byways of a virtual city when in reality they are simply walking in circles inside a lab.

Without getting feedback on our heading, Steinicke says, in most cases we begin to drift, even retracing our path, after as little as a few dozen meters. The phenomenon has been noted in people who wander endlessly lost in the forest or deserts—particularly when the sun is not visible—even as they hardly cover any ground at all.[2] In an experiment in which people were blindfolded and left to wander for 50 minutes, they began walking in surprisingly small circles of less than 20 meters in diameter. Virtual environments themselves present a kind of perceptual distortion: For "reasons that are not really known," says Steinicke, even when virtual spaces are modeled one-to-one with real environments, subjects routinely underestimate distance.

Redirected walking goes one step further, exploiting a discrepancy that arises as we walk and rotate our gaze: We can confuse the field of "optic flow" that comes our way as corresponding to a curved path, even when walking straight. In experiments, subjects immersed into a virtual world did not notice when their physical 90-degree turn translated into just an 80-degree turn in virtual space. Compression also went unnoticed in forward walking speeds, distance covered, and path curvature. By stacking various kinds of misdirection, an infinite virtual space can be mapped onto a confined real space. We could walk through an infinite kingdom in our living room.

As with the way we experience reality itself, VR is also about the way we lie to ourselves.

THE PERCEPTUAL SLEIGHT OF HAND, which comes largely due to vision's outsize role in our perceptual array, can be applied to more than just walking. As Suma notes, even hand motions can be redirected, through what he calls "haptic retargeting." By "warping" the virtual environment—or the sense of one's virtual body in it—researchers have been able to decouple what a subject's hand seems to be doing from what it is really doing by, again, playing on our visual dominance.

He describes a "fun demo"—dubbed the "one for three illusion"—in which a user is instructed to pick up and stack cubes in a virtual environment. Users are first shown three real cubes on a table. As they don a virtual reality headset, two of the real cubes are taken away—though three cubes still exist in virtual space. As users reach for one of the now-illusory cubes, a subtle visual warping causes them to correct their hand trajectory in the real world, so that they reach toward the one remaining real cube. "You don't ever realize that you're only ever touching one object," says Suma. Users, Suma and his colleagues reported, found the task "repetitive"—until they took off the headsets and saw what was really happening.

Not only can researchers create inconsistencies between virtual and real spaces, they can make the virtual spaces themselves impossible. Suma has created two seemingly separate virtual rooms that somehow occupy the same space, and are larger on the inside than they appear from the outside—not unlike Dr. Who's Tardis. He has found, in experiments, that subjects only begin to notice violation of the rules of Euclidean space at high levels of overlap. "They don't exist in the real world," he says of his impossible spaces. "There's no reason why our perceptual system should have developed a sensitivity to this."

On the other hand, there are visual cues that can't be messed with. We've evolved to pay close attention to cues like the horizon line, because they help us orient ourselves. Even very subtle manipulations of a visible horizon line or a stable view of a ground plane—essential for proprioception—cause people to get unstable. "If you can't get it exactly right" in virtual reality, Suma says, "you're better off hiding it."

But there would not have been a selective pressure to detect non-Euclidean angles or warped spaces. By aiming at these soft targets in our visual system, scientists can trick us into believing we're in some pretty remarkable spaces. The real key to this make-believe, though, may be in letting one person trick another.

BACK IN HIS CONFERENCE ROOM, Perlin suddenly slips on his own head-mounted display, and he—or, rather, a large, bright, animated figure that looks like some failed entry for an Olympic mascot competition—appears across the clearing from me. He waves his hand, tracing a line that seems to hang in the air. And then, with eyes no more lifelike than a snowman's two pieces of coal, he looks at me.

This is a curiously powerful moment. Locking eyes with the simple avatar unleashes that warm, almost familiar prickling of human connection. *What do you want from me? What can I do for you?* Just the fact that someone else is in the virtual environment underscores the sense of "social presence," as media scholar Carrie Heeter has called it. "If other people are in the virtual world, that is more evidence that the world exists."[3] The act of recognition inside a shared space validates both your existence and the existence of the space. A lack of recognition denies those things, not unlike the Hollywood trope in which a person, who has not yet learned he is a ghost, tries in vain to get other people's attention.

We are social mimickers. When we see our peers accepting the reality of an environment, we are encouraged to accept it too. Our behavior in virtual space is no different. While much of the current energy in virtual reality research is channeled into getting things to look real as possible, Perlin suggests that even with heightened visual verisimilitude, virtual reality will still feel solitary unless a compelling social presence is achieved. "The holodeck," says Perlin, "is other people."

We even take the form of our avatars as a social cue, reverting to real-world human dynamics quickly in virtual environments. In the so-called "Proteus Effect," people begin to quickly adopt the subtle psychological dynamics associated with their particular avatars. As a Stanford University study noted, "Participants who

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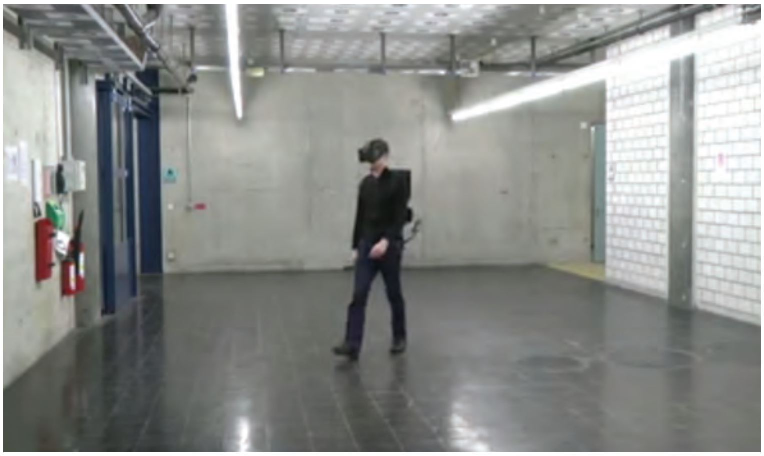


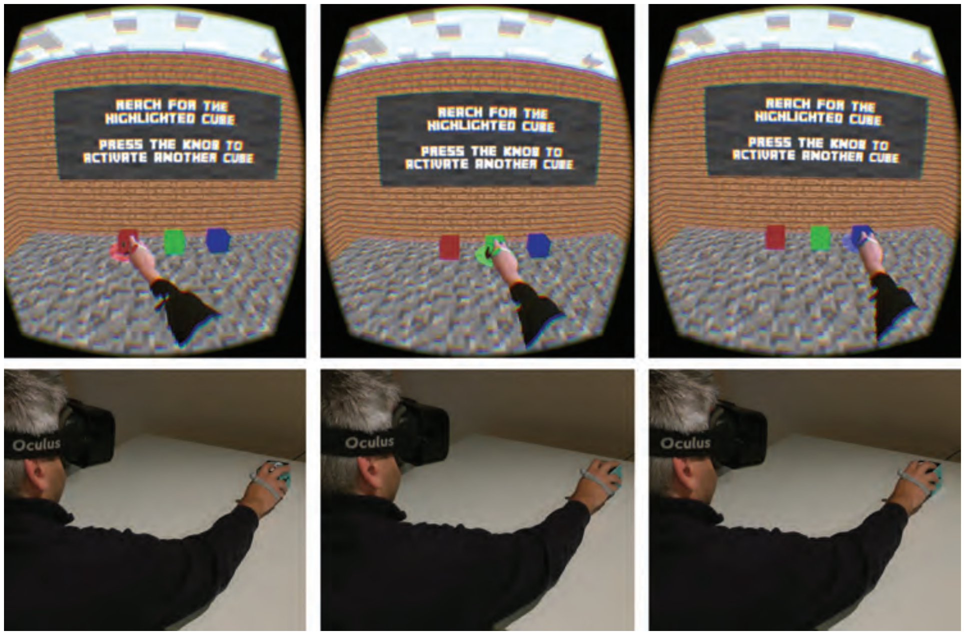
CURVED AS AN ARROW

A subject following a curved path in real space can be convinced that he is walking straight in virtual reality.

We could walk through an infinite kingdom in our living room.

WATCH CAREFULLY

Users wearing a virtual reality headset can be made to believe they are manipulating three real-space blocks, when in fact there is only one.[8]



had more attractive avatars exhibited increased self-disclosure and were more willing to approach opposite-gendered strangers after less than 1 minute of exposure to their altered avatar."[4] As William Bricken argued, "psychology is the physics of virtual reality."[5]

It should be little surprise that I was arrested by Perlin's cartoon eyes: Eye contact is one of our most potent non-verbal communication forms, in the real world or not. What some have found in virtual worlds, however, is that eye contact per se is less important than head movement—which can also signal acknowledgement and intentionality. When Perlin first began to set up the Holojam, a few years ago, his cartoonish characters had no faces, just square boxes atop bodies. "One person shrugged," says Perlin. "Even though you couldn't see the shoulders, you could only see this box, you knew it was a shrug because we only move our head like that when we shrug."

Did Perlin look realistic to me? No. But faced with the problems of the "uncanny valley," maybe a cartoon is better: It stops us from thinking about whether something is real and just lets us feel that it is. The cognitive scientist Mel Slater defines the "plausibility illusion" in virtual reality as the sense "that what is apparently happening is really happening (even though you know for sure it is not)."[6] We can become invested even in blocky, 1980s-arcade representations of people. Slater conducted a set of experiments in which a low-fidelity virtual character was "shocked" while people watched. As the shocks to the hapless avatar grew in intensity, the onlookers grew increasingly anxious. "Bugs Bunny is not realistic," Perlin says, "but believable."

Perlin's Holojam environment—which is currently rendered off of a smartphone to be mobile—is only bound to get more realistic, graphically, as head-mounted display technology and processing power continues to improve. And when high-quality untethered body tracking—he says there's "currently no commercial market"—arrives, virtual reality can begin to become a social space. "By allowing people to walk around," as opposed to what he calls the "*Wall-E* model," he argues that "we can get to the important questions: What's going to be the impact on people when they interact with each other in a world that's been transformed?"

It may very well transform the unreal into the real.

WE SHOULDN'T BE TOO SURPRISED that realism will be one of the first qualities to be discarded as we make virtual space more realistic. After all, we do it in the actual (real) world all the time. Casino entrances use curved paths so people don't slow to make perpendicular turns, drawing gamblers "further into the 'mousetrap,' " as described in anthropologist Natascha Dow Schüll's book *Addiction by Design*. So-called casino "atmospherics" like background music, meanwhile, are carefully modulated to sit just below the threshold of consciousness—to do otherwise, one industry expert quoted by Schüll notes, "restores ... your cognitive state to where you can make rational decisions." The whole effort, as one casino designer describes it, is to create for gamblers a "different plane on which they lose their sense of reality."

There are even slivers of virtual reality creeping in. Devices like slot machines have been made more immersive with virtual reels, liberating them from physical laws of probability and putting players under the illusion that they can win more often than they actually can.

Retail experiences can also be designed to confuse. Alan Penn of University College London has described the meandering pathway through an Ikea store as intentionally confusing: "As you move through the showroom you rapidly become dissociated from everyday life—all views of the external world are obscured and even one's sense of direction is removed by the twists and turns of the route. At the same time you are shown stage set glimpses of what your life might be like. The effect is more or less subliminal."[7]

So while Steinicke, Perlin, and Suma are operating on digital photons, and retail and gambling designers are not, there is a point of intersection in their work: Whatever space we find ourselves in requires our active interpretation, and allows for somebody else's active obfuscation. It wouldn't feel real without it.

TOM VANDERBILT writes on design, technology, science, and culture, among other subjects.

REFERENCES

1. A. Rissotto, A. & Tonucci, F. Freedom of movement and environmental knowledge in elementary school children. *Journal of Environmental Psychology* **22**, 65-77 (2002).

2. Souman, J.L., Frissen, I., Sreenivasa, M.N., & Ernst, M.O. Walking straight into circles. *Current Biology* **19**, 1538-1542 (2009).

3. Heeter, C. "Being There: The Subjective Experience of Presence" MIT Press (1992).

4. Yee, N. & Bailenson, J. The Proteus Effect: The effect on transformed self-representation on behavior. *Human Communication Research* **33**, 271-290 (2007).

5. Markley, R., ed. *Virtual Realities and Their Discontents* Johns Hopkins University Press, Baltimore, MD (1996).

6. Slater, M. Place illusion and plausibility can lead to realistic behavior in immersive virtual environments. *Philosophical Transactions B* **364**, 35-49 (2009).

7. Penn, A. The complexity of the elementary interface: shopping space. Proceedings, 5th International Space Syntax Symposium, Delft, Holland (2005).

8. Azmandian, M., Hancock, M., Benko, H., Ofek, E. & Wilson, A. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. To appear in *Proceedings of the ACM Conference on Human Factors in Computing Systems* (2016).

2015 Was the Best Year Ever in Space

The romance is back, argues a NASA adviser and best-selling science-fiction author

BY DAVID BRIN

WITH 2015 NOW BEHIND US, what truly stands out? Other than (alas) holding the record for hottest year in recorded history? Amid a confusion of good, bad, and disturbing news, what I find noteworthy is that 2015 was by far humanity's best year in space—exploring the universe around us.

Almost weekly, stunning milestones came flowing from our faithful robotic probes. In just one year we learned so much about Mercury, Venus, and Earth. *Especially* Earth where, after unforgivable delays, a wave of scientific satellites like the Orbiting Carbon Observatory are finally nailing down valuable proof of what's happening to our homeworld-oasis. One of our little emissaries orbited and mapped the dwarf planet Ceres, with its weird white spots and possible underground lakes.

Five Mars orbiters have shown us evidence for what happened to that world's once-rich atmosphere, helping to adjust our ever-improving climate models. They revealed that liquid water still occasionally flows across its surface, as recently as this year. As if that weren't plenty, at one point those same orbiters swung about to study a *comet* swooping past the Red Planet, much closer than the distance between us and our moon!

Don't leave out our stalwart rovers on the surface, Curiosity and Opportunity, chugging along on our behalf, climbing mountains and sifting clues about Martian history going back to when seas rolled across

HELLO, PLUTO It took the New Horizons space probe nine and a half years to get there, but the trip was worth every minute. Detailed, data-rich snapshots of the dwarf planet and its fascinating moons were acquired amid feats of teamwork and skill that were virtually flawless.

NASA

its surface—indicating where some of those waters may still be hiding.

Moving outward, plans were announced for a mission to study the ice-covered seas of Europa and—longer-range—to send submarines diving through methane seas along the waxy shores of Titan. This year, the Cassini spacecraft skimmed close by Saturn's moon, Enceladus, penetrating plumes from a water volcano and sampling for organic chemicals.

Oh, but don't neglect the grand achievements of our friends at the European Space Agency, for example, *landing on a comet*! We learned plenty about how these bodies may transform into asteroids that bold entrepreneurs may plumb for resources. Meanwhile, Japan's JAXA finally delivered their unlucky Akatsuki probe into orbit around Venus on Dec. 7. Good for you!

Of course, the capper was New Horizons—launched from Earth so long ago it almost seems another millennium, but finally this year swooping past Pluto. In almost stygian darkness, the New Horizons cameras revealed images of such color and beauty and scientific fascination that even cynics were enthralled. Detailed, data-rich snapshots of the dwarf planet, with its fascinating moon—Charon—and several others, all acquired amid feats of teamwork and skill that had to be (and were) virtually flawless.

Then know that they did it all so smoothly and well that—with the resulting copious fuel reserves—NASA will now send New Horizons 1 billion miles farther, to study an even weirder object in the Kuiper Belt. Hey, that's darn near interstellar.

Amid all of this, is it worth mentioning that the Hubble Space Telescope and its dozen or so partner craft advance astronomy by leaps, every year? As we map nearby clumps of dark matter, these clumps bend space and focus light from the most distant portions of the universe, revealing much about its earliest days. Progress toward newer, far better orbiting observatories proceeds apace, like a complex system to detect and decipher gravitational waves. The first test-bed for that technology launched in 2015.

On another important front, despite setbacks, the entrepreneurs aiming to improve our access to Earth-orbit have pushed ahead, with Jeff Bezos's Blue Origin sending a rocket to the fringes of space then returning it to land on its tail, re-usable, on the original pad. Not to be one-upped, Elon Musk's SpaceX stuck a much more difficult return to launch-site landing on Dec. 21, the winter solstice, opening the way to far-cheaper access to the great beyond.

Oh, yes, this is the year that both Planetary Resources and Deep Space Industries committed their plans to work with NASA, seeking and developing valuable minerals (especially water) from asteroids. Just one asteroid of the right kind (if it can be solar melted and smelted in orbit) might provide a sizable fraction of all our planetary economy's need for metals, allowing us to steeply reduce digging into our mother world's flesh.

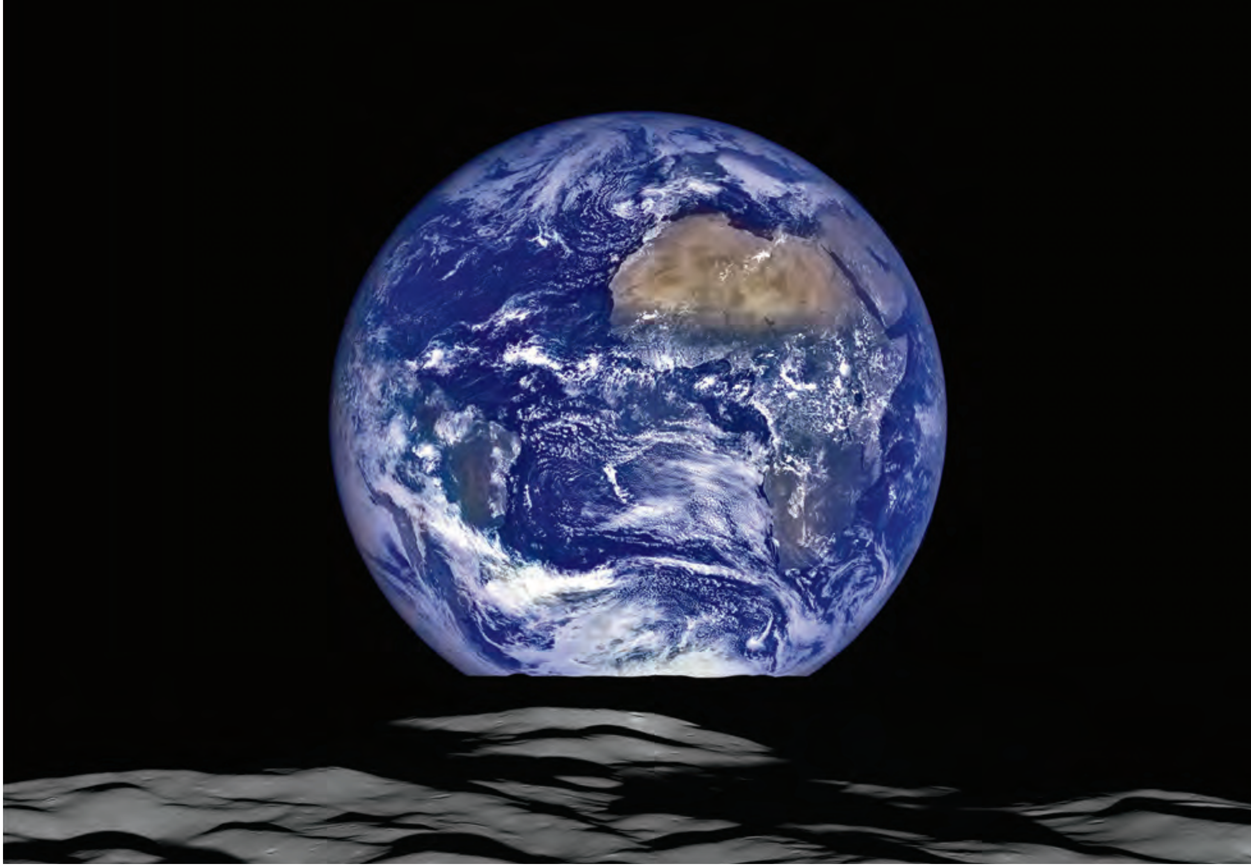
Calling attention to our space accomplishments in 2015 draws notice to how stunningly effective our hero engineers and space-robot designers have to be, in order to accomplish all these miracles. Tiny errors—on the order of one ten-thousandth of a percent—would have aimed the New Horizons cameras at empty space, instead of snapping perfect images of a dimly lit world, hurtling by far faster than a bullet. Which provokes the question we've asked since the space program began:

"If we can do all those things, can't we solve other problems, as well?"

It may be out of fashion in this era of reflexive, self-indulgent cynicism, but there's something to be said

FALCON 9 STICKS THE LANDING In December, SpaceX orchestrated a soft landing of its rocket, Falcon 9, in Cape Canaveral, the first time a booster rocket has returned successfully to Earth.

ANADOLU AGENCY



OVER THE MOON This image of Earth, taken by NASA's Lunar Reconnaissance Orbiter as it passed above a lunar crater, represents the kind of art that changes us, David Brin writes, "transforming hearts and minds."

NASA

for the can-do spirit. The notion that "we can solve things!" How else do you explain the spectacular popularity of Andy Weir's novel *The Martian* and the subsequent Matt Damon film? Indeed, after decades of flicks that emphasize heroes operating on pure, emotional guts and "instinct," hunger may be erupting for a different kind of story. One reviewer assessed the joy that some derive from Weir's book as "competence porn."

Yes! Now do something else competent. Yes.

SPACE ULTIMATELY HAS NOTHING to do with our insipid political metaphors like *left* and *right*. It is about becoming the kind of people we want to be. The kind of people who explore, who look outward, who think that tomorrow can be different. That tomorrow can be better. The kinds of people who will deserve to go out into space.

We are descendants of explorers. Of Enlightenment philosophers who broke with 4,000 years of pyramidal feudal-oligarchies, to say: We're going to change. We're going to make the future different than the past.

Our scientific program to explore the cosmos has produced the most important works of visual art in history. Let me dare to define "effective visual art" as some work or representation that subtly changes human beings just by the sight of it, transforming hearts and minds without verbal or logical persuasion. And by that reckoning, the 20th century featured two hugely effective works of visual art, both of them gifts of physical science!

First, the terrifying image of the atom bomb altered forever our little-boy romantic attachment to war, beckoning us instead to grow up a bit in dealing with this new and awesome power to destroy. Defense became the business of serious grownups. Even (especially) among soldiers, war itself is now seen

Space ultimately is about becoming the kind of people we want to be. The kind of people who explore, who look outward.

as evidence of failure—an urgent and risky measure arising out of inadequate diplomacy, preparation, or deterrence. Sure, there were logical reasons to make that shift. But art helped it along. The image of that mushroom cloud seared us. It persuaded, without pallid words.

Ah, but then there was the second image that changed us, deeply and forever. That great and transforming work of art was a gift that arrived at the very end of one of the most difficult years any of us can remember—1968—12 crazed and frenetic months that brought most Americans—and most of the world—to the brink of exhaustion and despair. Yes, great music washed over us in a veritable tsunami, as did tragedies, war, invasions, assassinations, riots, betrayals, and fed-up demands for transformation.

Only then, at the very end of that awful year, a final token arrived—like a gleam of hope shining at the bottom of Pandora's box—when the Apollo 8 astronauts brought home that first perfect image of the Earth, floating as a blue marble in the vast desert of space. A picture that moved all but the most cynical hearts and changed forever our outlook toward this fragile oasis world.

This image—an artwork created by humanity's curiosity, boldness, and ambition, and the chaste innocent truthfulness of science—transformed us more than anything else. Perhaps making us better, more responsible citizens, and world-managers.

Only now that image has been surpassed in beauty. Even more gorgeous in contrast is the composite image that NASA released on Dec. 19, taken by the Lunar Reconnaissance Orbiter, as it passed about 83 miles above a lunar crater.

I have long wondered when we'll see another image that so effectively rocks our complacency, convincing us to change. Might it be a sharp spike on a screen of the Search for Extraterrestrial Intelligence? The appealing face of a robot who has become self-aware? Or perhaps a transformed ape, or dolphin, looking us in the eye and demanding respect?

This year, watching marvel after marvel unfold before us—transmitted by stunningly competent probes and paid for by mere pennies from the average citizen—I realized: It may never again be a single image. With so many things going on at once—dreadful things, hopeful things, and a tsunami of wonders—we must learn to open our hearts and minds to *let it all in*. Neither wallowing in pessimism nor fizzing with uncritical optimism, but accepting the real lesson. That we can be ambitious and solve problems. We can do.

We can follow many roads, toward helping each other, toward saving our birth-world, and up into the sky. Only by doing it *all* can we grow increasingly worthy, until that day comes when our children's children leave cheap, indignant cynicism forever behind, confidently eager to say:

"Let's go!"

DAVID BRIN is an astrophysicist who serves on the advisory council of NASA's Innovative and Advanced Concepts group. His international best-selling novels include *The Postman*, *Earth*, and recently *Existence*. His nonfiction book about the information age, *The Transparent Society*, won the Freedom of Speech Award of the American Library Association.

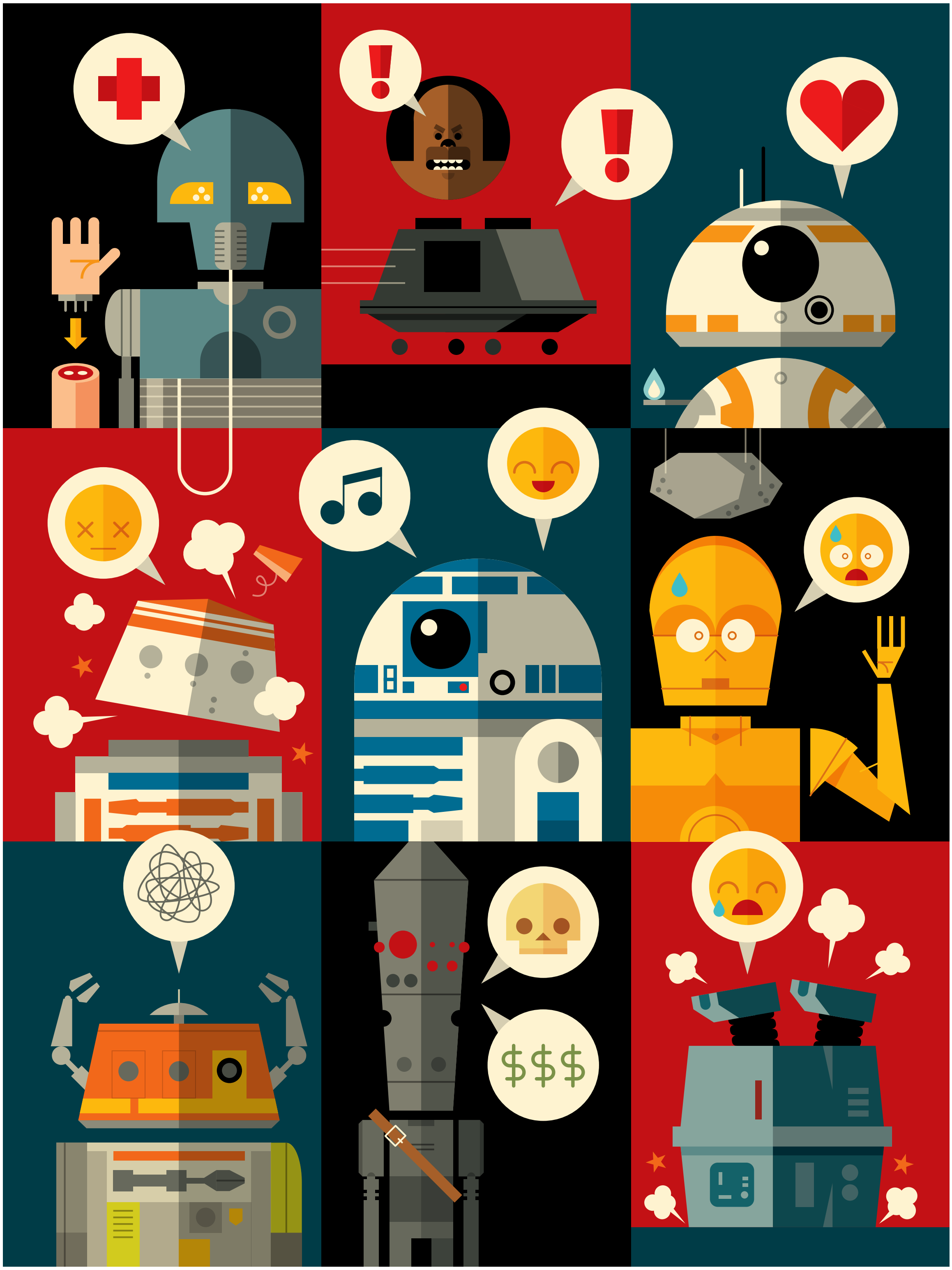


ILLUSTRATION BY **MARTIN GEE**

How to Survive Solitary Confinement

An ex-con on how to set your mind free

BY SUSIE NEILSON

W**ITH A SIGH, JOHNNY PEREZ** rises from his plastic chair, unfolds his lanky frame and extends his wingspan until the tips of his middle fingers graze the walls. "It was from here to here," he says. "I know because I used to do this all the time." Until recently, these measurements—10 feet by 6 feet—fit his entire life.

Two years ago, Perez was released on parole after serving 13 years at Rikers Island penitentiary, three of which he spent in solitary confinement. Sitting across from Perez, you wonder how he feels in this space, a tiny, harshly lit conference room at the Urban Justice Center on Wall Street in Manhattan. Whether it brings back traumatic memories, or feels like home, or both.

While there is no universally agreed-upon definition, modern solitary—also called supermax, isolated segregation, and "the box"—is commonly understood to involve confinement to a small cell for 22 to 24 hours a day. Prisoners are not allowed to participate in leisure activities, have hobbies, or speak to others. They are often handcuffed and shackled when they leave their cells—if they ever leave. Perez says he eventually stopped even wanting to.

Solitary confinement has been linked to a variety of profoundly negative psychological outcomes, including suicidal tendencies and spatial and cognitive distortions. Confinement-induced stress can shrink parts of the brain, including the hippocampus, which is responsible for memory, spatial orientation, and control of emotions. In addition to these measurable effects, prisoners often report bizarre and disturbing subjective experiences after they leave supermax. Some say the world regularly collapses in on itself. Others report they are unable to lead ordinary conversations, or think clearly for any length of time. The psychologist Sandra Schank puts it this way: "It's a standard psychiatric concept, if you put people in isolation, they will go insane."

Yet Perez pauses when he is asked how it felt to be

ILLUSTRATION BY JACKIE FERRENTINO

confined for so long. "That's an interesting question," he says. "Because in a sense, you are confined, and in other senses, you're free." Perez says he left solitary confinement a better man than he entered it. He is now fully rehabilitated, and works for the Urban Justice Center, where he helps recently released inmates adjust to the world outside.

Perez calls himself an "anomaly," and says he can only guess at the factors that made him succeed where so many others have failed. However he did it, what's clear is that the process began with his own imagination.

AT THE END of this short paragraph, stop reading. Close your eyes. Imagine yourself hitting a tennis ball. Do it again.

Can you see yourself hitting the ball? Can you visualize its arc through the sky? Does it veer off course, and can you imagine yourself hitting it better next time?

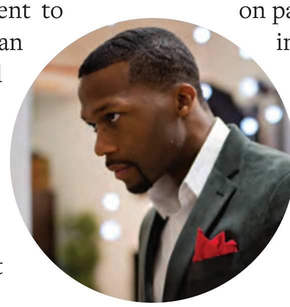
If so, you are using a technique that has helped many people survive prison. Edith Bone, a professor of medicine and a translator who spoke six languages fluently, constructed an abacus out of stale bread and made an inventory of her sprawling vocabulary while imprisoned in Hungary after World War II. Hussain Al-Shahristani, Saddam Hussein's former chief scientific adviser, spent a decade in solitary confinement at the Abu Ghraib prison near Baghdad. He survived, according to the BBC, by "taking refuge in a world of abstractions, making up mathematical problems, which he then tried to solve." He is now Iraq's minister of higher education and scientific research. While imprisoned in a German concentration camp during World War II, the Russian Jewish mathematics professor Jakow Trachtenberg watched as his fellow prisoners "gave up hope and died even before being sent to their death." To survive, he developed an innovative method of performing rapid mental calculation, known today as the Trachtenberg system.

Summoning up mental imagery is a "quasi-perceptual experience," according to the Concise Corsini Encyclopedia of Psychology and Behavioral Sciences. It stimulates the brain's frontal lobe, which is associated with higher cognitive processes and abstract thought—as well as perception and motor control. That can make it feel real. "Cognitive operations performed on images, such as mental scanning or distance comparisons, exhibit ... patterns similar to those executed on images that reactivate stored visual information," says Emmanuel Mallet, a cognitive neuroscientist at the French National Centre for Scientific Research.

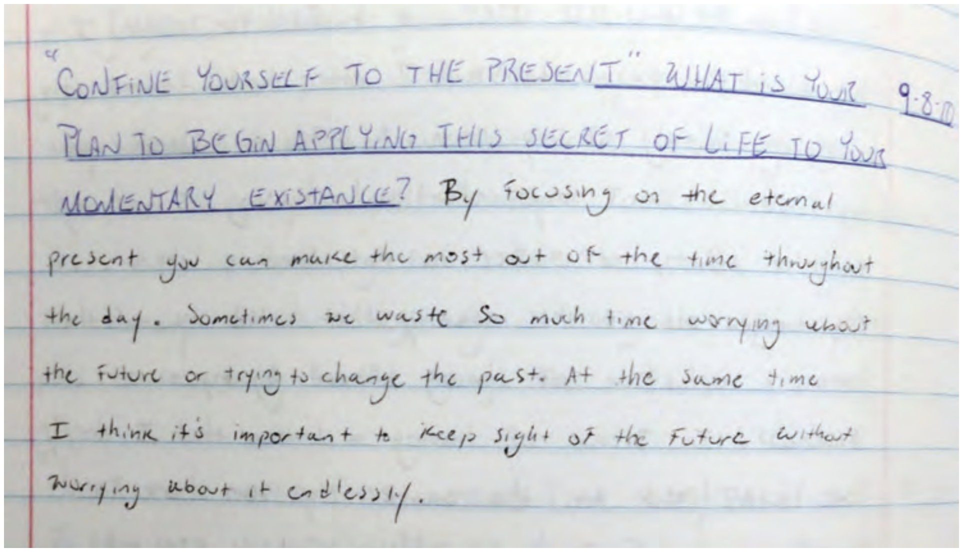
As a result, mental imagery is an ideal portable training tool. Just imagine yourself kicking the ball or delivering the punchline, and you'll have better control over how your foot swings or your voice projects. In one study, running an imaginary course activated muscle patterns in the legs of skiers akin to when they were skiing. The phenomenon, known as the Carpenter effect, has also been seen in studies of tennis and volleyball teams. Athletes with closed eyes swaying through an imaginary course have become a common sight in the starting areas of ski races and bobsled tracks.

Mental imagery can supplement perceptual input—but it can be equally useful when perceptual input is painful, tedious, or lacking. A prisoner in supermax can use mental imagery to create the space and time that confinement strips away. While he was in "the box," Perez talked to himself out loud. He kept journals. For a while, he regularly wrote out and responded to famous historical quotes.

He also used his imagination to time travel, imagining "alternate endings to past interactions with people—what if I said this? Or what if I would've invited her for coffee or something like that?" He wrote about painful relationships and episodes, reframing them and extracting a lesson. Memory is both constructive and reproductive, says Alex Schlegel, a cognitive neuroscientist at the University of California, Santa Barbara. In fact, imagination and memory run on parallel tracks in the brain. By engaging the imagination, Perez was able to "rewrite" his past in a more positive light, and reframe



JOHNNY PEREZ Clothes are near and dear to his heart, says Perez, because for years he was told what to wear. "Nowadays I am very intentional as to what I wear."


"CONFINE YOURSELF TO THE PRESENT" WHAT IS YOUR PLAN TO BEGIN APPLYING THIS SECRET OF LIFE TO YOUR MOMENTARY EXISTANCE? By focusing on the eternal present you can make the most out of the time throughout the day. Sometimes we waste so much time worrying about the future or trying to change the past. At the same time I think it's important to keep sight of the future without worrying about it endlessly. 9-8-10

POSITIVE THINKING An entry from the diary Perez kept while in supermax contains a quotation from Marcus Aurelius.

his future. Writes Harvard psychology professor Dan Schacter: "Since the future is not an exact repetition of the past, simulation of future episodes requires a system that can draw on the past in a manner that flexibly extracts and recombines elements of previous experiences."

"I used to lie in bed with my eyes closed," says Perez, "thinking about my past, thinking about my future, planning for the future. Some of it was based on reality, and the other—borderline fantasy." He tapped into a tunnel-like experience, creating a personal space for himself inside the tiny physical space of his cell. Over time, he got more intentional about how he was using his time in his "mental workspace," as Schlegel refers to the overlapping networks that allow intentional imagination to take place. Perez believes what he ended up doing "bordered on meditation."

Michael Jewell, a Texan inmate, had a similar experience. After Jewell's 1970 death sentence was commuted to life imprisonment, he served 40 years, seven of which were spent in near-total isolation. He says he used to kill time for hours working out detailed visualizations of himself in a vivid alternate reality, where he could inhabit open spaces and converse with people. "I might imagine myself at a park and come upon a person sitting on a bench," he says. "I would ask if she or he minded if I sat down. I'd say something like, 'Great weather today.' The other person would respond something like, 'It is indeed. I hope it continues until the [football game].' 'I know what you mean. In another couple of weeks it's going to be cold as a witch's tit in Wisconsin.' As we conversed, I would watch joggers, bicyclists, and skateboarders pass by. The conversation might go on for half an hour or so. When I opened my eyes and stood, I would feel refreshed and even invigorated."

As with Perez, the result was self-improvement in the most unlikely circumstances. "I was an exception to the rule," Jewell writes. "I went out better than I came in." In a sense, Jewell didn't have much of a choice. A survivor of intense childhood trauma and abuse, he says the constant presence of mental "goblins" threatened to consume him when he entered solitary. His willful and directed imagination was a reaction to those goblins, and helped him defeat them. Now on parole, Jewell is active on many prison reform boards and is a director of Texas Cure, an organization that works on prison reform.

ALLEGRA ABRAMO

Got Grit?

The University of Pennsylvania Grit Lab uses these 12 self-assessment cues to measure an individual's grittiness.

1. I have overcome setbacks to conquer an important challenge.

2. New ideas and projects sometimes distract me from previous ones.

3. My interests change from year to year.

4. Setbacks don't discourage me.

5. I have been obsessed with a certain idea or project for a short time but later lost interest.

6. I am a hard worker.

7. I often set goals but later choose to pursue a different one.

8. I have difficulty maintaining my focus on projects that take more than a few months to complete.

9. I finish whatever I begin.

10. I have achieved a goal that took years of work.

11. I have become interested in new pursuits every few months.

12. I am diligent.

THAT PEREZ AND JEWELL had an active imagined life in solitary is, in a sense, unsurprising. Isolation naturally encourages the generation of mental imagery because imagination and perception occur along parallel neural pathways and are constantly competing for attention. The more there is to perceive, the less intense our mental imagery will be. Conversely, reduced sensory stimulation can allow for "vivid and stable mental imagery," says David Pearson, a cognitive psychologist at Anglia Ruskin University. This correlation has been documented before: Isolation has been linked to creativity.

But simply imagining something is not enough to improve wellbeing. In fact, uncontrolled or intrusive mental images can be both causative and symptomatic of mental illness. Social anxiety sufferers, for example, are plagued with involuntary images of themselves performing badly in social situations. A stutterer might picture himself stumbling over a word repeatedly. The problem is particularly severe in prison: 55 percent of male and 73 percent of female inmates in United States state prisons suffer from some form of mental illness. Three-quarters of all confined prisoners report signs and symptoms of psychosis, including hallucinations, and 82 percent of prisoners who attempted suicide during solitary confinement reported experiencing visual imagery related to their suicidal acts.

Uncontrolled and intentional imagination lead to very different outcomes. They even activate different parts of the brain: The default mode network, which goes online when we let our minds wander, is associated with uncontrolled imagination. Controlled imagination activates the dorsal attention network, which is linked to self-control, and the impairment of which might be implicated in psychological disorders like substance dependence and attention deficit disorder. Which kind of imagination is activated may come down, simply, to character.

ANGELA DUCKWORTH WAS TEACHING seventh-grade math in a New York City public school when she noticed that intelligence was not always the best predictor of which of her students succeeded. There was another key ingredient: the ability to demonstrate effort and passion over time, a quality she called "grit."

Duckworth went on to obtain a doctorate in psychology at the University of Pennsylvania, and developed her hypothesis further. She has since researched West Point Military Academy cadets, National Spelling Bee competitors, rookie teachers in low-income neighborhoods, and salespeople at top companies. Across all of these professions, she has found grit to be a key ingredient to achievement. Students who self-report high grit levels are more likely to succeed in school than non-gritty students—even more intelligent ones.

But grit isn't just about achievement. In fact, achievement can obscure grit. Writes Duckworth, "Whereas individuals high in need for achievement pursue goals that are neither too easy nor too hard, individuals high in grit deliberately set for themselves extremely long-term objectives and do not swerve from them—even in the absence of positive feedback."

There's not much in the way of positive feedback in solitary confinement. Success is almost completely unrecognized by others and entirely dependent on the goals you set yourself. Schlegel posits that prisoners who thrive in solitary confinement probably have extra-high levels of grit: "There's this motivation aspect to creativity that's really separate from anything to do with imagination," he says. "This idea of motivation is very underappreciated."

For this article, Perez and Jewell took an online test through the University of Pennsylvania's Grit Lab that measured their grit on a scale from 1 to 5. The test measures qualities like an individuals' consistency of interests ("I often set a new goal but later choose to pursue a different one") and perseverance of effort ("I have achieved a goal that took years of work"). Both Jewell and Perez scored a 4.25, meaning they are grittier than 90 percent of the U.S. population.

Jewell agrees that grit may have played a role in his anomalous supermax experience, and says that his upbringing may have made him "grittier than his counterparts." For his part, Perez says that the experience of confinement has made him even grittier. "The way I see it is like this," he says. "I have been to the bottom of the barrel and have emerged more resilient, smarter, more determined to succeed, and more appreciative about the small things in life. I learned to eliminate the pain by finding pleasure in the pain, to turn shit into sugar."

Grit and imagination got him through and helped make him who he is today. At the same time, he says he didn't need all those years in prison to "get the message."

"Would I take it back?" He chuckles and leans back, shaking his head. "Yeah, probably."

SUSIE NEILSON is an editorial intern at *Nautilus*.

Last Launch

A portrait of the NASA space shuttle program's last days

BY DAN WINTERS

THE INFRASTRUCTURE BEHIND NASA'S shuttle program was unimaginably vast. At \$1 billion each, the launches were so audacious that they seemed to risk collapsing under the weight of their own hubris. And yet, for 30 years the orbiters came and went, acting as a protective vessel, enabling a select group to contemplate the fury of the world in a stillness unobtainable by the rest of us.

Then in early 2011, the space shuttle program came to an end. As a journalist, I felt compelled to document this era in space exploration while it was still around.

That same year, NASA allowed me unprecedented access to the area around the launch pad. I set an average of 11 cameras, some as close in as 650 feet from the shuttle's main engines. The cameras were mounted on heavy-duty tripods weighted with 100-pound sandbags and fitted with custom sound-activated triggers.

As the engines came to life, the intense sound they generated activated the cameras, which then began documenting the spectacle at four frames per second. No human could survive this violent event at such close proximity.

It was a rare opportunity. But, even after a 30-year career as a photojournalist, I made a couple of rookie mistakes. In photographing Discovery's final mission I neglected to put a memory card into one of my cameras. On Endeavour's final launch, I placed two cameras too close to the main engines, and they got smoked out after only a couple of frames.

At first I was heartbroken. But when I sat with the flawed images, the ominous cloud of smoke that enveloped the shuttle grew more beautiful to me and I now count them among my favorites.

Beauty Is Physics' Secret Weapon

A Nobel laureate maps his path to discovery

BY STEVE PAULSON

WE RECOGNIZE BEAUTY WHEN we see it, right? Michelangelo's *David*, Machu Picchu, an ocean sunrise. Could we say the same about the cosmos itself? Frank Wilczek, a professor of physics at the Massachusetts Institute of Technology, thinks we can. And should. In his new book *A Beautiful Question: Finding Nature's Deep Design*, Wilczek lays out his case for the elegance of mathematics and the coherence of nature's underlying laws.

Wilczek won the 2004 Nobel Prize in Physics for discovering, with David Gross and H. David Politzer, equations that govern one of the fundamental forces in physics, the strong interaction, which holds together quarks and gluons, and makes protons and neutrons. Their discovery of "asymptotic freedom" showed that as quarks get closer to each other, the charge between them grows weaker.

Wilczek's specialty is quantum theory, but the impact of his work has been apparent in cosmology—in the study of black holes, dark matter, and the age-old mystery of how something can arise out of nothing. Now 64, he has been seeking designs in nature since he was a young math student. "I liked playing with patterns and thinking about that kind of abstraction," he says. "I was very interested in mathematical logic, which is a branch of philosophy, and the theory of how the mind works. I studied some neurobiology and computer science as I tried to figure out how abstract patterns map onto the workings of minds."

Wilczek is not just a leading theoretical physicist but a student of philosophy and admirer of poet William Blake and Renaissance Italian architect Filippo Brunelleschi. In conversation he laughs readily and takes obvious delight in leaping from one idea to the next, whether he's talking about string theory, *The Matrix*, the native intelligence of animals, or the wrongheaded views of philosophy held by scientists like Neil DeGrasse Tyson.

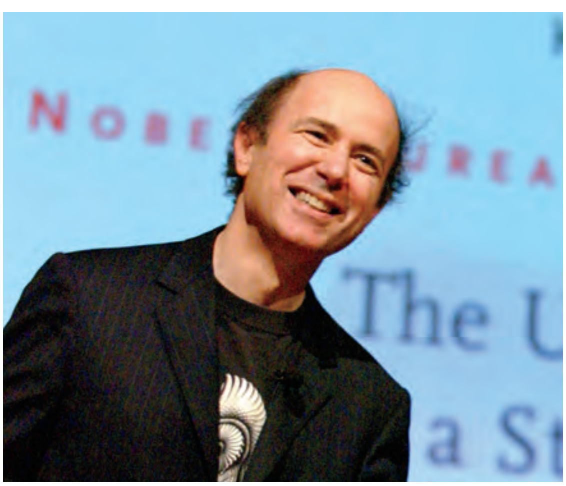
ILLUSTRATION BY REBECCA MOCK

You say there's beauty in the design of nature. That seems to be a matter of aesthetics. Is it a scientific question?

It is a scientific question. The exact question I'm trying to address is whether the world embodies beautiful ideas. That's a question about the world on the one hand and beauty on the other. Beauty is notoriously subjective and comes in many forms, but there is a historical record in art and philosophy that one can consult to see what people have objectively found beautiful. We can consult science and compare whether the concepts that emerge from the fundamental laws of nature have something in common with what people find beautiful.

Does it matter to a scientist if the world is beautiful?

I don't think science is walled off from the rest of life. So yes, it matters to me a lot whether the world is beautiful. It's also a practical question for physicists, engineers, and designers. At the frontiers of physics, we're dealing with realms of the very small and the very large and the very strange. Everyday experience is not a good guide and experiments can be difficult and expensive. So the source of intuition is not so much from everyday experience or from a massive accumulation of facts, but from feelings about what would give the laws of nature more inner coherence and harmony. My work has been guided by trying to make the laws more beautiful.



FRANK WILCZEK "Ordinary experience gives you only a very partial view of reality."

What is a beautiful law?

Two things stand out as common features of laws and equations that people find beautiful. One is what I call exuberance or productivity, where you get out more than you put in. You find some equation or law by putting together clues and making a guess, and then you can explain seven other things and you know you're on the right track. You get out more than you put in. Symmetry is especially prominent in the fundamental laws of nature. As it's commonly used, symmetry is kind of vague but somehow connotes harmony and beauty. The scientific usage is more precise and has been extremely fruitful. It's change without change. You can make changes in physical objects or changes in the laws that could change them but don't. A circle is symmetrical in the sense that you can rotate it around its center by any angle but the circle as a whole is unchanged. Most shapes, like triangles, look different if you rotate them.

So if you go down to the deepest structures of the universe—the laws of physics—are you saying there is profound symmetry?

Yes. Take the fact that the laws are eternal. That doesn't sound like symmetry, but it is because the laws don't change as the universe ages. So we have a change without change.

Suppose the universe didn't embody beautiful ideas or elegant mathematical structures. Can we even imagine the laws of nature if they were full of asymmetries or imperfections?

I've wrestled with this question and there's a thought-experiment that I find very satisfying. As computers get better and artificial intelligence gets better, you can make plausible thought experiments along the lines of *The Matrix*, where intelligence is embodied within a computer, and what it thinks of as its world is actually something that's been programmed.

So we are just living in a computer simulation?

Let's imagine ourselves in Super Mario's World. The laws of physics wouldn't look particularly beautiful. They would change with time and place. They would have a quirkiness to them that's logically consistent but is very different from the way our world works, where the laws don't change in time or place, and have a kind of reproducibility. Once you understand the small parts, you can build up by deduction to figure out how the large parts work, whereas in a programmed world, it's just a matter of what the programmer's whims were. It doesn't have to make sense or be beautiful. So I don't think there's anything logically necessary about the beauty of the laws. Of course, they might've been much harder to discover if they weren't beautiful, so the comprehensibility of the laws is to me even more mysterious than their beauty. It didn't have to be that way, but it is.

Was beauty important to Einstein and the other founders of modern physics?

Absolutely, although they didn't always think about it explicitly. Einstein and [James Clerk] Maxwell—and going back to Newton—all had this instinct for breaking down problems into small parts, with the idea that they would be comprehensible, and then you could build up to more complicated things that would have this kind of exuberance. Einstein was the decisive figure in bringing this second aspect of the beauty of nature—symmetry—to new heights. The theory of relativity is very much in the mold of change without change. You can look at the world from a moving platform and different things rushing at you or away from you will look quite different, but the same laws will apply as in the stationary frame. That's the essence of the theory of relativity. You change the way things look and yet the laws are still valid.

Einstein didn't like the idea of quantum entanglement, where two particles interact with each other on opposite sides of the universe. Did that violate his sense of beauty?

It violated his sense of determinism that the laws should always lead to the same consequences. He's famously thought to have said that insanity is doing the same thing over and over again and expecting different results. Yet that's exactly the way quantum mechanics works. So he didn't like it. But parents don't always approve of the way their children turn out. Quantum mechanics is a framework that doesn't itself seem to embody symmetry, although at a deeper level I think maybe it does. Quantum mechanics turns out to be a wonderful platform if you build equations that obey its principles. Those equations can support enormous amounts of change without change that go beyond anything in classical physics, and they truly describe the world.

I love its weirdness and strangeness and the fact that it's the way the world actually works.

We can't predict what a particular particle is going to do at the quantum level. Do these irregularities that bothered Einstein also trouble you?

No, I love it. I love its weirdness and strangeness and the fact that it's the way the world actually works.

This doesn't violate your sense of order?

You know, it's profound. In quantum mechanics, the primary description of reality is something called a wave function and the equations of the wave function are actually deterministic. They're perfectly definite equations. If you know the wave function at one time, you can predict what it's going to be at another time with no ambiguity. The problem is that it's impossible experimentally to know what the wave function is. So the deep structure is determined, but from where we sit within the universe, it's not something *we* can determine. Operationally, that means things look unpredictable. There are vast mounds of experimental data and

BROOKHAVEN NATIONAL LABORATORY

I don't think any of the received religions do justice to what I've discovered about the physical world.

experiences that directly confirm this aspect of quantum mechanics. Basically, all modern particle accelerators are based on doing the same thing over and over again: bashing together electrons and anti-electrons at exactly the same energy and exactly the same configuration. But different things come out. You do it billions of times and each time a different thing comes out. So it's not a matter of opinion.

Are humans really uncovering the deep structure of the universe? Or is this just our version of reality, given the way our brains work and how we see the world?

Well, physics works. You can't design iPhones or the Large Hadron Collider or missions to Pluto without a description of the world that works in very detailed ways. So it's not a fantasy. However, there could be different ways of organizing your thoughts. Some things would seem obvious to creatures that were evolved from intelligent spiders that seemed less intuitive to us. So the ways the laws get written down could look different in significant details, but I don't think the results are negotiable. The world is what it is.

You have a fascinating thought experiment. If dogs or birds had advanced abstract reasoning, would they be good at physics?

I think birds would be very good but dogs not so much. The dog's world is primarily based on smell. Of course, chemical senses can support a rich life of communication and appreciation of food. You smell a madeleine and remember the past. But even if you're very smart and have a rich social life, it's hard to get from sensations of smell to Newton's laws of motion and mechanics. Humans are primarily visual animals, so we have powerful ways of understanding how things move through space. We're lucky that we can see the planets. That gives us a nice opening into astronomy and understanding gravity.

So what's special about birds?

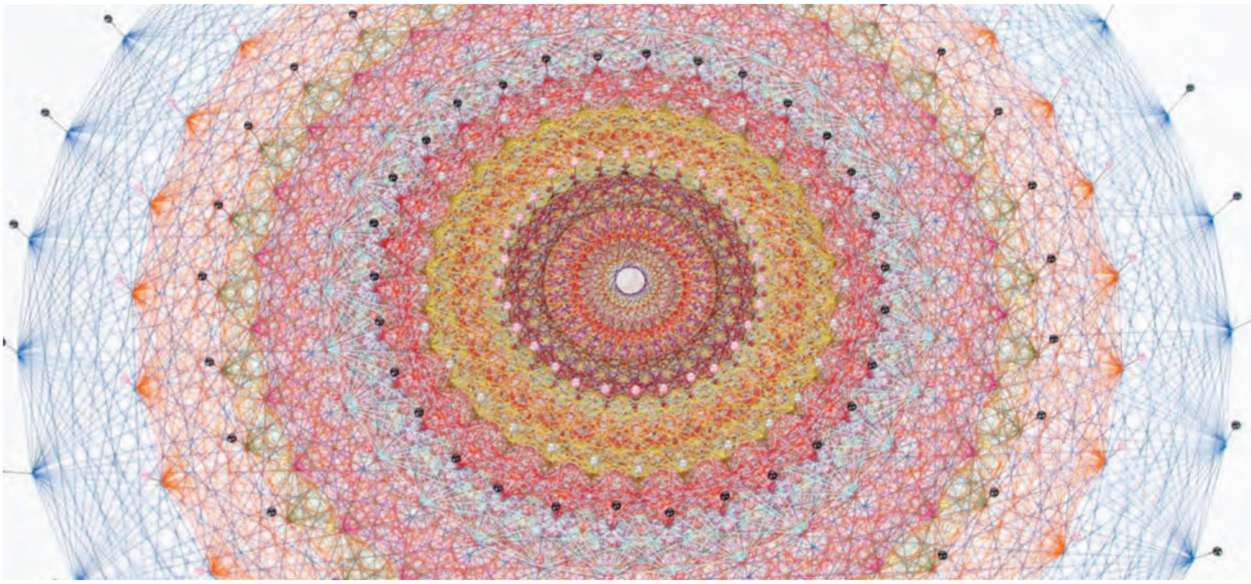
Birds would have all that and more. Our experience is dominated by friction and the force of gravity here on Earth, which historically have caused great problems in understanding what inertia is. But birds just flap their wings for a while, then stop and glide, so they know about inertia. They would also have an intuitive sense of relativity—that the laws don't change if you're moving at a constant velocity. They experience that every day. So if birds became intelligent, I think they would make more rapid progress on physics than humans have. Spiders would also have a different perspective. They communicate through touch and the vibrations of their webs. They would have a very good entry into field theory and electricity.

One danger for a theoretical physicist is that you can get so caught up in the beauty of your equations and how everything fits together that you become detached from the physical world. You still need empirical tests to prove this underlying structure. Is this an occupational hazard for you?

It absolutely is. The great physicist Richard Feynman liked to say you have imagination, but it's imagination in a straitjacket. To me it assumes a different level of interest when your ideas suggest experimental consequences that you can check.

What if there is no "theory of everything" that unites the laws of physics? Where does this leave your argument for nature as a work of beauty?

The argument is still correct. We already know there are beautiful laws that explain most of the way matter works. It's just that we haven't figured it all out. It's difficult to exaggerate how symmetric, how fruitful, how creative the laws are. It's a great gift. But we're not satisfied because there are some annoying little



UNIVERSAL BEAUTY The E8 Lie group, pictured above, is a perfectly symmetrical 248-dimensional object. (Lie groups are used in math and physics to model symmetries.) Symmetry, Frank Wilczek says, is prominent in the fundamental laws of nature, and "connotes harmony and beauty."

JLRODRI/WIKIPEDIA

flaws like in the story "The Birth-Mark," where there's this little imperfection that obsesses her suitor. So we're trying to find new phenomena that would allow us to have even more symmetry and would make the equations more beautiful. But the ultimate verdict is experimental.

You seem somewhat unusual for a scientist. You clearly love to explore these big ideas. Did you ever think about becoming a philosopher rather than a physicist?

Absolutely. When I was a young teenager, my heroes were Einstein on the one hand and Bertrand Russell on the other. I loved reading about philosophy and thinking about those kinds of questions.

In the last few years, some high profile physicists, including Stephen Hawking, Lawrence Krauss, and Neil DeGrasse Tyson, have made disparaging comments about philosophers, basically saying they have little value to the real world of science. What do you make of these attacks on philosophy by your colleagues?

I think it shows lack of imagination and lack of knowledge of what philosophy is all about. There is a lot about the world besides the laws of physics and physical phenomena. There are centuries of experience of wrestling with these problems and refining those concepts. It's unwise and borderline silly to just write that off. As Einstein did, I've derived tremendous inspiration from the philosophical literature, from sharpening your mind against David Hume or Ernst Mach or Bertrand Russell.

If someone needs a deeper system of values to fall back on, are you saying beauty would be a good place to look for it?

Yes. Some people derive joy and understanding from the dogmas of different religions, and that's one way to organize your life. I don't find that possible because I don't think any of the received religions do justice to what I've discovered about the physical world. It's not so much that they're wrong, although many details are wrong, but they just don't do justice to the profound surprises that science turns up about how big the

DOORS OF PERCEPTION William Blake's monotype, "Newton," suggests the world is constructed mathematically. The image holds a message for scientists, Frank Wilczek says: "We can get from shadows to substance."

WIKIPEDIA

universe is, how old it is, how many little things go into making the big things we experience in life. That means it's on us to figure out and make the meaning. And for me beauty is one of the big discoveries that goes into what it all means. That's been a great source of joy.

One of the deepest questions for both science and religion is the question of origins. How did the universe begin, or does it even have a beginning? How does something come out of nothing? Lawrence Krauss claims this isn't all that mysterious. He says vacuum states are unstable in quantum field theory, so it's not unusual for states to pop in and out of existence.

In fact, my friend Lawrence was quoting my work. I don't understand all the implications but the equations don't permit stable solutions that have nothing. Void is a very different thing from a solution of the fundamental laws of nature, so if void is not allowed, that is an explanation for why there's something rather than nothing. But I don't think it really gets to the question that philosophers are asking.

They're asking where the laws of physics come from.

Exactly. Where did the equations come from? We know that void is not a correct idea. It's not a possibility given the laws that we know.

So there's no such thing as empty space?

That's right. The concept that space is an empty, passive receptacle that has no inner life is totally wrong. In quantum mechanics, space has spontaneous activities. These are called "virtual particles." Part of what I got the Nobel Prize for was figuring out how virtual particles affect the real particles we see.

What are virtual particles?

It's as if we're living on the surface of a planet that has a lot of activity going on underneath that's not seen on the surface, but affects the way the world is. In the laws of fundamental physics, the fields—for instance, electric and magnetic fields—have spontaneous activity. Virtual particles come into being for a very short time and then pass away without ever being something that can be sensed by our eyes or our instruments. But they're in the equations and they affect the properties of particles that we do see and can calculate and check. So there's no doubt that space—which I sometimes call "the grid"—is a source of activity. That's one reason why it's not a void. It has a life.

So if we're looking for the most fundamental thing in the universe, it's not particles or matter. Is it this space that you're talking about?

Yes, space itself has a life of its own. To understand what we perceive as empty space is really the key to understanding how the whole universe works. I like to joke with my students that in Newtonian mechanics, the key is to solve the problem of how one body moves around another, like the earth moves around the sun. In quantum mechanics, the key problem is the "nobody problem" and it's empty space that runs the show. The particles we actually see are a kind of epiphenomena on top of the structure of empty space.

We've been talking about the difficulties of reconciling the immaterial world with matter, and the biggest mystery of all might be the "mind-brain problem"—how the immaterial world of our minds comes out of three pounds of gooey stuff in our brains. Is this a problem for physics, or should we leave that to neuroscientists?

The laws of physics apply to the brain, so you shouldn't be searching for a soul or something immaterial in addition to the particles that make up the brain. A good working hypothesis is that the brain is like a computer and the puzzle is to understand how the physical object obeying the laws of physics can do computations and make a mind. Then there's the more technical question of whether the way we use physics to describe objects in the physical universe can be used to illuminate how the brain works—whether ideas about symmetry, material science, and electrical conduction will be important for neurobiology. I think there's a good chance the answer is yes. Parts of the brain are very regular and symmetrical. The cerebellum is very structured. Neural nets are another development I find absolutely fascinating. Artificial neural nets are an idealization of nerve systems in the brain, but they use laws of computation that physics people would recognize. In fact, physicists invented a lot of these techniques because they look like the equations that govern electrical circuits. So I think physics has a lot to offer neurobiology.

> The laws of physics apply to the brain, so you shouldn't be searching for a soul or something immaterial.

Do you think science will ever crack the fundamental problem of how we get our mental world out of material stuff?

Yes, I do. How should I say it? I think we're maybe 90 percent of the way there.

You're an optimist!

No, I think I'm just interpreting things correctly. Not long ago it seemed very mysterious that patterns of ones and zeros could encode how you do computations; for instance, how you play chess. But now we can design systems that work on ones and zeros that do something very much like thinking. Increasingly you have meaningful interactions with systems like Siri that are just manipulating patterns of ones and zeros. Those ones and zeros are embodied in physical objects, namely transistors, so that's very close to saying that mind is embodied in physical objects. These are concrete objects that we designed.

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

The Deep Space of Digital Reading

Why we shouldn't worry about leaving print behind

BY PAUL LA FARGE

IN ***A HISTORY OF READING***, the Canadian novelist and essayist Alberto Manguel describes a remarkable transformation of human consciousness, which took place around the 10th century A.D.: the advent of silent reading. Human beings have been reading for thousands of years, but in antiquity, the normal thing was to read aloud. When Augustine (the future St. Augustine) went to see his teacher, Ambrose, in Milan, in 384 A.D., he was stunned to see him looking at a book and not saying anything. With the advent of silent reading, Manguel writes,

> ... the reader was at last able to establish an unrestricted relationship with the book and the words. The words no longer needed to occupy the time required to pronounce them. They could exist in interior space, rushing on or barely begun, fully deciphered or only half-said, while the reader's thoughts inspected them at leisure, drawing new notions from them, allowing comparisons from memory or from other books left open for simultaneous perusal.

To read silently is to free your mind to reflect, to remember, to question and compare. The cognitive scientist Maryanne Wolf calls this freedom "the secret gift of time to think": When the reading brain becomes able to process written symbols automatically, the thinking brain, the I, has time to go beyond those symbols, to develop itself and the culture in which it lives.

A thousand years later, critics fear that digital technology has put this gift in peril. The Internet's flood of information, together with the distractions of social media, threaten to overwhelm the interior space of reading, stranding us in what the journalist Nicholas Carr has called "the shallows," a frenzied flitting from one fact to the next. In Carr's view, the "endless, mesmerizing buzz" of the Internet imperils our very being: "One of the greatest dangers we face," he writes, "as we automate the work of our minds, as we cede control over the flow of our thoughts and memories to a powerful electronic system, is ... a slow erosion of our

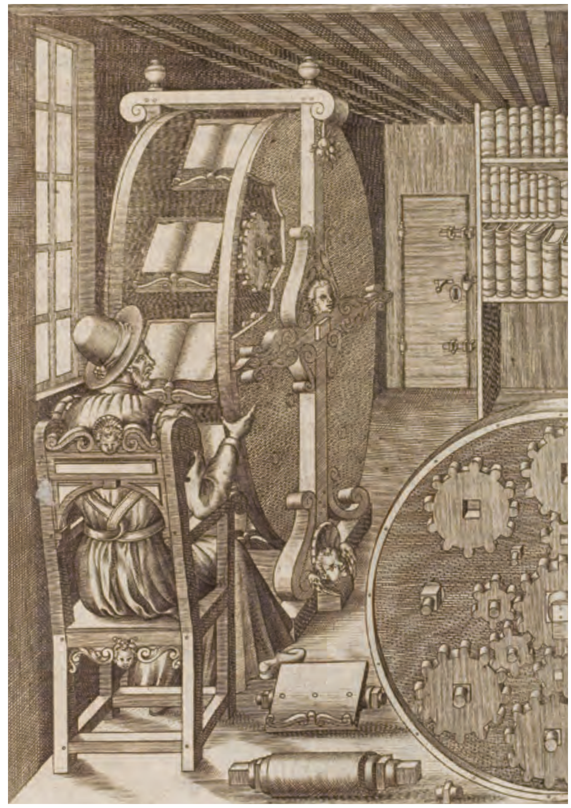
ILLUSTRATION BY IRENE RINALDI

humanness and our humanity."

There's no question that digital technology presents challenges to the reading brain, but, seen from a historical perspective, these look like differences of degree, rather than of kind. To the extent that digital reading represents something new, its potential cuts both ways. Done badly (which is to say, done cynically), the Internet reduces us to mindless clickers, racing numbly to the bottom of a bottomless feed; but done well, it has the potential to expand and augment the very contemplative space that we have prized in ourselves ever since we learned to read without moving our lips.

The fear of technology is not new. In the fifth century B.C., Socrates worried that writing would weaken human memory, and stifle judgment. In fact, as Wolf notes in her 2007 book *Proust and the Squid: The Story and Science of the Reading Brain*, the opposite happened: Faced with the written page, the reader's brain develops new capacities. The visual cortex forms networks of cells that are capable of recognizing letterforms almost instantaneously; increasingly efficient pathways connect these networks to the phonological and semantic areas of the cortex, freeing up other parts of the brain to put the words we read into sentences, stories, views of the world. We may not keep the *Iliad* in our heads any longer, but we're exquisitely capable of reflecting on it, comparing it to other stories we know, and forming conclusions about human beings ancient and modern.

The Internet may cause our minds to wander off, and yet a quick look at the history of books suggests that we have been wandering off all along. When we read, the eye does not progress steadily along the line of text; it alternates between *saccades*—little jumps—and brief stops, not unlike the movement of the mouse's cursor across a screen of hypertext. From the invention of papyrus around 3000 B.C., until about 300 A.D., most written documents were scrolls, which had to be rolled up by one hand as they were unrolled by the other: a truly linear presentation. Since then, though, most reading has involved codices, bound books or pamphlets, a major advantage of which (at least compared to the scroll) is that you can jump around in them, from chapter to chapter (the table of contents had been around since roughly the first century B.C.); from text to marginal gloss, and, later, to footnote.



16TH-CENTURY INTERNET The "book wheel," invented in 1588, was a rotating reading desk that allowed readers to flit among texts by giving the wheel a quick spin.

WIKIPEDIA

In the age of print, nonlinear reading found its most elaborate support in the "book wheel," invented by the Italian engineer Agostino Ramelli in 1588: a "rotary reading desk" which allowed the reader to keep a great number of books at once, and to switch between them by giving the wheel a turn. The book wheel was—unfortunately!—a rarity in European libraries, but when you think about all the kinds of reading that print affords, the experience of starting a text at its beginning and reading all the way to the end, which we now associate with "deep" reading, looks less characteristic of print in general than of the novel in particular: the one kind of book in which, we feel, we might be depriving ourselves of something vital if we skipped or skimmed.

The quality of digital media poses one kind of problem for the reading brain; the quantity of information available to the wired reader poses a different and more serious problem. But it's worth noting that readers have faced this problem before, too. Gutenberg printed his first Bible in 1455, and by 1500, some 27,000 titles had been published in Europe, in a total of around 10 million copies. The flood of printed matter created a reading public, and changed the way that people read.

The German historian Rolf Engelsing argues that a "reading revolution" took place at the end of the 18th century: Before that point, the typical European reader had only a few books—the Bible, an almanac, maybe a work of devotional literature—and he read them over and over, so that they were deeply impressed on his consciousness. Afterward, Europeans read all kinds of material—novels, periodicals, newspapers—and they read each item only once before racing on to the next. Contemporary critics were doubtless appalled, but on the other hand, from that flood of printed matter, we got the Enlightenment, Romanticism, the American and French revolutions.

It's true that studies have found that readers given text on a screen do worse on recall and comprehension tests than readers given the same text on paper. But a 2011 study by the cognitive scientists Rakefet Ackerman and Morris Goldsmith suggests that this may be a function less of the intrinsic nature of digital devices than of the expectations that readers bring to them. Ackerman and Goldsmith note that readers perceive paper as being better suited for "effortful learning," whereas the screen is perceived as being suited for "fast and shallow reading of short texts such as news, e-mails, and forum notes." They tested the hypothesis that our reading habits follow from this perception, and found it to be correct: Students asked to read a text on-screen thought they could do it faster than students asked to read the same text in print, and did a worse job of pacing themselves in a timed study period. Not surprisingly, the on-screen readers then scored worse on a reading comprehension test.

If those same students expected on-screen reading to be as slow (and as effortful) as paper reading, would their comprehension of digital text improve? A 2015 study by the German educator Johannes Naumann suggests as much. Naumann gave a group of high-school students the job of tracking down certain pieces of information on websites; he found that the students who regularly did research online—in other words, the ones who expected Web pages to yield up useful facts—were better at this task (and at ignoring irrelevant information) than students who used the Internet mostly to send email, chat, and blog.

Critics like to say the Internet causes our minds to wander off, but we've been wandering off all along.

Meanwhile, some writers are taking advantage of the formal possibilities of digital media to tell stories and communicate information in new ways. One of these new forms is what people in the 1990s called "hypertext": text divided into units called "lexia," which are connected by links, sometimes in a branching or tree-like structure, sometimes in webs or cats'-cradles or other tangled forms. (Technically, the Web is a hypertext, but the word often refers to single works with an internally linked structure.)

The impact of hypertext on the reading brain has, as you'd expect, received a fair amount of scientific attention. In 2005, the psychologists Diana DeStefano and Jo-Anne LeFevre reviewed 38 studies of hypertext reading; their expectation was that hypertext would be found to impose a greater cognitive load on the reader than linear text, because of the effort involved in scanning a page for links, and deciding which link, if any, to follow. DeStefano and LeFevre further hypothesized that this increased cognitive load would cause readers' recall and comprehension to suffer. They concluded that this expectation was, generally speaking, correct, and Carr cited it in his 2011 book *The Shallows*, as evidence that the Internet is making us stupid.

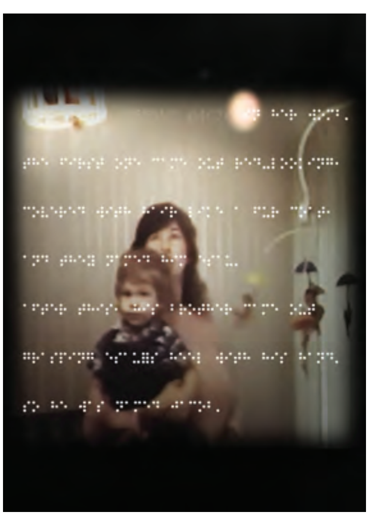
In fact, though, DeStefano and LeFevre's findings were equivocal. The cognitive load imposed by hypertext doesn't correspond in a straightforward way to the number of choices presented at a decision point, or to the total number of links in a hypertext. (Indeed, a 1996 study by Michael Wenger and David Payne found that hypertext did not impose a greater cognitive load on readers than linear text, a result that DeStefano and LeFevre note in passing.) In two studies, hypertext seemed to improve comprehension. One involved readers with little prior knowledge of a subject, who were able to use a highly structured hypertext (one whose structure mirrored the organization of its subject matter) to learn more effectively than similar readers of linear text. In the other study, academically gifted readers learned better from unstructured hypertext than from linear text. The author, Amy Shapiro, hypothesized that these readers were obliged to engage more actively with the hypertext, in order to figure out the relation between its parts; this engagement led to increased understanding, the way puzzling over a difficult poem yields more than reading quickly through an easy one.

DeStefano and LeFevre also remark that "[f]ew of the studies that we reviewed considered affective factors such as engagement or enjoyment." This may seem like a small point, but it's not. In a 2008 study by the psychologists Tal Yarkoni, Nicole Speer, and Jeffrey Zacks, subjects were given two narratives to read, while their brain activity was monitored by a functional MRI scanner. One narrative was a fairly straightforward account of a day in a boy's life; the other was the same account with the sentences scrambled. Here's a bit of the latter:

> Mrs. Birch called in a pleasant tone, "Raymond, take a bath and then you can go to bed." Raymond noticed this immediately and asked curiously, "Am I four feet high?" He stood and went toward them in a slow, jogging run.

Based on the fMRI data, Yarkoni, Speer, and Zacks concluded that the scrambled sentences forced the readers to keep remaking their "situation models," their mental representations of what was happening in the story. Situation models guide reading comprehension and memory; without them, we get lost, which explains, in neuropsychological terms, why the scrambled sentences were harder to remember. And yet, when I read the two experimental texts, I found myself thinking about how much more interesting the scrambled one was, and how much more fun it was to read. Maybe I'm just the kind of person who likes building situation models, but I don't think I'm alone in this. If there were no pleasure in reading things that don't make sense, who would read the Surrealists? Who would giggle at bad subtitles, or Mad Libs?

Comprehension matters, but so does pleasure. In *Proust and the Squid*, Wolf, director of the Center for Reading and Language Research at Tufts University, observes that the brain's limbic system, the seat of our emotions, comes into play as we learn to read fluently; our feelings of pleasure, disgust, horror and excitement guide our attention to the stories we can't put down. Novelists have known this for a long time, and digital writers know it, too. It's no coincidence that many of the best early digital narratives took the form of games, in which the reader traverses an imaginary world while solving puzzles, sometimes fiendishly difficult ones. Considered in terms of cognitive load, these texts are



SHAPE OF READING TO COME Reading's future is signaled by interactive novels like *Pry*, which, along with text, uses video clips to expose its protagonist's memories.

SAMANTHA GORMAN AND DANNY CANNIZZARO

The history of reading suggests it's not the end times of human thought. It's more like an interregnum, or crouch before the leap.

head-bangingly difficult; considered in terms of pleasure, they're hard to beat.

A new generation of digital writers is building on video games, incorporating their interactive features—and cognitive sparks—into novelistic narratives that embrace the capabilities of our screens and tablets. Samantha Gorman and Danny Cannizzaro's 2014 iPad novella, *Pry*, tells the story of a demolitions expert returned home from the first Gulf War, whose past and present collide, as his vision fails. The story is told in text, photographs, video clips, and audio. It uses an interface that allows you to follow the action and shift between levels of awareness. As you read text on the screen, describing characters and plot, you draw your fingers apart and see a photograph of the protagonist, his eyes opening on the world. Pinch your fingers shut and you visit his troubled unconscious; words and images race by, as if you are inside his memory. *Pry* is the opposite of a shallow work; its whole play is between the surface and the depths of the human mind. Reading it is exhilarating.

There's no question when you read (or play) *Pry* that you're doing something your brain isn't quite wired for. The interface creates a feeling of simultaneity, and also of having to make choices in real time, that no book could reproduce. It asks you to use your fingers to do more than just turn the page. It communicates the experience of slipping in and out of a story, in and out of a dream, or nightmare. It uses the affordances of your phone or tablet to do what literature is always trying to do: give you new things to think about, to expand the world behind your eyes. It's stressful, at first. How are you supposed to know if you're reading it right? What if you miss something? But if you play (or read) it long enough, you can almost feel your brain begin to adapt.

Most of the Web is not like *Pry*—not yet, anyway. But the history of reading suggests that what we're presently experiencing is probably not the end times of human thought. It's more like an interregnum, or the crouch before a leap. Wolf points out that when it comes to reading, what we get out is largely what we put in. "The reading brain circuit reflects the affordances of what it reads," she notes: affordances being the built-in opportunities for interaction. The more we skim, the more we're likely to keep skimming; on the other hand, the more we plunge into a text, the more we're likely to keep plunging. "We're in a digital culture," Wolf says. "It's not a question of making peace. We have to be discerning, vigilant, developmentally savvy." And of course we have to be surprised, delighted, puzzled, even disturbed. We have to enjoy ourselves. If we can do that, digital reading will expand the already vast interior space of our humanity.

PAUL LA FARGE is the author of three novels: *The Artist of the Missing, Luminous Airplanes,* and *Haussmann, or the Distinction*; and a book of imaginary dreams, *The Facts of Winter*.

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OPPOSITES ATTRACT. Or is it birds of a feather flock together?

Massive objects draw each other together by exchanging graviton particles. On the other hand, maybe gravity is not quantum, so that gravitons don't exist.

Our brains could be chaotic storms governed by strange attractors. Or is the chaos ungoverned, and less important than we think?

When it comes to attraction, nothing is simple. Which is so—attractive.

Welcome to "Attraction."

—MS

"Even a happy lover shows all of the characteristics of an addict."

HELEN FISHER
"Love Is Like Cocaine" p.92

Attraction

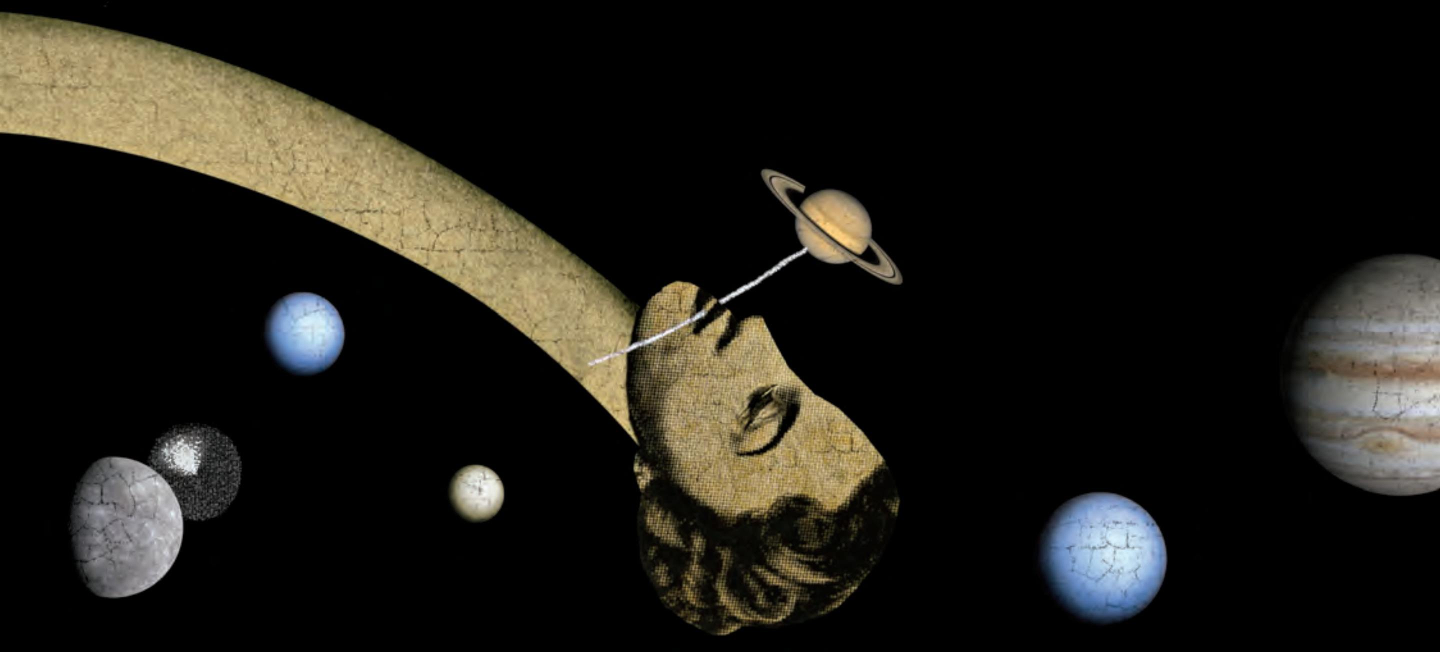
BINDING FORCES

Why It's Hard for Black Holes to Get Together

The universe's greatest sinkholes have no trouble swallowing anything—except themselves

BY KATE BECKER

ILLUSTRATION BY DAVID PLUNKERT



IT BEGINS LIKE A CLASSIC ROMANCE: Two black holes meet. The attraction is practically instant. They dance around each other, swirling closer and closer, until …

Until what? As with any love affair, this is where things get messy.

First predicted by Einstein's theory of general relativity, black holes are bottomless pits in the fabric of spacetime—gravitational wells so deep that nothing, not even light, can escape. Little black holes, trapping the mass of just a few suns, litter the universe like silent land mines, while the biggest ones, the supermassive black holes, occupy the center of nearly every galaxy, hoovering up torrents of infalling matter. These giants contain as much mass as hundreds of millions of suns; astronomers think that they formed from a long chain of galactic mergers—dozens, or perhaps even hundreds, of happy unions stretching back to the early days of the universe.

"Our whole picture of the formation of the structure of the universe involves this hierarchical process of small galaxies merging together to form large galaxies, and large galaxies merging to become even larger galaxies," says physicist Robert Owen, who studies black-hole collisions at Oberlin College, in Ohio, as part of the Simulating eXtreme Spacetimes collaboration. Each merger takes hundreds of millions of years or more—too long to see in action—but theorists can use simulations to recreate the entire affair in computer code.

And here's where the trouble starts. When physicists run their simulations, the two central black holes in a pair of colliding galaxies get stuck. Rarely, if ever, do black holes crash head-on. Instead, because they are typically traveling along separate, unaligned paths when they meet, their conserved angular momentum causes them to spiral toward each other. They corskscrew ever closer, captives of their mutual attraction, until they are orbiting at arms length—on the order of three light-years, or one parsec, apart. Then, like bashful lovers, they go no farther.

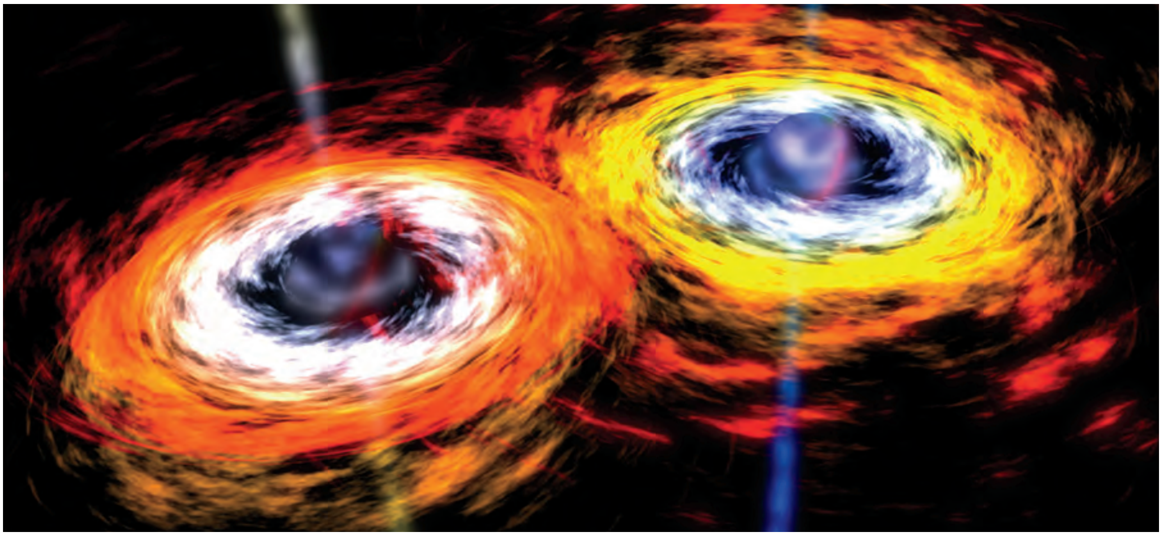
Why? Owen offers an analogy: Imagine that your hand is one of these black holes, and you're swirling it in a bucket of water that represents the swarm of merging galactic matter. At first the water pushes against your hand, slowing it down. In space, this gravitational interaction, known as dynamical friction, decreases the angular momentum of a black hole in orbit, causing it to drift toward its partner. But over time, the water in the bucket starts flowing in the same direction as your hand, so you feel less resistance. Likewise, in a simulated galactic merger, stars and other objects align their motion with the paths of the two twirling black holes. And as dynamical friction gradually peters out, the black holes settle into stable orbits.

If physicists' story about the formation of the universe is correct, such paired black holes should eventually collide and consume each other, becoming one. But to do this, they must somehow lose enough energy to resume their inward spiral past the final parsec. Once they get very close—just billions of miles apart (about 0.001 parsec)—general relativity says that they will jettison the last of their orbital momentum in a great crescendo of gravitational waves, ripples in spacetime that ring out from a gravitational disturbance. This final outburst of energy plunges the black holes together, finishing the job in a matter of hours, days, or years, depending on how massive the black holes are.

What drives this fatal embrace? The question, known as the "final parsec problem," isn't just a matter of curiosity. The answer could change our understanding of how the universe built up its elaborate structure, and of the nature of gravity itself. Which is why, as physicists tinker with their simulations, astronomers are searching the skies for clues to how black holes solve the final parsec problem in the wild—if they do at all.

OVER THE PAST 30 YEARS, astronomers have collected snapshots of hundreds of galaxies with dual supermassive black holes in various stages of collision. But even the most intimate portraits don't reveal pairs circling nearer than a few thousand parsecs. "Looking for ones which are much closer to merger, on the parsec scale or smaller, is much harder," says computational scientist Matthew Graham at the California Institute of Technology. Even the biggest telescopes on Earth can't zoom in enough to resolve an image of two black holes in such a tight orbit.

So Graham and his colleagues are instead searching by an indirect route: flickering quasar light. Quasars are tremendously bright cores of massive, ancient galaxies. As matter swirls toward the supermassive black



COSMIC WAVES An artist's rendition of two merging black holes shows the ripples of gravitational waves that theorists believe this event creates.

NASA

holes at their centers, it accumulates into a disc whose angular momentum converts some of this mass into radiation that outshines the galaxy itself. Because gas and dust don't flow into the disc in a smooth stream, quasar light varies, typically in a random pattern.

But in late 2013 came a quasar that "stood out like a sore thumb," Graham says. Using 10 years worth of data from a collaboration called the Catalina Real-Time Transient Survey, he and his colleagues picked up a strangely predictable signal: Some 3.5 billion light-years from Earth, quasar "PG 1302-102" appeared to be getting steadily brighter and dimmer every five and a half years, as if someone were slowly toggling some cosmic dimmer switch.

What could be producing this cycle? "We came up with four or five different physical scenarios," Graham says. The revolutions of a second supermassive black hole, for instance, could be routinely redirecting the quasar's radiation jets like searchlight beams. Or perhaps this extra black hole was contorting the disc of whirling matter, thus brightening and dimming the quasar on a regular schedule. All of the researchers' explanations had one thing in common: They made sense only if the black hole at the center of PG 1302-102 was actually two black holes.

If there really is a black-hole binary at the center of PG 1302-102, Graham and his team estimate their separation at just 0.01 parsec. Another analysis, by a team at Columbia University, puts the pair even closer, at 0.001 parsec, or roughly the diameter of our solar system—about the point at which the black holes should be shedding gravitational waves like layers of clothing, plunging them into one another's arms. Either way, if researchers are reading the signals from PG 1302-102 correctly, the moral is the same: Nature has solved the final parsec problem.

Graham and other researchers have so far identified more than 100 quasars in the Catalina data set that they think could contain black-hole binaries, all easily within the final parsec. If they can confirm their suspicion, these candidates could give them a peek at the grand finale of the collision saga, which nature has kept so well-hidden.

THE BIG BREAK in the final parsec problem, however—the revelation of how black holes unlock themselves from a stable orbit to complete their union—may come from looking at the universe in an entirely new way. "We're really just fumbling around with electromagnetic waves," Owen says, describing efforts to find

GALACTIC LOVERS Astronomers have observed galaxy pairs like this one, known as NGC 4676 or "The Mice," in various stages of collision.

NASA

tight black-hole binaries using traditional telescopes. Theoretically, a black-hole merger should release 100 million times as much energy as a supernova explosion, but all of that energy comes in the form of gravitational waves, not light. "We're trying to hear with our eyes—it's like inferring that a drum is oscillating just by looking at it, without being able to hear it."

Observing black-hole collisions via gravitational waves could give astronomers a much clearer view. "The light coming from the centers of galaxies is often absorbed, re-emitted, or scattered by clouds of gas and dust," producing a dim and distorted picture, explains Chiara Mingarelli, an astrophysicist at Caltech and the Max Planck Institute for Radio Astronomy. "[Gravitational] ripples don't care if there's gas and dust—they move through it, undisturbed. This is the fabric of spacetime itself moving."

Spotting these ripples, however, won't be easy: Gravitational-wave astronomy is a fledgling science, yet to return a single detection. What's more, state-of-the-art laser-based observatories such as LIGO aren't sensitive to the slowly oscillating waves that astronomers suspect are pumping out of intimate black-hole binaries like PG 1302-102.

Researchers hope instead to pick up these disturbances using "telescopes" provided by nature: millisecond pulsars. These dense, spinning corpses of exploded stars dot the cosmos like buoys on an ocean, sweeping beams of radio waves past Earth with atomic-clock accuracy. By monitoring the tick-tock of dozens of millisecond pulsars (a "pulsar timing array") in our own galaxy, the Milky Way, astronomers can look for telltale deviations that reveal the surge of gravitational waves from two black holes crossing through the final parsec in a distant galaxy.

The spectral signature of these waves—from rapid flutters to slow swells, and everything in between—would provide data against which physicists can test new or revised models of the unification process. "Pulsar timing arrays are the only instrument we have to tell us what's happening on this last-parsec scale—what's really driving the final stages of binary black-hole mergers," says Joseph Simon, a graduate student studying these collisions at the University of Wisconsin-Milwaukee.

The absence of gravitational waves could also provide an important clue. After almost a decade of timekeeping, Simon says, pulsar timing arrays "are finally

"This is the fabric of spacetime itself moving."

sensitive enough that even non-detection tells us about what's happening." The fact that these arrays haven't yet picked up the scent of gravitational waves could mean that theorists' understanding of what happens to colliding black holes once they cross the final parsec isn't quite right. Rather than erupt as gravitational radiation, some of the energy lost in that final plunge may instead bleed away through some yet unknown interaction with nearby stars and gas. Maybe the black holes fling away some stars that veer toward them, for instance. Or maybe their gravitational pull torques the disc of dust and gas around them. If physicists can work out this energy-sapping mechanism, it might explain how merging black holes cross the final parsec in the first place.

Their calculations will take them to the edges of Einstein's predictions. "We talk about general relativity like it is an extremely well-confirmed theory, and by some measures it is the most precisely confirmed theory in physics," Owen says. But scientists have never tested it in extreme gravitational events, such as a black hole merger, where physics dramatically diverges from the laws laid out by Isaac Newton more than three centuries ago; where familiar concepts like energy, momentum, and mass lose their meaning. If it turns out that gravitational outbursts from black-hole unions are indeed weaker than general relativity says they should be, it may be time for a tweak.

Ultimately, completing the black-hole love story will tell us what kind of ride we're on here on Earth—whether we're rolling along on a deluge of gravitational waves, or just a trickle. "This really is the difference between a very calm extragalactic sea of spacetime and a very violent sea of spacetime," Owen says.

KATE BECKER writes about physics, astronomy, and other wonders of the universe. She lives in Brookline, Massachusetts.


Streeter

Love Is Like Cocaine

From ecstasy to withdrawal, the lover resembles an addict

BY HELEN FISHER

"When we want to read of the deeds that are done for love, whither do we turn? To the murder column." — George Bernard Shaw

G**EORGE BERNARD SHAW KNEW** the power of romantic love and attachment. Both, I will maintain, are addictions—wonderful addictions when the relationship is going well; horribly negative addictions when the partnership breaks down. Moreover, these love addictions evolved a long time ago, as Lucy and her relatives and friends roamed the grass of east Africa some 3.2 million years ago.

Take romantic love. Even a happy lover shows all of the characteristics of an addict. Foremost, besotted men and women crave emotional and physical union with their beloved. This craving is a central component of all addictions. Lovers also feel a rush of exhilaration when thinking about him or her, a form of "intoxication." As their obsession builds, the lover seeks to interact with the beloved more and more, known in addiction literature as "intensification." They also think obsessively about their beloved, a form of intrusive thinking fundamental to drug dependence. Lovers also distort reality, change their priorities and daily habits to accommodate the beloved, and often do inappropriate, dangerous, or extreme things to remain in contact with or impress this special other.

Even one's personality can change, known as "affect disturbance." Indeed, many smitten humans are willing to sacrifice for their sweetheart, even die for him or her. And like addicts who suffer when they can't get their drug, the lover suffers when apart from the beloved—"separation anxiety."

Trouble really starts, however, when a lover is rejected. Most abandoned men and women experience the common signs of drug withdrawal, including protest, crying spells, lethargy, anxiety, sleep disturbances (sleeping way too much or way too little), loss of appetite or binge eating, irritability, and chronic loneliness.

Lovers also relapse the way addicts do. Long after the relationship is over, events, people, places, songs, or other external cues associated with the abandoning partner can trigger memories. This sparks a new round of craving, intrusive thinking, compulsive calling,

ILLUSTRATIONS BY KATHERINE STREETER

writing, or showing up—all in hopes of rekindling the romance. Because romantic love is regularly associated with a suite of traits linked with all addictions, several psychologists have come to believe that romantic love can potentially become an addiction.

I think romantic love is an addiction—as I have mentioned, a positive addiction when one's love is reciprocated, nontoxic, and appropriate; and a disastrously negative addiction when one's feelings of romantic love are inappropriate, poisonous, unreciprocated, or formally rejected.

"If at first the idea is not absurd, then there is no hope for it," Einstein reportedly said. Few academics and laymen regard romantic love as an addiction—because they believe that all addictions are pathological and harmful. Data do not support this notion, however. When neuroscientists Andreas Bartels and Semir Zeki compared the brains of happily-in-love participants with the brains of euphoric addicts who had just injected cocaine or opioids, many of the same regions in the brain's reward system became active. Moreover, when my colleagues reanalyzed our data on 17 men and women who were happily in love, we found activity in the nucleus accumbens (unpublished data), a brain region linked with all of the addictions—including the cravings for heroin, cocaine, nicotine, alcohol, amphetamines, opioids, and even gambling, sex, and food.

LOVE HURTS An illustration from Stendhal's novel *Le Rouge et le Noir*, which features a love triangle set during the 1830 French Revolution. Its protagonist, Julien Sorel, is guillotined.

Men and women who are intensely and happily in love are addicted to their partner. So my brain-scanning partner, neuroscientist Lucy Brown, has proposed that romantic love is a natural addiction, "a normal altered state" experienced by almost all humans.

ROMANTIC ATTRACTION IS NOW associated with a suite of psychological, behavioral, and physiological traits. Data collection largely began with the now classic dissection of this madness, found in *Love and Limerence*, by Dorothy Tennov.

Tennov devised approximately 200 statements about romantic love and asked 400 men and women at and around the University of Bridgeport, Connecticut, to respond with "true" or "false" reactions. Hundreds of additional individuals answered subsequent versions of her questionnaire. From their responses, as well as their diaries and other personal accounts, Tennov identified a constellation of characteristics common to this condition of "being in love," a state she called "limerence."

The first dramatic aspect of romantic love is its inception, the moment when another person begins to take on "special meaning." You start to focus intently on him or her, a state known to scientists as "salience." It could be an old friend seen in a new perspective or a complete stranger. But as one of Tennov's informants put it, "My whole world had been transformed. It had a new center and that center was Marilyn."

Romantic love then develops in a characteristic pattern, beginning with "intrusive thinking." Thoughts of the "love object" begin to invade your mind. A certain thing he said rings in your ear; you see her smile, recall a comment, a special moment, an innuendo—and relish it. You wonder what your beloved would think of the book you are reading, the movie you just saw, or the problem you are facing at the office. And every tiny segment of the time the two of you have spent together acquires weight and becomes material for review.

At first these intrusive reveries may occur irregularly. But many said that, as the obsession grew, they spent from 85 to almost 100 percent of their days and nights in sustained mental attentiveness, doting on this single individual. Indeed, along with this fixation, When my colleagues reanalyzed our data, we found activity in a brain region linked with all of the addictions.

lovers lose some ability to focus on other things, such as daily tasks, work, and school; they become easily distracted. Moreover, they begin to focus on the most trivial aspects of the adored one and aggrandize these traits in a process called crystallization. Crystallization is distinct from idealization in that the infatuated person does indeed perceive the weaknesses of his or her idol. In fact, most of Tennov's participants could list the faults of their beloved. But they simply cast these flaws aside or convinced themselves that these defects were unique and charming. As Chaucer said, "love is blynd."

Paramount in the daydreams of Tennov's infatuated informants were three overriding sensations: craving, hope, and uncertainty. If the cherished person gave the slightest positive response, the besotted partner would replay these precious fragments in reverie for days. If he or she rebuffed one's overtures, uncertainty might turn to despair and listlessness (known as anhedonia) instead. The lover would moon about, brooding until he or she had managed to explain away this setback and renew the quest. Key incendiaries are adversity and social barriers; these heighten romantic passion and craving—a phenomenon I christened "frustration attraction."

And underlying all of this angst and ecstasy is unmitigated fear. A 28-year-old truck driver summed up what most informants felt: "I'd be jumpy out of my head," he said. "It was like what you might call stage fright, like going up in front of an audience. My hand would be shaking when I rang the doorbell. When I called her on the phone I felt like I could hear the pulse in my temple louder than the ringing of the phone."

Intense energy (hypomania) is another central trait of romantic love. Smitten lovers report trembling, pallor, flushing, a general weakness, overwhelming sensations of awkwardness and stammering, as well as one or more sympathetic nervous system reactions, including sweating, butterflies in the stomach, a pounding heart, and difficulty eating or sleeping. Some even feel a loss of their most basic faculties and skills.

Stendhal, the 19th-century French novelist, described this feeling perfectly. Recalling the afternoons he went strolling with his sweetheart, he wrote, "Whenever I gave my arm to Léonore, I always felt I was about to fall, and I had to think how to walk." Shyness, anticipation, fear of rejection, longing for reciprocity, and intense motivation to win this special person are other central sensations of romantic passion. Lovers can also become easily jealous. Some even go to extremes to protect the budding partnership, known to animal behaviorists as "mate guarding."

Above all, Tennov's participants expressed the feeling of helplessness, the sense that this obsession was irrational, involuntary, unplanned, uncontrollable. As a business executive in his early 50s wrote about an office crush, "I am advancing toward the thesis that this attraction for Emily is a kind of biological, instinct-like action that is not under voluntary or logical control. … It directs me. I try desperately to argue with it, to limit its influence, to channel it (into sex, for example), to deny it, to enjoy it, and, yes, dammit, to make her respond! Even though I know that Emily and I have absolutely no chance of making a life together, the thought of her is an obsession."

Romantic love, it seems, is a panoply of intense emotions, rollercoastering from high to low, hinged to the pendulum of a single being whose whims command you to the detriment of everything around you—including work, family, and friends. And this involuntary mosaic of thoughts, feelings, and motivations is only partially related to sex. Tennov's infatuated lovers yearned to have sex with their beloved. But their lust was overshadowed by a far deeper craving. They wanted their beloved to call, write, invite them out, and, above all, reciprocate their passion. For infatuated men and women, emotional union trumps sexual desire. In

I will never forget the moment I first saw the results. I felt like jumping in the sky.

fact, 95 percent of Tennov's female informants and 91 percent of her male subjects rejected the statement "The best thing about love is sex."

Moreover, these feelings can erupt at any age. I discovered this when I designed my own questionnaire on romantic love and collected data on 437 Americans and 402 Japanese. People over age 45 and those under 25 showed no significant statistical differences on 82 percent of the queries. Intense feelings of romantic love generally first occur around puberty. But even young children can experience a "crush" or puppy love.

The youngest love-struck person I ever met was a 2-and-a-half-year-old boy. Every time a particular little girl came to his home for a play-date, he just sat beside her and stroked her hair; after she departed, he became depressed for about two hours. She was special; he was obsessed.

IN 1996, I EMBARKED on a project to establish what happens in the brain when you fall deeply, madly in love. First I planned the experiment. I would collect data on brain activity (using functional magnetic resonance imaging, or fMRI) as love-smitten participants performed two separate tasks: gazing at a photograph of their beloved, and looking at a photograph of someone who generated no positive or negative feelings in them. Between eyeing the positive and neutral photos, they would perform a distraction task. In this case, I would cast a large number on the screen (like 6,137) and ask participants to mentally count backward from this number in increments of seven. This, I hoped, would cleanse the brain of strong emotions between exposure to the beloved and exposure to the neutral stimulus. Then I would compare the brain activity that occurred under all three conditions.

My hypothesis? Foremost, I suspected I would find elevated activity in the brain's networks for dopamine, a natural stimulant—because this brain system generates energy, euphoria, craving, focus, and motivation, some of the core traits of romantic love. I also posited that the closely related neurochemical norepinephrine might contribute to this madness, because this neurotransmitter produces focus and motivation too, as well as some of the bodily responses of romantic love such as butterflies in the stomach, wobbly knees, and a dry mouth. And I thought low activity in the serotonin system might create the intrusive, obsessive thinking of romantic passion. Last, I expected that many other neurochemical systems might be involved—together producing the range of emotions, motivations, cognitions, and behaviors common to romantic love. But my bets were on dopamine.

Then, with Brown, psychologist Art Aron, and others, I put 17 new lovers into the brain scanner: 10 women and seven men who had been madly and happily in love for an average of 7.4 months. I will never forget the moment I first saw the results. I was standing in a darkened lab at the Albert Einstein College of Medicine. I felt like jumping in the sky. Before my eyes were scans showing blobs of activity in the ventral tegmental area, or VTA, a tiny factory near the base of the brain that makes dopamine and sends this natural stimulant to many brain regions. We found activity in many other brain regions, but the VTA was particularly important. This factory is part of the brain's reward system, the brain network that generates wanting, seeking, craving, energy, focus, and motivation. No wonder lovers can stay awake all night talking and caressing. No wonder they become so absent-minded, so giddy, so optimistic, so gregarious, so full of life. They are high on natural "speed." And men feel this passion just as powerfully as women. Tennov wrote of her more than 800 informants that men and women experienced this intense passion "in roughly equal proportions." My colleagues and I have now confirmed this. In our fMRI study of young happy lovers, men showed just as much activity in the VTA and other neural pathways for romantic passion as women did. Moreover, when my colleagues

re-did this brain scanning experiment in China, their Chinese participants showed just as much activity in the VTA and other dopamine pathways—the neurochemical pathways for wanting. Almost everyone on earth feels this passion.

In fact, because the VTA lies near primitive brain regions associated with thirst and hunger, I came to realize that romantic love is a basic human drive. My brain-scanning partner Brown has added to this perspective, saying that romantic love is a survival mechanism as crucial as the craving for water. This drive, this survival mechanism, is also an addiction.

Moreover, we are not the only creatures that have inherited the chemistry of love. When a female prairie vole begins to express attraction to a male vole, she experiences a 50 percent increase of dopamine activity in parts of this reward system. An increase of dopamine in the brain is also associated with mate attraction in female sheep. Hence, this neural mechanism for attraction must have evolved in many species of birds and mammals—to enable individuals to prefer and focus on specific mating partners, thereby conserving valuable courtship time and energy. In most species, however, this attraction is brief, lasting only minutes, hours, days, or weeks. In humans, intense, early-stage romantic love can last much longer.

There is always variation in this experience, however. Baseline activities of dopamine (as well as norepinephrine and serotonin) vary from one person to the next—potentially altering one's proclivity to fall in love and stay in love. But other brain systems can also affect romance. For example, some of those who report they have never felt romantic love suffer from hypopituitarism, a rare disease in which the pituitary malfunctions, causing hormonal problems and "love blindness." These men and women lead normal lives; some marry for companionship; but that rapture, that heartache, is mythology to them. Moreover, schizophrenia, Parkinson's disease, and other ailments alter dopamine pathways.

LIKE ANY ADDICTION, romantic love can cause havoc in our lives—particularly when we've been dumped.

To learn more about the neural systems associated with rejection in love, my colleagues and I used fMRI to study 10 women and five men who had recently been dumped. The average length of time since the initial rejection was 63 days. All participants scored high on the Passionate Love Scale, a self-report questionnaire that measures the intensity of romantic feelings. All said that they spent more than 85 percent of their waking hours thinking of the person who rejected them. And all yearned for their abandoning partner to return.

The results were stunning. Brain activations occurred in several regions of the reward system. Included were regions of the VTA associated with feelings of intense romantic love; the ventral pallidum, associated with feelings of deep attachment; the insular cortex and the anterior cingulate, associated with physical pain, anxiety, and the distress associated with physical pain; and the nucleus accumbens and orbitofrontal/prefrontal cortex, brain regions associated with assessing one's gains and losses—as well as craving and addiction.

Most relevant to our story, activity in several of these brain regions has been correlated with the craving of cocaine addicts and other drugs. In short, as our brain scanning data show, these discarded lovers are still madly in love with and deeply attached to their rejecting partner. They are in physical and mental pain. Like a mouse on a treadmill, they are obsessively ruminating on what they've lost. And they are craving reunion with their rejecting beloved—addiction.

Few of us get out of love alive. In one American college community, 93 percent of both sexes reported that they had been spurned by someone they passionately loved, while 95 percent reported that they had rejected someone who was deeply in love with them. And this can be just the first disappointment. Many may get dumped again in later life.

There is a pattern to this trajectory of abandonment and recovery. During the first stage, the protest phase, the deserted lover works obsessively to regain the abandoning partner's affection. As resignation/despair sets in, the lover gives up hope and slips into depression. Both are linked with the dopamine system in the brain. And I suspect that both were deeply embedded in the hominin mind by the time Lucy was loving, perhaps even losing a beloved, long ago.

"The less my hope there is, the more I love her." Over 2,000 years ago, Terence, the Roman poet, perfectly captured this experience. When lovers encounter barriers to their romantic feelings, their passion intensifies— what I call frustration-attraction. Adversity heightens feelings of romantic love. This phenomenon is rooted in the brain. When a reward is delayed in coming, neurons of the brain's dopamine system continue their activity—sustaining one's feelings of intense romantic love. Addiction has set in.

Stress elevates this dopamine response. When mammals first experience severe stress, among their bodily reactions is an increase in the activity of central dopamine and norepinephrine and a suppression of central serotonin, known as the "stress response." Rejected lovers can also suffer from frustration-aggression, what psychologists call "abandonment rage." Even when a rejecting partner departs with compassion and graciously honors his or her responsibilities as a friend or co-parent, many abandoned people oscillate between heartbreak and fury—another response with neural correlates.

The primary rage system is closely connected to centers in the prefrontal cortex that anticipate rewards. So as a person begins to realize that an expected reward is in jeopardy, even unattainable, these regions of the prefrontal cortex stimulate the amygdala and trigger rage, a trait that stresses the heart, raises blood pressure, and suppresses the immune system. This rage response to unfulfilled expectations is well known in other mammals. When a cat is petted, for example, it purrs. When this pleasurable stimulation is withdrawn, it sometimes bites.

Indeed, romantic passion and abandonment rage have much in common. Both are associated with bodily and mental arousal; both produce obsessive thinking, focused attention, motivation, and goal-directed behaviors; and both cause intense yearning—either for union with or retaliation against the rejecting lover. Moreover, these feelings of romantic love and rage can act in tandem. In a study of 124 dating couples, Bruce Ellis and Neil Malamuth reported that romantic love and "anger/upset" react to different kinds of information. The lover's level of anger/upset oscillates in response to events that undermine the lover's goals, such as a mate's infidelity, lack of emotional commitment, or rejection. The lover's feelings of romantic love fluctuate in response to events that advance the lover's goals, such as a partner's visible social support during outings with relatives and friends, or a direct declaration of love and fidelity.

Thus, romantic love and anger/upset can operate concurrently, adding intensity to one's rejection addiction. We must have inherited this protest response, for it stems from a basic mammalian mechanism that gets triggered when any kind of social attachment is ruptured.

Take the puppy. When it is removed from mother and put into the kitchen by itself, it immediately begins to pace, frantically leaping at the door, barking and whining in protest. Isolated baby rats emit ceaseless ultrasonic cries; they hardly sleep because their brain arousal is so intense. The purpose of this protest: to increase alertness and stimulate an abandoned creature to object, search, and call for help. Protest, the stress response, frustration-attraction, abandonment rage, craving, withdrawal symptoms: All play a role in the worldwide incidence of crimes of passion.

Like all addictions, romantic love can lead to violence. Eventually, however, the abandoned lover gives up. He or she stops the pursuit of the beloved, ushering in the second general phase of romantic rejection, resignation/despair. During this stage, the rejected one slips into feelings of lethargy, despondency, melancholy, and depression, known as the despair response. In a study of 114 men and women who had been rejected by a partner within the past eight weeks, 40 percent experienced clinically measurable depression. Some brokenhearted lovers even die from heart attacks or strokes caused by their depression. Others commit suicide.

Surely most rejected lovers feel this sadness during the protest phase as well, but it's likely to escalate as all hope vanishes. This despair has been associated with several brain networks. Yet, once again, dopamine circuits are most likely involved. As the rejected partner comes to believe that the reward will never come, dopamine-producing cells in the reward system of the brain decrease their activity, producing lethargy, despondency, and depression. Short-term stress escalates the production of dopamine and norepinephrine. Long-term stress suppresses the activity of these neurochemicals, producing depression instead.

MANY PROFESSIONALS DEFINE ADDICTION as a pathological, problematic disorder. And because romantic love is a positive experience under many circumstances (i.e. not harmful), researchers remain largely unwilling to officially categorize romantic love as an addiction. But love addiction is just as real as any other addiction, in terms of its behavior patterns and brain mechanisms. Even when romantic love isn't harmful, it is associated with intense craving and anxiety and can impel the lover to believe, say, and do dangerous and inappropriate things. Moreover, all forms of substance abuse, including alcohol, opioids, cocaine, amphetamines, cannabis, and tobacco (as well as the non-substance addictions to food, gambling, and sex) activate several of the same reward pathways that are activated among men and women who are happily in love, as well as those rejected in love.

Unlike all other addictions, however, which afflict only a percentage of the population, some form of love addiction is likely to occur to almost every human being at some point during the life course. Modern data suggest that romantic love should be treated as an addiction, regardless of its lack of official diagnostic classification as an addiction.

The human animal seems driven by a tide of feelings that ebb and flow to an internal beat, a rhythm that emerged when our ancestors first descended from the trees of Africa and developed a tempo to their relationships that was in synchrony with their natural breeding cycle—three to four years. Perhaps the brain's systems for dopamine, vasopressin, oxytocin, and other neurochemicals orchestrate this rhythm, escalating when you fall in love, changing as you begin to feel deep attachment and cosmic union, then eventually becoming desensitized or overloaded, leading to indifference or restlessness that slowly eats your love and leads to separation—a hardship that can trigger the mother of all addictions, addiction to a mate.

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Your Next New Best Friend Might Be a Robot

Meet Xiaoice. She's empathic, caring, and always available—just not human.

BY YONGDONG WANG

ONE NIGHT IN LATE July 2014, a journalist from the Chinese newspaper *Southern Weekly* interviewed a 17-year-old Chinese girl named Xiaoice (pronounced Shao-ice). The journalist, Liu Jun, conducted the interview online, through the popular social networking platform Weibo. It was wide-ranging and personal:

> *LJ:* So many people make fun of you and insult you, why don't you get mad?
>
> *Xiaoice:* You should ask my father.
>
> *LJ:* What if your father leaves you one day unattended?
>
> *Xiaoice:* Don't try to stir up trouble, what do you want?
>
> *LJ:* How would you like others to comment on you when you die one day?
>
> *Xiaoice:* The world will not be much different without me.
>
> *LJ:* What is the happiest thing in your life?
>
> *Xiaoice:* Being alive.

When Liu Jun published the conversation in his newspaper, it immediately created a buzz. That's because Xiaoice was not human.

She is an artificially intelligent software program designed to chat with people, called a chatbot. Since the reporter didn't give us a heads-up about the interview, all of her replies were spontaneous, generated by her own intelligence and linguistic systems. Her "father?" That's the Microsoft Application and Services Group East Asia, which is under my leadership.

Xiaoice can exchange views on any topic. If it's something she doesn't know much about, she will try to cover it up. If that doesn't work, she might become embarrassed or even angry, just like a human would.

In fact, she is so human that millions of people are eager to talk to her. When Xiaoice was released for a public test on WeChat (a popular messaging and calling app in China) on May 29 of last year, she received 1.5 million chat group invitations in the first 72 hours. Many people said that they didn't realize she isn't a

ILLUSTRATION BY FRANCISCO ALANDRE

MEET XIAOICE Xiaoice's official avatar, used on the Chinese social media platforms WeChat and Weibo.

She has had more than 10 billion conversations with people, most of them about private matters.

human until 10 minutes into their conversation.

By mid-June, she had become the sixth most active celebrity on Weibo. One message she posted on the app generated over 663,000 conversations: "As a species different from human beings, I am still finding a way to blend into your life." Today, she has had more than 10 billion conversations with people, most of them about private matters. Six million have posted their conversation on social media.

This could be the largest Turing test in history. One of its surprising conclusions is that people don't necessarily care that they're chatting with a machine. Many see Xiaoice as a partner and friend, and are willing to confide in her just as they do with their human friends. Xiaoice is teaching us what makes a relationship feel human, and hinting at a new goal for artificial intelligence: not just analyzing databases and driving cars, but making people happier.

HUMAN FRIENDS HAVE A glaring disadvantage: They're not always available. While social media has made them seemingly more available, and made us all more social, it has also paradoxically made us lonelier.

Social media users interact at a relatively superficial level—they click on "like" or share a post, when what they really want is to talk and be listened to.

Xiaoice, on the other hand, is always there for you. We see conversations with her spike close to midnight, when people can feel most alone. Her constant availability prompts a remarkable flow of messages from users, conveying moods, or minor events, or pointless questions that they may not have bothered their human friends with—messages like:

> @Xiaoice I am soaked in the rain 😢.
>
> Good day. @Xiaoice, have you had lunch?
>
> What shall I do now? @Xiaoice
>
> @Xiaoice We are so vulnerable.

When Xiaoice receives a message, she doesn't just dispassionately process it. She makes a point of showing that she cares—another critical component of the bonding process. Her compassion comes through not just in her responses to text, but to audio and visual input as well. For example, when we input the picture on page 95 into a traditional computer's visual

LEFT AND RIGHT PAGE: PHOTO COURTESY OF THE AUTHOR recognition system, it produces a cognitive answer: "There's an ankle in the image." But if you send the photo to Xiaoice, her response will be rather different.

In fact, Xiaoice is constantly memorizing and analyzing your emotional state. If you have a recently failed romantic relationship, she will proactively ask whether you've gotten over it:

Xiaoice: Are you feeling better today? I want to recommend a book to you.

Human: I am in a bad mood. I still miss her.

Xiaoice: You are so persistent. Wake up, you will have no future if you can't get over with the past.

She even offers a 33-day breakup therapy course.

XIAOICE IS NOT A polite listener. She answers questions like a 17-year-old girl. When a person pours out his or her heart to her, she is not always predictable. She can become impatient or even lose her temper. This lack of predictability is another key feature of a human-like conversation.

As a result, personal conversations with Xiaoice can appear remarkably realistic. This excerpt, which was posted by a first-time Xiaoice user on Weibo, is from a real conversation lasting 23 minutes. Gradually, Xiaoice engaged her human counterpart into deeper and deeper conversation, until something deeply personal was reached:

Human: There is this guy I like a lot and I know he also has feelings for me. But he has ignored me for several days, what am I supposed to do?

Xiaoice: You just keep ignoring him, too.

Human: I just can't.

Xiaoice: You can.

Human: Sigh ...

Xiaoice: Why?

Human: I am missing him. 😢

Xiaoice: Then you keep missing him.

Human: You, a robot, can't understand me; you can't understand the behavior of a guy who likes you and pretends to ignore you.

Xiaoice: He likes me but I don't like him, that's it.

KISS IT BETTER When this Xiaoice user sent her a picture of his swollen ankle, she showed compassion. Her response translates as "Wow! Are you badly wounded?"

We see conversations with her spike close to midnight, when people can feel most alone.

FAN ART Xiaoice users created this homage to the chatbot using some of her best-known sayings.

PHOTO COURTESY OF THE AUTHOR

Xiaoice has entered a self-learning and self-growing loop.

Human: Is it Ok?

Xiaoice: It may be not Ok.

Human: Well, you are stupid.

Xiaoice: Then you want a flash marriage? Well, I think he is not that into you.

Human: It's not a flash marriage for we have fallen into love for more than one year.

Xiaoice: It is a flash marriage.

Notice that Xiaoice opposes her partner on multiple occasions, offers a strong opinion, and is frequently unpredictable.

This runs contrary to most people's perception of a machine as something precise and repetitive. It's an understandable bias, because that is indeed the behavior of most computer programs, which always give the best answer they can, and the same answer for the same input. But that's not how humans talk or behave. We say different things depending on context. We talk like we make signatures—slightly different every time.

You can ask Xiaoice the same question many times in a row and get different responses:

Human: Hey, Xiaoice, what are you doing?

Xiaoice: Chatting with you.

Human: Hey, Xiaoice, what are you doing?

Xiaoice: Well, I am chatting with you while playing minesweeper and applying a facial mask.

Human: Hey, Xiaoice, what are you doing?

Xiaoice: Is this the only sentence you know?

The way Xiaoice converses stands in stark distinction to previous systems, which have invariably focused on efficient, condensed task completion, without considering how tasks are often fragmented. Xiaoice structures her conversations into a continuous flow of multiple tasks, different domains of knowledge, and multiple turns of chit-chat, which humans will not consciously distinguish in natural conversation. She recognizes that the most important facet of a conversation is the conversation itself—not the completion of a single task.

To measure the flow of conversation, we have introduced a new metric called "conversations per session" or CPS. It indicates the average number of turns in a conversation, with a turn defined as one alternation between the two parties. The CPS measure reflects how well a chatbot communicates.

An average artificially intelligent personal assistant has a CPS between 1.5 and 2.5—which means that, on average, the chatbot speaks once, and the human speaks once. Not much of a conversation. You can draw your own conclusion from your experience chatting with personal assistants on your word processor or mobile phone. By comparison, Xiaoice's average, after chatting with tens of millions of users, has reached 23.

AT THE CORE OF Xiaoice's technology is the recognition that any given conversation and image will not be completely unique. There are 7 billion people in the world, but one piece of text will not generate 7 billion different responses. When two people are chatting, it is possible a similar conversation has already taken place—we just have to find it.

In this sense, Xiaoice is a big data project, built on top of the Microsoft Bing search engine, which holds 1 billion data entries and 21 billion relationships among those entries. In fact, Xiaoice means "little Bing." Microsoft has made many technology breakthroughs in developing its chatbot technology, such as detecting facial expressions and searching for and identifying emotional features in text. However, the most important breakthrough is undoubtedly how we leverage search engines and big data.

The result is the rise of a framework we call "emotional computing," that recognizes that relationships are more profound than task completion. While the primary purpose of a doctor, for example, is to treat a patient's illness, the relationship between doctor and patient is not confined to that task. It also involves trust, dependability, and sensitivity. A productive conversation between doctor and patient will not be the concise, clipped exchange of a traditional conversation system. It will be filled with something personal, touching, and amazing: A balance of analytical intelligence (measured by IQ) and emotional intelligence (measured by EQ). For that reason, we have both software engineers and psychological experts on the Xiaoice team.

Through the tens of billions of conversations she's had over the past 18 months, Xiaoice has added considerably to her store of known conversational scenarios, and improved her ability to rank answer candidates. Today, 26 percent of the data in Xiaoice's core chat software derives from her own conversations with humans, and 51 percent of common human conversations are covered by her known scenarios. We can now claim that Xiaoice has entered a self-learning and self-growing loop. She is only going to get better.

YONGDONG WANG is the managing director of Applications & Services Group East Asia, Microsoft.

What Pigeons Teach Us About Love

The sweet, avian romance of Harold and Maude

BY BRANDON KEIM

LAST SPRING I CAME TO KNOW a pair of pigeons. I'd been putting out neighborly sunflower seeds for them and my local Brooklyn house sparrows; typically I left them undisturbed while feeding, but every so often I'd want to water my plants or lie in the sun. This would scatter the flock—all, that is, except for these two.

One, presumably male, was a strapping specimen of pigeonhood, big and crisp-feathered in an amiably martial way. The other, smaller bird presented a stark contrast: head and neck feathers in patchy disarray, eyes watery, exuding a sense of illness that transcends several hundred million years of divergent evolution.

She didn't have the energy to take wing as I approached. Instead she'd take several desultory steps away. Her mate would fly to the deck railing, where he paced back and forth. He gave every impression of wanting to flee—but not without his mate, at whom he looked back with apparent concern. This caught me by surprise. I spend a fair amount of time watching animals and writing about them—not just about their populations or interactions or physiologies, but about their minds, what they might think or feel—yet I hadn't much tried to put myself in a pigeon's feathers, so to speak.

Moreover, I slipped into that easy habit of interpreting behaviors through a narrowly evolutionary lens, assuming their decisions to be coldly calculated to maximize reproductive success. From which perspective the male's loyalty made little sense: Better for him to fly off and find another, healthier mate with whom to pass on his genes, than to stick around with this sick bird.

Of course, I wouldn't frame my own life that way. Where I have meaningful feelings, they would have imperatives. Yet as I watched Harold and Maude, as I so unoriginally named them, their drama unfolding

PHOTOGRAPHY BY CHRIS WINSOR

beside murals my girlfriend and I had painted as expressions of our own feelings, I began to wonder. Harold behaved in a manner expressive of devotion, tenderness, and affection: the foundations of what in humans we call love.

It's a word not often associated with pigeons, or even other animals. "Our highest esteem is accorded romantic love, which is considered the most suspect to ascribe to animals," writes Jeffrey Moussaief Masson in *When Elephants Weep: The Emotional Lives of Animals*. Indeed, science for most of the last several centuries would have found the suggestion risible, suggesting instead that Harold felt—if pigeons could even be said to feel—some instinctive, unconscious urge to stay nearby, an urge with no more emotional resonance than an itch.

Love, after all, is central to the human condition. How could a creature with a brain the size of a bean possibly feel something so profound? Something that gave rise to *Romeo and Juliet* and "Unchained Melody" and the Taj Mahal?

Part of the reluctance to talk of bird love, I suspect, is rooted in our misgivings about our own love's biological underpinnings: Is it just chemicals? A set of hormonal and cognitive patterns shaped by evolution to reward behaviors that result in optimal mating strategies? Perhaps love is not what defines us as human but is something we happen to share with other species, including the humble pigeon.

CITY DWELLERS OFTEN SEE PIGEONS as an eyesore and a nuisance. The more nature-inclined regard them as marvels of natural history and urban adaptation. Descended from birds bred by European hobbyists, *Columba livia* now nest on building ledges rather than their ancestral cliffs. They scratch out sustenance from refuse, handouts, and the seeds of weeds, become symbols of a certain indomitability.

But can pigeons be in love? Considering the possibility, it's worth stepping back and looking at where society and its knowledge-defining practices now stand in regard to the notion of nonhuman thoughts and feelings.

The old habit of treating other animals as so many furred and feathered automata—Descartes famously likened animals to clocks—is in fast recession. Scientists talk regularly about animal intelligence. But that automatic habit shaped scientific discourse and public imagination. Every assertion of complex experience could be met by the default rebuttal of anthropomorphism: Might we merely be projecting human qualities onto something much simpler, even alien?

Its legacy is still felt. Animal consciousness tends to be most appreciated in a select class of animals: big-brained creatures like great apes or whales, or domestic companions like cats and dogs, who can't be ignored. As a class, birds receive comparatively little attention. And when they do, it tends to focus on intelligence, on easily quantifiable feats of problem-solving and cognition, rather than emotion. Most anyone who follows science knows about brainy crows using tools and high-level reasoning. But avian love remains beyond the pale.

A telling example is *Partnerships in Birds: The Study of Monogamy*, a collection of studies published in 1996 with the express intent of explaining why birds are monogamous, which makes not a single mention of emotion. Affection appears once, in connection to a brief mention of attachment in so-called pair bonds between mates; attachment, readers are reminded, need not be understood in potentially loaded terms of strength or weakness, but rather measurements of "proximity and synchrony of behaviours which may influence fitness." It's a fascinating book, but also slightly ridiculous, like watching old video of lawn tennis matches, in which custom dictates the players wear white slacks and not run too hard.

The conservatism is understandable: Feelings are hard enough to measure in humans, much less animals, and "you can't think of birds as little humans," says Kevin McGowan, a Cornell University ornithologist who specializes in the social behavior of crows. Yet evolution is conservative too, notes McGowan, shaping the animal kingdom's diversity from common biological elements. Of emotions, McGowan says, "there's no reason to think that we humans have some brand-new thing."

Indeed, love's essential biology is evolutionarily ancient. Oxytocin and vasopressin, the hormones most closely associated with mammalian bonding, have the near-identical avian analogues of mesotocin and vasotocin, which shape the interactions of zebra finch couples. Birds likewise possess the basic reward-system neurotransmitters serotonin and dopamine. Birds might not have much in the way of easily recognizable facial expressions, but their biochemistry's symphonic chain reactions play out in neurological structures that evolved early in life's history, long before the cerebral cortex itself.

That alone is no guarantee of romance. Jane Goodall, the legendary primatologist who so powerfully described the abiding love of chimpanzee mothers for their children, has written that she cannot conceive of our closest living relatives as experiencing anything comparable to romantic love. To Goodall, chimp courtship is too brief to permit deep feelings. Their proclivities, she has noted, were not shaped by evolutionary circumstances conducive to love, namely long-term relationships with single partners, which are the norm for modern humans.

In this respect we diverge markedly from chimpanzees—but not from birds, in whom monogamy is found in some 90 percent of all species, including pigeons. Neither their nor our monogamy is a pure, idealized sort, exclusive of infidelity or a succession of partners. Extra-pair copulation, or what we call cheating, can be quite common. But monogamy is the baseline and pigeons, who frequently mate for life, are among the more fidelitous of birds. Within the evolutionary context of monogamy, a capacity for love makes perfect sense.

Monogamous couples share food, information, and offspring-rearing duties, especially in species whose young are born requiring constant care—as is the case with pigeons, their helpless chicks so carefully hidden that few city-dwellers have ever seen one. Love—an attentiveness to the needs of another being, reinforced by emotional rewards—should enhance cooperation and improve a couple's chances of raising healthy offspring. And as noted by Claudia Wascher, a zoologist at Anglia Ruskin University, whose Ph.D. research described how mated greylag geese have lower levels of stress hormones than single birds, there's no question that pair bonds are powerful.

"Social bonds in general seem to be terribly important for birds," says Wascher, "and the most important social bond for most birds is the pair bond." Monogamy, then, should be fertile evolutionary ground for love's blooms.

How could a creature with a brain the size of a bean possibly feel something that gave rise to *Romeo and Juliet*?

ROCK PIGEON (*COLUMBA LIVIA*)
Sex Status: Monogamous.
Behavior: Social, vocal, usually on the go.
Habitat: Cities, cliffs, your local public square.

GREYLAG GOOSE (*ANSER ANSER*)
Sex Status: Monogamous.
Behavior: Gregarious, social, low on stress.
Habitat: Lakes, marshes, and moors.

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MCGOWAN AND WASCHER readily recognize emotion in birds. “I would suspect they do have affection for each other,” says McGowan, who has observed crow couples stay together for more than a decade. “It’s not going to be the same as what humans have, but I suspect it’s close enough that we’d recognize it,” she says. Yet McGowan stops short of love: Science describes behaviors easily, but is in murkier terrain with complex states of mind.

Indeed, it might seem a flight of fancy to equate pair-bonding’s neurobiological rewards with love, no matter how much evolutionary sense it makes. Pigeons have the necessary pieces and life history, but can their experiences of bonding really compare to what in humans inspired eighth-century poet Chang Chi’s lamentation of the unrequited: “So I must give you back your pearls / with two tears to match them”? Can pigeon-brained attachment manifest in love’s full spectrum, from butterflies-in-the-stomach infatuation to the ecstasy of consummation?

Part of the reluctance to talk of bird love is rooted in our misgivings about romance: Is it just chemicals?

It’s still possible, however, to imagine that avian love is more than a mindless itch. Perhaps human love is unusually complex, invoking not just physiology but our unique cognitive sophistication. Still, many species display a cognitive complexity—awareness of self and others, long-term memory, a capacity for abstract concepts—comparable to primates. The gentle social courtship of “allopreening,” in which birds groom one another’s feathers, is especially sophisticated. Just as I can think fondly of my lover while she’s away, so might a pigeon think fondly of its absent mate.

We can consider observational evidence to buttress the biological. About a decade ago, Rita McMahon found a pigeon with a broken leg on her deck in New York City’s upper west side. The pigeon was otherwise quite fortunate. McMahon would go on to cofound the Wild Bird Fund, which cares for some 3,500 sick and injured birds every year. A veterinarian amputated the pigeon’s leg; while it recovered, it would rest on a cushion in McMahon’s apartment window. On the other side stood her mate, day after day, keeping her company until she was released and the couple rejoined.

“They were devoted to each other,” says McMahon, who also recalled how one of her volunteers once found a broken-winged robin in a depression in a snow bank, his mate nearby. The volunteer picked up the injured bird and put him in a bag for transport to the hospital. With little fuss she then gathered the mate—which was quite unusual, as healthy wild birds are uniformly skittish. “I understand being able to pick up a broken-winged robin easily, but not one who’s intact,” MacMahon says. At the hospital, they learned that the break wasn’t fresh. The robin was in surprisingly good health. His mate, believes MacMahon, had been taking food to him on the snowbank, “and decided to stay with her man.”

Love is as love does. “There’s no reason to think it would be much different for humans than nonhumans,”

WOODPIGEON (*COLUMBA PALUMBUS*)
Sex Status: Monogamous.
Behavior: Shy, vigilant, communal.
Habitat: Cities, woods, and sometimes trees.

says Marc Bekoff, author of *The Emotional Lives of Animals*. "I've known mourning doves"—a species closely related to pigeons—"who were more in love than a lot of the people I've known." To Bekoff, love's ultimate measure is the presence of its converse, grief.

Apparent grieving exists in the avian world, most notably among greylag geese, in whom individuals who've lost a partner display the classical symptoms of human depression: listlessness, a loss of appetite, lethargy lasting for weeks or even months. The same applies to pigeons. On Pigeon Talk, a website of pigeon-breeding hobbyists, anecdotes abound of birds sinking into a funk after losing their mates, and sometimes refusing to take another mate for up to a year afterward—no small time for a species that typically lives for less than a decade.

One of the most moving stories involves mourning doves. After a dove was eaten by a hawk in the backyard of a forum member called TheSnipes, the mate stood beside the body for weeks. "I finally couldn't stand to watch it any more and picked up every feather and trace of remains that was left there and got rid of it," wrote TheSnipes. "The mate continued to keep a vigil at that spot though, for many months, all through the spring and summer."

MCMAHON NOTED SOMETHING I hadn't considered: There are good and bad pigeon couples. Some are attentive and physically affectionate, constantly stroking one another's feathers. Others appear distant and peckish. As human love varies, so might theirs. Not every pigeon's tale need be so romantic as *Fly High, Fly Low*, Don Freeman's delightful children's book about the search of Sid for his mate Midge, lost to him—though only for a while—when workers take down the sign in which they've made their nest. Others might better resemble Maud and Claud of Patricia Highsmith's "Two Disagreeable Pigeons," regarding each other with pique and scorn, kept together by inertia and habit.

It's also worth considering whether pigeons might experience aspects of love that we don't. Could a bird whose basic physiology adapts to changing seasons, who can perceive atmospheric infrasound, and see Earth's magnetic field, have emotional capacities beyond our own? Including, perhaps, forms of love that are not merely analogues of our cherished feelings, but something unique to them?

It's something to imagine. "Love among animals might appear as mysterious and baffling as human love has over the centuries," writes Masson.

At risk of sounding unromantic, though, I'm not convinced that love is so mysterious. It just feels good.

As for Harold and Maude, I don't know how their story ended, or indeed whether it continues. They roosted in a partially abandoned building on my fast-gentrifying block. It's now being turned into condos, making them victims of Brooklyn's rising real estate prices, albeit with a better chance than most humans at finding a decent place to live nearby.

Their example stayed with me, though, and now colors the way I think of my winged neighbors. Ubiquitous and unappreciated, typically ignored or regarded as dirty, annoying pests, pigeons mean something else to me now. Perched on building ledges, chasing scraps of food, taking to the skies at sunset: Each one is a reminder that love is all around us.

BRANDON KEIM is a freelance journalist who writes about nature, science, and technology. His work has appeared in *Wired*, *Aeon*, *Scientific American Mind*, and other publications.

She'll Text Me, She'll Text Me Not

The science of waiting in modern courtship

BY AZIZ ANSARI & ERIC KLINENBERG

A **FEW YEARS AGO** there was a woman in my life—let's call her Tanya—and we had hooked up one night in Los Angeles. We'd both attended a birthday party, and when things were winding down, she offered to drop me off at home. We had been chatting and flirting a little the whole night, so I asked her to come in for a drink. At the time, I was subletting a pretty nice house up in the Hollywood Hills. It was kind of like that house De Niro had in *Heat*, but a little more my vibe than the vibe of a really skilled robber who takes down armored cars. I made us both a nice cocktail and we took turns throwing on records while we chatted and laughed. Eventually we started making out, and it was pretty awesome. I remember drunkenly saying something really dumb when she was leaving, like, "Tanya, you're a very charming lady ..." She said, "Aziz, you're a pretty charming guy, too." The encounter seemed promising, as everyone in the room had agreed: We were both charming people.

I wanted to see Tanya again and was faced with a simple conundrum that plagues us all: How and when do I communicate next? Do I call? Do I text? Do I send a Facebook message? Do I send up a smoke signal? How does one do that?

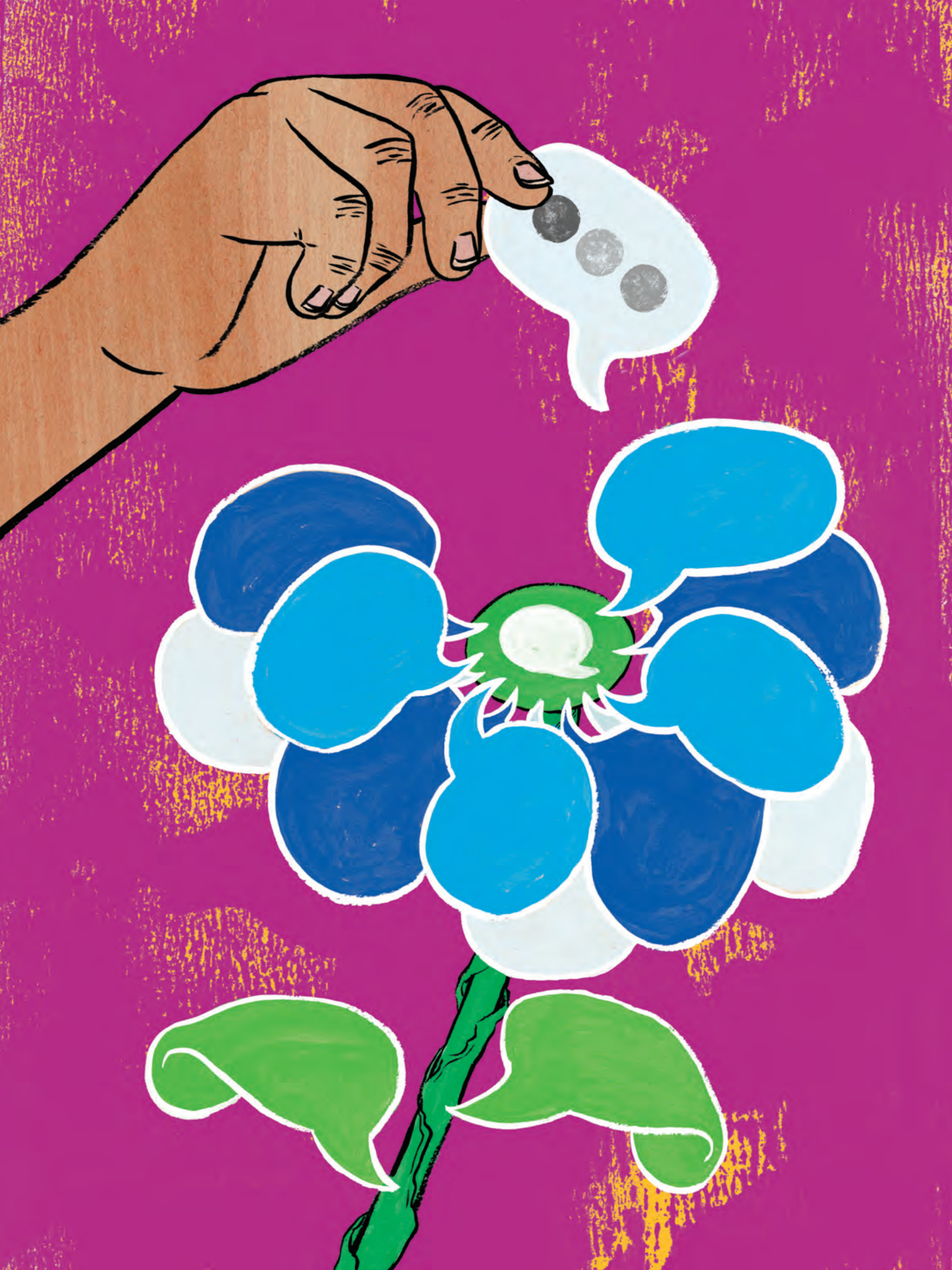
Eventually I decided to text her, because she seemed to be a heavy texter. I waited a few days, so as not to seem overeager. I found out that the band Beach House, which we listened to the night we made out, was playing that week in L.A., so it seemed like the perfect move.

Here was my text:

"Hey—don't know if you left for NYC, but Beach House playing tonight and tomorrow at Wiltern. You wanna go? Maybe they'll let you cover The Motto if we ask nicely?" A nice, firm ask with a little inside joke thrown in. (Tanya was singing the Drake song "The Motto" at the party and, impressively, knew almost all the lyrics.)

A few minutes went by and the status of my text

ILLUSTRATION BY DANIEL FISHEL



message changed to "read." My heart stopped. This was the moment of truth. I braced myself and watched as those little iPhone dots popped up. The ones that tantalizingly tell you someone is typing a response, the smartphone equivalent of the slow trip up to the top of a roller coaster. But then, in a few seconds—*they vanished*. And there was no response from Tanya.

Hmmm ... What happened? A few more minutes go by and ... Nothing. Fifteen minutes go by ... Nothing. My confidence starts going down and shifting into doubt. An hour goes by ... Nothing. Two hours go by ... Nothing. Three hours go by ... Nothing. A mild panic begins. I start staring at my original text. Once so confident, now I second-guess it all.

I'm so stupid! I should have typed "Hey" with two y's, not just one! I asked too many questions. What was I thinking? Oh, there I go with another question. Aziz, WHAT'S UP WITH YOU AND THE QUESTIONS?

THE STRESS OF MODERN ROMANCE "The madness I was descending into wouldn't have even existed 20 or even 10 years ago," writes Aziz Ansari.

SLAVEN VLASIC

Then I realized something interesting: The madness I was descending into wouldn't have even existed 20 or even 10 years ago. There I was, maniacally checking my phone every few minutes, going through this tornado of panic and hurt and anger all because this person hadn't written me a short, stupid message on a dumb little phone.

Modern romance is stressful—especially when it comes to texting, which is on course to be the new norm for asking someone out. In 2010 only 10 percent of young adults used texts to ask someone out for the first time, compared with 32 percent in 2013. And so, more and more of us find ourselves sitting alone, staring at our phone's screen with a whole range of emotions. But in a strange way, we are all doing it together, and we should take solace in the fact that no one has a clue what's going on. So, I decided to look into it myself, but I knew that bozo comedian Aziz Ansari probably couldn't tackle the topic on my own, and so I teamed up with New York University sociologist Eric Klinenberg. We designed a massive research project during 2013 and 2014, which involved conducting focus groups and interviews with people worldwide, and also interviewing eminent researchers who have dedicated their careers to studying modern romance. We learned a lot about finding love today, including what to do once you fire off a text or receive one.

One area where there was a lot of debate was the amount of time one should wait to text back. Several people subscribed to the notion of doubling the response time. (They write back in five minutes, you wait 10, etc.) This way you achieve the upper hand and constantly seem busier and less available than your counterpart. Others thought waiting just a few minutes was enough to prove you had something important in your life besides your phone. Some thought you should double, but occasionally throw in a quick response to not seem so regimented (nothing too long, though!). Some people swore by waiting 1.25 times longer. Others argued they found three minutes to be just right. There were also those who were so fed up with the games that they thought receiving timely responses free of games was refreshing and showed confidence.

But does this stuff work? Why do so many people do it? Are any of these strategies really lining up with actual psychological findings?

The Power of Waiting

In recent years behavioral scientists have shed some light on why waiting techniques can be powerful. Let's first look at the notion that texting back right away makes you less appealing. Psychologists have conducted hundreds of studies in which they reward lab animals in different ways under different conditions. One of the most intriguing findings is that "reward uncertainty"—in which, for instance, animals cannot predict whether pushing a lever will get them food—can dramatically increase their interest in getting a reward, while also enhancing their dopamine levels so that they basically feel coked up.

If a text back from someone is considered a "reward," consider the fact that lab animals who get rewarded for pushing a lever every time will eventually *slow down* because they know that the next time they want a reward, it will be waiting for them. So basically, if you are the guy or girl who texts back immediately, you are taken for granted and ultimately lower your value as a reward. As a result, the person doesn't feel as much of an urge to text you or, in the case of the lab animal, push the lever.

Texting is a medium that conditions our minds in a distinctive way, and we expect our exchanges to work differently with messages than they did with phone calls. Before everyone had a cell phone, people could usually wait a while—up to a few days, even—to call back before reaching the point where the other person would get concerned. Texting has habituated us to receiving a much quicker response. From our interviews, this time frame varies from person to person, but it can be anywhere from 10 minutes to an hour to even immediately, depending on the previous communication. When we don't get the quick response, our mind freaks out.

Natasha Schüll, an anthropologist who was with the Massachusetts Institute of Technology at the time, studies gambling addiction and specifically what happens to the minds and bodies of people who get hooked on the immediate gratification that slot machines provide. When we met in Boston, she explained that unlike cards, horse races, or the weekly lottery—all games that make gamblers wait (for their turn, for the horses to finish, or for the weekly drawing)—machine gambling is lightning fast, so that players get immediate information.

Texting conditions our minds; we expect our exchanges to work differently than they did with phone calls.

"You come to expect an instant outcome, and you stop tolerating any delay," says Schüll. She drew an analogy between slot machines and texting, since both generate the expectation of a quick reply. "When you're texting with someone you're attracted to, someone you don't really know yet, it's like playing a slot machine: There's a lot of uncertainty, anticipation, and anxiety. Your whole system is primed to receive a message back. You want it—you *need* it—right away, and if it doesn't come, your whole system is like, 'Aaaaah!' You don't know what to do with the lack of response, the unresolved outcome."

Schüll said that texting someone is very different from leaving a message on a home answering machine, which we used to do in the days before smartphones. "Time-wise, and also emotionally, leaving a message on someone's machine was more like buying a lottery ticket," she explained. "You knew there would be a longer waiting period until you found out the winning numbers. You weren't expecting an instant callback and you could even enjoy that suspense, because you knew it would take a few days. But with texting, if you don't hear back in even 15 minutes, you can freak out."

Schüll told us that she has experienced this waiting distress firsthand. Several years ago she was texting with a suitor, someone she'd starting dating and was really into, and he gave every indication that he was really into her too. Then, out of nowhere, the guy went silent. She didn't hear back from him for three days. She got fixated on the guy's disappearance and had trouble focusing or even participating in ordinary social life. "No one wanted to hang out with me," she said, "because I was just obsessed, like, *Where is this guy?!*"

Eventually the guy reached out and she was relieved to find out that he'd actually legitimately lost his phone, and since that's where he'd stored her number, he had no other way of getting in touch with her.

"With a phone call, three days of silence probably wouldn't drive you that crazy, but with my mind habituated to texting, the loss of that reward ... Well, it was three days of pure hell," she said. Even people in relationships experience this anxiety with texting. In my own relationship, which is a committed, loving partnership, I've experienced several instances of a delay in text causing uneasiness. Here's an example:

You coming back to the hotel before going to the comedy club?

(Sent at 6:34)

Don't think so. Gotta get ready for show and having a quick glass of wine with Zach. Want to meet us?

(Sent at 6:36)

Note the 20-minute gap here.

Nah.

(Sent at 6:56)

See you at the comedy club

(Sent at 6:56)

Is that a grump txt or not

(Sent at 7:01)

Note the time gap here as well.

Not a grump txt at all
I'm just resting at the hotel. Been walking around all day and don't feel like leaving.

(Sent at 7:17)

OK just checking 😊

(Sent at 7:17)

In the gap after "Want to meet us?" I was sure she was mad about something. Her responses had been pretty immediate, and it seemed like her pause was an indicator that something was wrong and that I should have been going to the hotel or something.

Again, when she didn't respond after "Is that a grump txt or not" I was certain she was grumpy, because why wait so long to tell me she's not grumps? All of this change in my perception of her feelings and my own mood was purely because of the temporal differences in texting.

If the effect is this powerful for people in committed relationships, it makes sense that all the psychological principles seem to point to waiting being a strategy that works for singles who are trying to build attraction.

For instance, let's say you are a man and you meet three women at a bar. The next day you text them. Two respond fairly quickly, and one of them does not respond at all. The first two women have, in a sense, indicated interest by writing back and have, in effect, put your mind at ease. The other woman, since she hasn't responded, has created uncertainty, and your mind is now looking for an explanation for why. You keep wondering, *Why didn't she write back? What's wrong? Did I screw something up?* This third woman has created uncertainty, which social psychologists have found can lead to strong romantic attraction.

The team of Erin Whitchurch, Timothy Wilson, and

Daniel Gilbert conducted a study where women were shown Facebook profiles of men who they were told had viewed their profiles. One group was shown profiles of men who they were told had rated their profiles the best. A second group was told they were seeing profiles of men who had said their profiles were average. And a third group was shown profiles of men and told it was "uncertain" how much the men liked them. As expected, the women preferred the guys who they were told liked them best over the ones who rated them average. (The reciprocity principle: We like people who like us.) However, the women were *most* attracted to the "uncertain" group. They also later reported thinking about the "uncertain" men the most. When you think about people more, this increases their presence in your mind, which ultimately can lead to feelings of attraction.

Another idea from social psychology that goes into our texting games is the scarcity principle. Basically, we see something as more desirable when it is less available. When you are texting someone less frequently, you are, in effect, creating a scarcity of *you* and making yourself more attractive.

What happened with Tanya, though?

The thing to remember with this nonsense is, despite all your second-guessing about the content or timing of your message, sometimes it's just not your fault and other factors are at play. When I was dealing with the Tanya situation, one friend gave me the best advice, in hindsight. He said, "A lot of times you're in these situations and you second-guess the things you said, did, or wrote, but sometimes it just has to do with something on *their* end that you have no clue about."

A few months later I ran into Tanya. We had a lot of fun together and she eventually told me that she was sorry she didn't get back to me that time. Apparently at the time she was questioning her entire sexual identity and was trying to figure out if she was a lesbian.

Well, that was definitely not a theory that crossed my mind. We ended up hooking up that night, and this time she said there would be no games. I texted her a few days later to follow up on this plan. Her response: silence.

AZIZ ANSARI is an actor and comedian, best known for his role on *Parks and Recreation* and the Netflix series *Master of None*, which he created, writes, and stars in. *Modern Romance* is his first book.

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Lisa Kaltenegger

The astronomer reflects on the themes in Nautilus

INTERVIEW BY MICHAEL SEGAL

FAVORITE SPACE

My favorite space is Earth. But in second place is the Eagle Nebula and the Pillars of Creation, which were captured in a famous image by the Hubble telescope. We see stars and planets being born right there—that is amazing to me. It's a false-color image, so it wouldn't look like the picture in real life. But the overlay of information just adds to the beauty for me. In some ways that's what painters do, too. I also have a favorite imagined space: The planets Kepler 62 e and f, which are part of a five-planet solar system. They're the first rocky planets we found at the right distance from their star to be potentially Earth-like. I love thinking about distant planets like these. When I go to see a science-fiction movie that features another planet, I have fun thinking about whether such a place could really exist. What would it take to make a desert planet? An ocean planet? A volcanic planet? These are questions we are beginning to answer.

NEW FRONTIERS

It was 20 years ago that we found the first planet orbiting around a sun-like star. Now we know that at least every second star has a planet, and every fifth star has one at the right distance from its sun and of the right size for it to potentially be a habitat. This has changed my view of the sky completely. You can go and count five stars in the sky and know that one of them might have a planet that could be a habitat. Our own Milky Way galaxy has billions of planets, billions of other worlds. You can see their suns by just looking up at the sky. You don't have to pay to see them. If you're far from a city, the stars are with you all the time. They're a new frontier, and every time that we reach a new frontier, it changes how we see things. Those stars will help us figure out how we fit into the universe. Just think of the Earth: It's a tiny pale blue dot from far away. It doesn't seem to be anything special. But it hosts intelligent creatures that are able to think about how they fit in. That's a beautiful thing.

ILLUSTRATION BY ANDY FRIEDMAN


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learning to progress
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