

NAUTILUS

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Choosing to know



Reimagining Time

JAMES GLEICK ON THE RIDDLES OF SPACETIME p.22

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New Vocabularies

W

HAT IS THE MODERN Frankenstein? Is it artificial life? Sky-net? Or—in the language of an open letter signed in 2015 by the likes of Stephen Hawking, Noam Chomsky, and Elon Musk—“military AI”? Whatever the answer, the question, “what are we creating, exactly?” has persisted. Its vocabulary has changed with science, but the intent has not.

On page 22 of this issue, James Gleick points out that time travel, too, is a new instance of an age-old question. “People have always wondered if they can escape destiny,” he writes. “Only now, in the era of time travel, we ask whether we can change the past.” Oedipus, rather than pondering his family’s curse, today might dream of stepping into a time machine to undo it.

We even have a real-life version of the fictional “Time Enforcement Commission,” from the also strangely persistent Jean-Claude Van Damme movie, *Timecop*. Ours is called the “chronology protection conjecture,” according to which the laws of physics protect themselves (or all of us?) from time travelers. Stephen Hawking dreamt it up. It “makes the universe safe for historians,” he writes, though, probably less safe for the hard sci-fi writer.

Paradox resolved (maybe). The question of destiny may soon move on to another form (epigenetics, anyone?). The AI Frankenstein, too, is coming into focus, and it, too, is not quite what we thought. The possibility of any angry, or jealous, or empathetic robot is increasingly remote. As Aaron M. Bornstein explains on page 68, we can no more understand our smartest robots than we can ourselves. Whatever their processes, skills, or motives are, they are foreign to us.

That makes them rather more of a complement than a competitor. Kevin Kelly points out in his new book, *The Inevitable*, that today’s best chess players are not human, but they are also not robotic. They are humans assisted by computers. When we worry about AI, we should worry about our neighbor using it better than we do. In this sense, we have been prescient in giving Victor Frankenstein’s monster the name of his creator. They are Frankenstein, together.

That is also a lesson that might survive the next vocabulary change.

Welcome to the September/October 2016 *Nautilus* print edition.

—Michael Segal
Editor in Chief

aging

is the climate change of human biology

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Learning

“What teachers ‘know’ about how children learn is sometimes more a product of the culture than of research and data.”

—Philip Ball, p. 46

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Selection

“In drama class, we wait to be noticed.
In astronomy class, we discuss the origin
and fate of the universe.”

—Kate Marvel p. 110

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Letters

Reader responses to the Jul/Aug 2016 print edition.

“HER SECOND ACT”

I thought the point of the Perimeter Institute was to be speculative. Or is it only “speculative and in possession of a penis?” I’m glad that Markopoulou is enjoying her new career, but the physics community is covered with shame. —SGA2



“NOISE IS A DRUG AND NEW YORK IS FULL OF ADDICTS”

Interesting article. Not sure that noise and sustained noise is actually good for us. The human brain evolved with significant and prolonged periods of silence. There is a significant body of research that indicates for us to function at our peak and during reflection we require periods of quiet, otherwise the brain is working all the time. Evolutionary biology doesn’t take a holiday in NYC—rather it is working to try and identify dangerous sounds and such.

—Anechidna

I think a doctor prescribing white noise to people who are agitated by a quiet setting is a terrible idea and the product of our medical system’s unhealthy default approach of symptom suppression. Especially

after what we know about the damaging effects of industrial noise on the body, even if temporarily it calms the mind. If noise is an addiction, then simply attempting to sustain what the body is used to rather than giving it a break to recharge is enabling the addictive behavior. But as always, this publication’s take is well-written, informative and insightful.

—Stefan Ravalli

“ARE FANTASY SPORTS REALLY GAMBLING?”

It’s interesting that the argument for the legality of these entities is also the problem. It makes you wonder if chance vs. skill is the best way to regulate something like gambling.

—Alex Woodring



“THE STRANGE BRAIN OF THE WORLD’S GREATEST SOLO CLIMBER”

This is a brilliant article, and its significance goes well beyond Alex Honnold. Fear or no fear, Honnold also has tremendous skill built up over years of practice from a very young age. The other thing I appreciate is how humble he remains, even as he’s become world famous. I’ve never met him, but he seems to me like a regular guy who’d be fun to have a beer with (if he drank).

—Richard



CORRECTIONS

As originally published in the May/June 2016 print edition of *Nautilus*, “Learning Chess at 40” incorrectly implied that the famous chess computer is called “Big Blue.” It’s really known as Deep Blue.

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

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“At Olin College I learned firsthand that problem solving doesn’t start or end with engineering. Appreciating the complexity of problems and embracing truly cross-disciplinary teams are what set me apart as an Olin engineer.”

-Avery Anderson '08

Olin Graduate

Founding Software Engineer

Minerva Project



Olin College – educating engineer-innovators and serving as a privately funded national laboratory for STEM education redesign



Olin College
of Engineering

Preludes



SCIENCE PRACTICE

We Shouldn't Accept Results That Haven't Been Repeated

A FEW YEARS AGO, I became aware of a serious problem in science: the irreproducibility crisis. A group of researchers at *Amgen* tried to replicate 53 landmark cancer discoveries in close collaboration with the authors. Many of these papers were published in high-impact journals and came from prestigious academic institutions. To everyone's surprise, they were able to replicate only six of those papers. This inability to replicate scientific findings is part of a larger problem that threatens to undermine trust in science.

The first question to ask is: Why do scientists do science? Sociologists have consistently identified “public recognition” as a primary motivating factor. Of course, other drivers do exist, like puzzle solving, knowledge building, and financial gain. But recognition seems to be the common, essential driver.

The nature of scientific motivation is also evident in scientific reward systems. These rewards often come as validation, like awards, titles, or press coverage, which then translates into career

The promotion of professors requires them to be famous.

ILLUSTRATIONS BY ROBIN DAVEY

advancement and opportunities for greater prestige. Guidelines for promotion in several academic centers where I have worked listed “Broader reputation than local area” as one of two promotion criteria for associate professors. In other words, the promotion of a professor requires them to be *famous* within their field.

Currently, publishing in prestigious journals and being extensively cited represent the height of recognition in the scientific community. These two metrics imply quality, but have long been proven to be hollow. Papers in high impact journals suffer from irreproducibility at almost the same rate as those in lower impact journals.

The inconvenient truth is that scientists can achieve fame and advance their careers through accomplishments that don’t prioritize the *quality* of their work. In the culture of modern science, it is better to be wrong than to be second.

To make the desire for recognition compatible with prioritizing good science, we need quality metrics that are independent of sociological norms. Objective quality should be based on independent replication: A finding would not be accepted as true unless it is independently verified.

Distinguishing between replicated and unreplicated studies would change how science is reported and discussed, increase the visibility of both strong and weak papers, incentivize scientists to only publish findings they have confidence in, and discourage publishing for the sake of publishing. Institutions would want faculty with stellar qualitative records. Funding agencies would be

In modern science, it is better to be wrong than to be second.

inclined to support grants whose hypotheses are built on strong premises, and are submitted by investigators and institutions both known for quality. The public would be more skeptical of unreplicated science, preventing the wide adoption of false ideas.

Of course, the transition to an institutionalized process to assess replication-based quality will require changes. First, scientists would need to be incentivized to perform replication studies, through recognition and career advancement. Second, a database of replication studies would need to be curated. Third, mathematical derivations of replication-based metrics would need to be developed and tested. Fourth, the new metrics would need to be integrated into the scientific process without disrupting its flow.

But these changes are all feasible and desirable. It is our responsibility as scientists to create transparency on how academic science is incentivized, produced, and evaluated. As Brian Nosek and colleagues from the Center of Open Science once said, “Openness is not needed because we [scientists] are untrustworthy; it is needed because we are human.”

—Ahmed Alkhateeb

Postdoctoral research fellow, Harvard Medical School

GENERALLY DESPISED BIRDS OF NORTH AMERICA



PHYSIOLOGY

Get Ready to Be Identified by Your Ear

LAST YEAR, THE UNITED STATES Customs and Border Protection rolled out a recognition pilot program that uses biometric recognition tools like face and iris scanners. The program will snag “imposters” using fake passports at airports, and what’s more, reduce wait times at security checkpoints. But what might identify individuals even more conclusively and speed travelers on their way more swiftly is another kind of biometrics, based on the ear.

The curves of the cartilage, the protrusions of the auricle, and the hollow of the concha cava are all, like fingerprints, features distinctive to each person. The way noise bounces within their folds allows the ears to guarantee a highly accurate identification of who we are, Steve Beeby, a professor at the University of Southampton, told the *Telegraph* in 2009. The sounds are “different from person to person,” he said, “which gives us a really nice biometric tool” in a wide range of fields, from computer logins to bank accounts.

The NEC Corporation, a Japanese tech giant, announced in March that it had designed biometric ear buds that could be used for identification, and planned to commercialize them by 2018. Instead of requiring a subject to correctly position their eye or finger for a scanner, the ear bud measures the reflection of sound waves off the tympanic membrane—a thin, cone-shaped tissue that separates the ear canal from the middle ear, forming the eardrum.

Takafumi Koshinaka, a researcher at NEC, says their research “originated from a virtual reality technology that makes binaural audio signals”—sound recorded with two microphones, to replicate human hearing—“more realistic, as if sound objects in the signals are coming from various directions in a 3-D space.”

NEC’s ear bud is equipped with a built-in microphone that generates and collects sound waves as they echo within the ear cavity. The speaker produces a “few



The curves of your ear’s cartilage are like fingerprints.

hundred milliseconds of acoustic signals,” ranging from zero Hertz to 22 kiloHertz, audible to humans, and the earphone receives the signals transmitted within the ear cavity through its microphone. Through a method called “synchronous addition,” say researchers at the company’s lab, the device mitigates the interference of noisy environments and the inherent noise of each signal it generates. By calculating the “average of the waveforms of the multiple signals received,” they say, the device eliminates any turbulence produced during the sound’s transmission—things like heartbeats, muscle and joint movements, breathing, vocal sounds—and analyzes the sound’s reverberation in the ear “within approximately one second.”

—Lucia De Stefani

ONE QUESTION



“How do we learn to distinguish new smells?”

Thomas A. Cleland

Dept. of Psychology, Cornell University

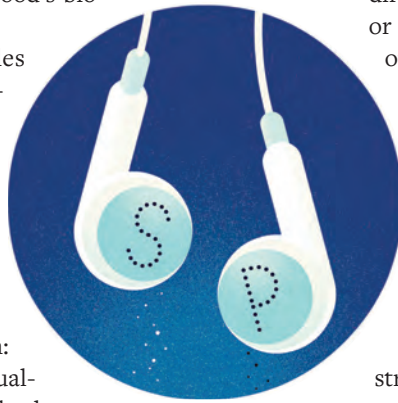
I work on the neural circuits underlying the sense of smell, which appear to operate like mathematical “attractors.” Every time you smell a particular scent, your brain learns more about that odor, using its neural networks to carve out an increasingly prominent conceptual niche for it—a sort of made-to-order mental category. When you encounter that scent again, even amidst complicated and messy background odors, your olfactory network can be “attracted” to that odor memory, enabling you to identify important odors under difficult circumstances that would confound any artificial system. This process is a pretty good example of general category learning in the brain.

FOOD

How Sound Impacts the Taste of Food

WHEN YOU CONSIDER the earthy richness of a cup of cappuccino or the salty tang of a potato chip, you may overlook the sounds they make as you savor them. The glug-glug of coffee as it's poured into your mug, the satisfying crunch of the chip, even music playing in the background—these details may not capture your attention. Nevertheless, sound plays a big role in the flavor of food: It can color our perception of smell and taste and even alter food's biochemical properties.

In 2003, Charles Spence, a professor of experimental psychology at Oxford University, invited 20 research subjects to his lab to try to answer a question that had been eating at him: Could the sonic quality of a chip's crunch alter one's perception of its taste? He had each subject enter a soundproof booth, sit in front of a microphone, and don headphones, a setup that allowed him to tweak both the frequency and volume of the sound the subject heard when she ate a Pringles potato chip. He found that participants rated the chips that seemed to have a higher-pitched, louder crunch 15 percent fresher than the



Sound can alter food's biochemical properties.

softer-sounding chips, though the chips were identical.

Sound can also change the taste of food more directly, by altering the food itself. Ultrasonic waves, or ultrasound, have the same physical properties as other sound waves, but with a frequency above the range of human hearing. When targeted with ultrasound, tiny bubbles in the liquids in foods (like the juices in fruits and meat) collapse into centers of intense heat, pressure, and turbulence known as hotspots, which can accelerate local chemical reactions. This is known as cavitation. Some researchers are experimenting with the use of ultrasound to speed up the process of brining meat, for example, or to improve the shelf life of strawberries and raspberries.

Food technologist Adil Gani and scientists from the University of Kashmir agitated 500-gram batches of local, ripened strawberries in an ultrasound bath for periods from zero to 60 minutes and analyzed them for just over two weeks. They found that ultrasound exposure lowered the potential for microbial activity. It also improved color and firmness, increased the berries' retention of antioxidants, and increased shelf life.

As Farid Chemat, a French sonochemist, and colleagues, once said: Using ultrasound with food is "one of the most promising research areas in the field of modern food engineering."

—Simran Sethi

How Language Helps Erase the Tragedy of Fatal Crashes

EVERY YEAR, 1.25 MILLION people are killed in road crashes around the world. A growing number of safety advocates, government officials, and journalists are moving away from the phrase “car accident” on the grounds that it presumes that the drivers involved are blameless—a presumption that is correct only 6 percent of the time, according to the U.S. Department of Transportation. The vast majority of such incidents are caused by drivers who make mistakes, take risks, or drive while distracted or impaired.

This linguistic shift is propelled by passionate advocates like Jeff Larason, who runs a blog and Twitter account called Drop the “A” Word, and Mark Rosekind, head of the National Highway Traffic Safety Administration, who explained at a conference on driver safety why his agency shuns that particular word: “When you use the word ‘accident,’ it’s like God made it happen.” These advocates believe that by changing the language we hear and use, they can shift how we think about the causes of car crashes—and, they hope, the choices we make as drivers.

Research conducted back in 1974 showed that wording can affect how people report and remember traffic acci—uh, collisions. Elizabeth Loftus and John Palmer, psychologists at the University of Washington, showed participants movies of traffic incidents and then asked them to estimate how fast the cars were going. People who heard a version of the question in which the verb *smashed* was used, rather than *hit*, gave higher speed estimates: an average of 40 miles per hour versus 34. A week later, they were more likely to say that they remembered seeing broken glass even though there was none.

A new study by Laura Niemi and Liane Young, psychologists at Harvard and Boston College, respectively, reports that subtle changes in syntax can tilt the apportioning of blame. Participants read descriptions of sexual assaults in which the structure of most



Subtle changes in syntax can tilt the apportioning of blame.

of the sentences placed focus on either the victim or the perpetrator. Those who read accounts focusing on the victim rated the victim’s responsibility as slightly higher and the perpetrator’s use of force as slightly lower than those whose descriptions focused on the perpetrator.

Showing that changes in wording can often change attitudes and behavior doesn’t mean that a particular one will. When a linguistic shift is too heavy-handed, too obviously driven by an agenda, it can run up against a response known as reactance—our mind’s instinctive defense against attempts to control our thoughts and behavior.

Marieke Fransen, a social psychologist who has conducted extensive research on resistance to persuasion, says most people are unlikely to pick up on the persuasive import of subtle shifts in wording, like the difference between “accident” and “collision,” unless they’re pointed out. And indeed, I only noticed that radio traffic updates were avoiding the word “accident” after I became aware of the campaign opposing its use.

The fact that these linguistic shifts can fly under our radar may be precisely what gives them power. And, paradoxically, the more successful an advocacy campaign is in raising our consciousness about the use of language, the more it may enable us to resist being persuaded.

—Julie Sedivy



—

Explorations on the nature/nurture front

19

FROM OUR

heads

WINE-DARK SEAS

William Gladstone thought Greek poet Homer described the sea as "wine-dark" because ancient Greeks had bad color vision.



1809-1898
British classicist
+ 4x Prime Minister

Some researchers think our conception of colors is rooted in our shared human biology, giving rise to a common way of seeing color.



a Mayan language in Chiapas, Mexico



TAHITIAN + TZELTAL

In the mid-20th century, anthropologists noticed these two languages share **common color categories** with English, including white, black, red, and yellow.

in common with English

UNIVERSAL COLOR TERMS

A 1969 study of 20 languages found 11 common color categories.

A later **survey of 110 languages** from nonindustrial societies upheld these assertions.

11

white, black, red, green, yellow, blue, brown, pink, purple, orange, and gray

World Color Survey



categorization of colors seems to reside in another brain area

WHERE COLOR LIVES



The ability to see "banana yellow" and "apple red" may arise near the bottom of the brain, in the **inferior temporal cortex**.

INBORN TRAITS

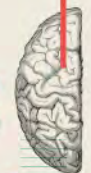
Pre-linguistic human babies perceive some of the same color boundaries as English-speaking adults.

recent study



where **language centers** reside

R



BABIES

Sometime between infancy and adulthood, for mysterious reasons, **color categories** may pack up and **move hemispheres**.



THE ORIGINS OF COLOR PERCEPTION

or

ZUNI

- In the 1950s, scientists found North American
- Native Zuni speakers confused orange and yellow color chips more than English speakers, suggesting that language indeed influences thought.

American linguist

because they use only 1 word for both orange and yellow

DIFFERENT COLOR TERMS

A 1980s world color survey found a surprising amount of diversity. Examples include:

The **Brazilian language Karajá** lumps yellow, green, and blue into a category



4 basic color terms

Russian and modern Greek have separate terms for light blues and dark blues

Korean separates yellow-green from green

yeondu

chorok

POVERTY OF WORDS



Benjamin Lee Whorf thought Greek poet Homer saw the sea as "wine dark" because ancient Greek didn't have words for green and blue.

Is it green or is it blue?

In Tahitian, Berinmo, and Himba, it's both

New Guinea

2000s

BERINMO + HIMBA

Namibia

GRUE

FROM OUR

tongues

Other researchers claim that language shapes color perception, and so color categories are arbitrary and vary across languages.

One study compared English speakers with Berinmo and Himba speakers, two groups who don't have separate words for green and blue, but one word for both: "grue."

FINDINGS

Berinmo and Himba speakers had more trouble distinguishing blue and green color swatches.

IMPLICATIONS

Words interfere with perception, making colors appear more similar or more different than they actually are.

or

FROM

both

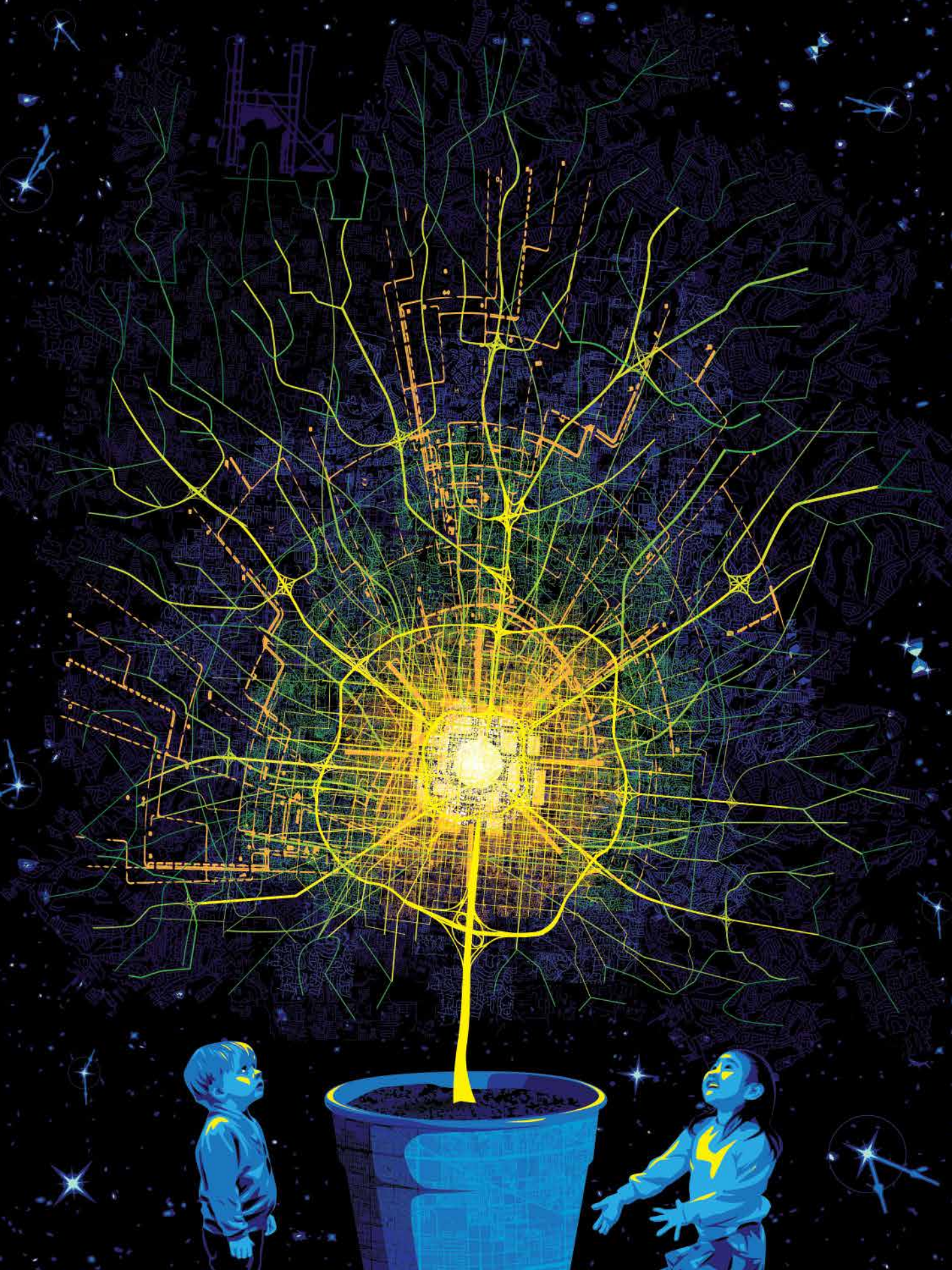
nature

nurture

Today many experts expect to find that color perception is due to both biology and language.

AMANDA PHINGBODHIPAKKIYA is an art director, TED Resident, and founder of The Leading Strand, an initiative using design to illuminate science.

ADULTS



A Nonlinear History of Time Travel

Births, deaths, and other time travel paradoxes

BY JAMES GLEICK

DOUBT THAT ANY PHENOMENON, real or imagined, has inspired more perplexing, convoluted, and ultimately futile philosophical analysis than time travel has. (Some possible contenders, determinism and free will, are bound up anyway in the arguments over time travel.) In his classic textbook, *An Introduction to Philosophical Analysis*, John Hospers tackles the question: “Is it logically possible to go back in time—say, to 3000 B.C., and help the Egyptians build the pyramids? We must be very careful about this one.”

It’s easy to say—we habitually use the same words to talk about time as we do when talking about space—and it’s easy to imagine. “In fact, H. G. Wells did imagine it in *The Time Machine* (1895), and every reader imagines it with him.” (Hospers misremembers *The Time Machine*: “A person in 1900 pulls a lever on a machine and suddenly is surrounded by the world of many centuries earlier.”) Hospers was a bit of a kook, actually, who achieved the unusual distinction for a philosopher of having received one electoral vote for President of the United States. But his textbook, first published in 1953, remained standard through four editions and 40 years.

His answer to the rhetorical question is an emphatic no. Time travel à la Wells is not just impossible, it is *logically* impossible. It is a contradiction in terms. In an argument that runs for four dense pages, Hospers proves this by power of reason.

“How can we be in the 20th century A.D. and the 30th century B.C. *at the same time*? Here already is one contradiction ... It is *not* logically possible to be in one century of time and in another century of time at the same time.” You may pause to wonder (Hospers doesn’t) whether a trap is lurking in that deceptively common expression, “at the same time.” The present and the past are different times, therefore they are not the same time, nor *at* the same time. Q.E.D. That was suspiciously easy.

The point of the time-travel fantasy, however, is that the lucky time travelers have their own clocks. Their time can keep running forward,

ILLUSTRATIONS BY DANIEL HERTZBERG

while they travel back to a different time as recorded by the universe at large. Hospers sees this but resists it. “People can walk backward in space, but what would ‘going backward in time’ literally mean?” he asks.

And if you continue to live, what can you do but get one day older every day? Isn’t “getting younger every day” a contradiction in terms—unless, of course, it is meant figuratively, as in “My dear, you’re getting younger every day,” where it is still taken for granted that the person, while *looking* younger every day, is still *getting older* every day?

(He gives no hint of being aware of F. Scott Fitzgerald’s short story in which Benjamin Button does precisely that. Born as a 70-year-old, Benjamin grows younger every day, until infancy and oblivion. Fitzgerald would have admitted the logical impossibility. The story has many offspring.)

Time is necessarily simple for Hospers. If you imagine that one day you are in the 20th century and the next day your time machine carries you back to ancient Egypt, he retorts: “Isn’t there a contradiction here again? For the next day after January 1, 1969, is January 2, 1969. The day after Tuesday is Wednesday (this is analytic—‘Wednesday’ is defined as the day that follows Tuesday)” and so on. And he has one final argument, the last nail in time travel’s logical coffin. The pyramids were built before you were born. You didn’t help. You didn’t even watch. “This is an unchangeable fact,” says Hospers and adds: “You can’t change the past. That is the crucial point: the past is what happened, and you can’t make what happened not have happened.” We’re still in a textbook about analytical philosophy, but you can almost hear the author shouting:

Not all the king’s horses or all the king’s men could make what has happened not have happened, for this is a logical impossibility. When you say that it is logically possible for you (literally) to go back to 3000 B.C. and help build the pyramids, you are faced with the question: Did you help them build the pyramids or did you not? The first time it happened you did not: You weren’t there, you weren’t yet born, it was all over before you came on the scene.

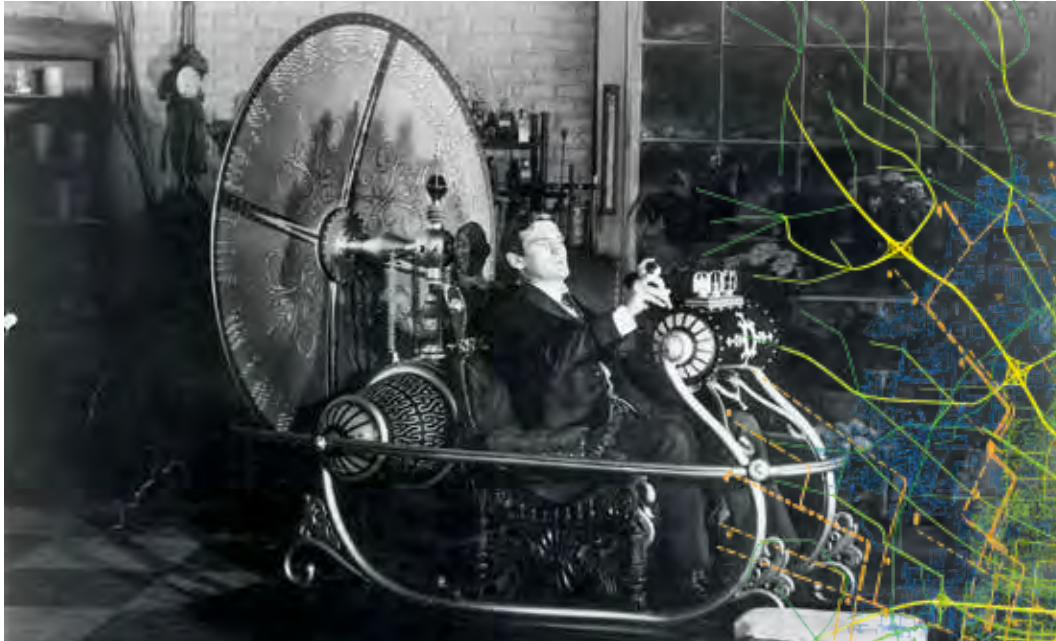
Admit it: You didn’t help build the pyramids. That’s a fact, but is it a logical fact? Not every logician finds these syllogisms self-evident. Some things cannot be proved or disproved by logic. The words Hospers deploys are more slippery than he seems to notice, beginning with the word *time*. And in the end, he’s openly assuming the thing he’s trying to prove. “The whole alleged situation is riddled with contradictions,” he concludes. “When we say we can imagine it, we are only uttering the words, but there is nothing in fact even logically possible for the words to describe.”

Kurt Gödel begged to differ. He was the century’s preeminent logician, the logician whose discoveries made it impossible ever to think of logic in the same way. And he knew his way around a paradox.

Where a logical assertion of Hospers sounds like this—“It is logically impossible to go from January 1 to *any other day* except January 2 of the

THE IMPOSSIBLE MACHINE

In H.G. Wells' 1895 novel *The Time Machine*, an inventor travels 800,000 years into the future. This still is from the 1960 film adaptation.



same year”—Gödel, working from a different playbook, sounded more like this:

That there exists no one parametric system of three-spaces orthogonal on the x_0 -lines follows immediately from the necessary and sufficient condition which a vector field v in a four-space must satisfy, if there is to exist a system of three-spaces everywhere orthogonal on the vectors of the field.

He was talking about world lines in Einstein's spacetime continuum. This was in 1949. Gödel had published his greatest work 18 years earlier, when he was a 25-year-old in Vienna: mathematical proof that extinguished once and for all the hope that logic or mathematics might assemble a complete and consistent system of axioms, provably true or provably false. Gödel's incompleteness theorems were built on a paradox and leave us with a greater paradox.¹ We know, for certain, that complete certainty must always elude us.

Now Gödel was thinking about time—"that mysterious and self-contradictory being which, on the other hand, seems to form the basis of the world's and our own existence." Having escaped Vienna after the Anschluss by way of the Trans-Siberian Railway, he settled at the Institute for Advanced Study in Princeton, where he and Einstein intensified a friendship that had begun in the early '30s. Their walks together, from Fuld Hall to Olden Farm, witnessed enviously by their colleagues, became legendary. In his last years Einstein told someone that he still went to the Institute mainly to have the privilege of walking home with Gödel.

For Einstein's 70th birthday, in 1949, his friend presented him with a

1. Gödel's proof "is more than a monument," said John von Neumann, "it is a landmark which will remain visible far in space and time ... The subject of logic has completely changed its nature and possibilities with Gödel's achievement."

surprising calculation: that his field equations of general relativity allow for the possibility of “universes” in which time is cyclical—or, to put it more precisely, universes in which some world lines loop back upon themselves. These are “closed time-like lines,” or, as a physicist today would say, closed time-like curves (CTCs). These are circular highways lacking on ramps or off ramps. A time-like line is a set of points separated only by time: same place, different times. A closed time-like curve loops back upon itself and thus defies ordinary notions of cause and effect: events are their own cause. (The universe itself—entire—would be rotating, something for which astronomers have found no evidence, and by Gödel’s calculations a CTC would have to be extremely large—billions of light-years—but people seldom mention these details.²)

If the attention paid to CTCs is disproportionate to their importance or plausibility, Stephen Hawking knows why: “Scientists working in this field have to disguise their real interest by using technical terms like ‘closed time-like curves’ that are code for time travel.” And time travel is sexy. Even for a pathologically shy, borderline paranoid, Austrian logician. Almost hidden inside the bouquet of computation, Gödel provided a few words of almost-plain English:

2. Also, the Gödelian universe does not expand; whereas most cosmologists are pretty sure that ours does.

In particular, if P , Q are any two points on a world line of matter, and P precedes Q on this line, there exists a time-like line connecting P and Q on which Q precedes P ; i.e., it is theoretically possible in these worlds to travel into the past, or otherwise influence the past.

Notice, by the way, how easy it had already become for physicists and



A WALK THROUGH TIME

Albert Einstein (right) and Kurt Gödel on one of their famous walks. For his 70th birthday, Gödel presented Einstein with a calculation showing that relativity allows for cyclical time.

mathematicians to speak of alternative universes. “In these worlds ...” Gödel writes. The title of his paper, when he published it in *Reviews of Modern Physics*, was “Solutions of Einstein’s Field Equations of Gravitation,” and a “solution” is nothing less than a possible universe. “All cosmological solutions with non-vanishing density of matter,” he writes, meaning *all possible universes that aren’t empty*. “In this paper I am proposing a solution” = *Here’s a possible universe for you*. But does this possible universe actually exist? Is it the one we’re living in?

Admit it: You didn’t help build the pyramids.

Gödel liked to think so. Freeman Dyson, then a young physicist at the institute, told me many years later that Gödel would ask him, “Have they proved my theory yet?” There are physicists today who will tell you that if a universe has been proved not to contradict the laws of physics, then yes, it is real. *A priori*. Time travel is possible.

That’s setting the bar fairly low. Einstein was more cautious. Yes, he acknowledged, “such cosmological solutions of the gravitation equations ... have been found by Mr. Gödel.” But he added mildly, “It will be interesting to weigh whether these are not to be excluded on physical grounds.” In other words, don’t follow the math out the window.³ Einstein’s caution did little to diminish the popularity of Gödel’s closed time-like curves among fans of time travel—and in their number we must count logicians, philosophers, and physicists. They wasted little time in launching the hypothetical Gödel rocket ships.

“Suppose our Gödelian spacetime traveler decides to visit his own past and talk to his younger self,” wrote Larry Dwyer in 1973. He specifies:

at t_1 , T talks to his younger self
at t_2 , T enters his rocket to begin his journey to the past.
Let $t_1 = 1950$; $t_2 = 1974$

Not the most original start, but Dwyer is a philosopher writing in *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition*, a far cry from *Astounding Stories*. Dwyer has done his homework, though:

Science fiction contains an abundance of stories where the plot centres around certain individuals who, having operated complex mechanical devices, find themselves transported back to the past.

3. Gödel’s biographer Rebecca Goldstein remarked: “As a physicist and a man of common sense, Einstein would have preferred that his field equations excluded such an Alice-in-Wonderland possibility as looping time.”

Besides reading the stories, he is reading the philosophical literature, beginning with Hospers' proof of the impossibility of time travel. He thinks Hospers is just confused. Reichenbach is confused, too (that would be Hans Reichenbach, author of *The Direction of Time*), and so is Čapek

Would you accept the assertion that the cause of a rock is that same rock an instant earlier?

(Milič Čapek, "Time and Relativity Theory: Arguments for a Theory of Becoming"). Reichenbach argued for the possibility of "self encounters"—the "younger ego" meets the "older ego," for whom "the same occurrence takes place a second time," and though this may appear paradoxical it is not illogical. Dwyer begs to differ: "It is this sort of talk that has given rise to so much confusion in the literature." Čapek is drawing diagrams with "impossible" Gödelian world lines. Likewise Swinburne, Whitrow, Stein, Gorovitz ("Gorovitz's problems, of course, are all of his own making"), and indeed Gödel himself, who misconstrues his own theory.

They all make the same error, according to Dwyer. They imagine that a time traveler could change the past. That cannot happen. Dwyer can live with other difficulties created by time travel: backward causation (effects preceding their causes) and entity multiplication (time travelers and time machines crossing paths with their doubles). But not this. "Whatever else time travel may entail," he says, "it does not involve changing the past." Consider old T, using his Gödelian spacetime loop to travel back from 1974 to 1950, when he meets young T.

The encounter is of course recorded twice in the mental history of the time traveller; while young T's reaction to his encounter with T may be one of fear, scepticism, joy, etc., T, for his part, may or may not recall his feelings when, in his youth, he was confronted by a person claiming to be his older self. Now of course it would be self contradictory to say that T does something to young T which, by his memory, he knows does not happen to him.

Of course.

Why can't T go back and kill his grandfather? Because he did not. It's that simple.

Except—of course—it's never that simple.

Robert Heinlein, having created his multitude of Bob Wilsons in 1939, punching one another before self-explaining the mysteries of time travel, revisited the paradoxical possibilities 20 years later in a story that outdid all its predecessors. It was titled “—All You Zombies—” and published in *Fantasy and Science Fiction* after a *Playboy* editor turned it down because the sex made him queasy (it was 1959).⁴ The story has a transgender plot element, a bit forward for the era but necessary to accomplish the time-travel equivalent of a quadruple axel: The protagonist is his (/her) own mother, father, son, and daughter. The title is also the punchline: “I know where I came from—but where did all you zombies come from?”

Could anyone top this? In purely numerical terms—sure. In 1973, David Gerrold, who had been a young television writer for the short-lived (and, later, long-lived) *Star Trek*, published his first novel, *The Man Who Folded Himself*, featuring a college student named Daniel who receives a Time-belt from a mysterious “Uncle Jim,” complete with instructions. Uncle Jim urges him to keep a diary, and a good thing, too, because life quickly gets complicated. We soon struggle to keep track as the cast of characters expands accordion-like to include Don, Diane, Danny, Donna, ultra-Don, and Aunt Jane—all of whom are (as if you didn't know) the same person, on a looping temporal rollercoaster.

4. The Heinlein story inspired a 2014 film, *Predestination*, with Ethan Hawke and Sarah Snook playing versions of the time traveler.

PARADOX MADE REAL

In some sense, a time travel loop is akin to a spatial paradox, like this one by artist Oscar Reutersvärd.



So many variations on a theme. The paradoxes multiply almost as fast as the time travelers, but when you look closely, they are all the same. There is just one paradox, wearing different costumes to suit the occasion. Sometimes it is called the Bootstrap Paradox—a tribute to Heinlein, whose Bob Wilson pulled himself by his bootstraps into his own future. Or the Ontological Paradox, a conundrum of being and becoming, aka “Who’s Your Daddy?” People and objects (pocket watches, notebooks) exist without origin or cause. Jane of “All You Zombies” is her own mother and father, begging the question of where her genes came from. Or: In 1935 an American stockbroker finds a Wellsian time machine (“polished ivory and gleaming brass”) hidden by palm leaves in the Cambodian jungle (“the land of mystery”); he throws the lever and arrives back in 1925, where the machine is polished up and cached in the palm leaves.⁵ That is its life cycle: a 10-year closed time-like curve. “But where did it come from *originally*?” the stockbroker asks a yellow-robed Buddhist. The wise man explains as if to a dunce: “There never was any ‘originally.’”⁶

Some of the cleverest loops involve pure information. “Mr. Buñuel, I had a nice idea for a movie for you.” A book on how to build a time machine arrives from the future. See also: Predestination Paradox. Trying to change what’s bound to happen somehow helps make it happen. In *The Terminator* (1984), a cyborg assassin (played with a peculiar Austrian accent by the 37-year-old bodybuilder Arnold Schwarzenegger) travels back in time to kill a woman before she can give birth to the man who is destined to lead a future resistance movement; the cyborg’s failure leaves detritus that makes its own creation possible; etc.

In a way, of course, the Predestination Paradox predates time travel by several millennia. Laius, hoping to defy the prophecy of his murder, leaves baby Oedipus in the wilderness to die, and sadly his plan backfires. The idea of the self-fulfilling prophecy is ancient, though the term is new, coined by the sociologist Robert Merton in 1949 to describe an all-too-real phenomenon: “a *false* definition of the situation evoking a new behavior which makes the originally false conception come true.” (For example, a warning of gasoline shortages causes panic buying that leads to gasoline shortages.) People have always wondered whether they can escape destiny. Only now, in the era of time travel, we ask whether we can change the past.

All the paradoxes are time loops. They all force us to think about causality. Can an *effect* precede its *cause*? Of course not. Obviously. By definition. “A cause is an object followed by another ...” David Hume kept saying. If a child receives a measles inoculation and then suffers a seizure, the inoculation may or may not have caused the seizure. The one thing everyone knows for sure is that the seizure didn’t cause the inoculation.

But we’re not very good at understanding causes. The first person on record as trying to analyze cause and effect by power of ratiocination was Aristotle, who created layers of complexity that have caused confusion ever after. He distinguished four distinct types of causes, which can be named (making allowances for the impossibility of trans-millennial

5. Wells might have admired this descriptive flourish: “The general impression which the contrivance gave was that of unreality. The right-angles, at which various bars joined each other, did not seem to be quite 90 degrees. The perspective was distinctly off; for regardless from which side one viewed it, the more distant side always seemed to be the larger ...”

6. Ralph Milne Farley, “The Man Who Met Himself” (1935). Of course the man is in a 10-year loop, too. He uses the time to make money in the stock market.

translation) the efficient, the formal, the material, and the final. Some of these are hard to recognize as causes. The efficient cause of a sculpture is the sculptor, but the material cause is the marble. Both are needed before the sculpture can exist. The final cause is the purpose for which it is made—its beauty, let's say. Considered chronologically, final causes do seem to come later. What is the cause of an explosion: The dynamite? The

Why can't he go back and kill his grandfather? Because he did not.

spark? The bank robber? The safecracking? This line of thought tends to strike modern people as pettifogging. (On the other hand, some professionals find Aristotle's vocabulary pitifully primitive. They would not want to discuss causal relations without mentioning immanence, transcendence, individuation, and adicity, hybrid causes, probabilistic causes, and causal chains.) Either way, we do well to remember that nothing, when we look closely, has a single unambiguous incontrovertible cause.

Would you accept the assertion that the cause of a rock is that same rock an instant earlier?

"All reasonings concerning matters of fact seem to be founded on the relation of *Cause and Effect*," said Hume, but he discovered that the reasonings were never easy or certain. Is the sun the cause of a rock's warming? Is an insult the cause of a person's anger? Only one thing could be said for sure: "A cause is an object followed by another ..." If an effect doesn't *necessarily* follow from a cause, was it a cause at all? The arguments echoed down the corridors of philosophy and continue to echo, despite Bertrand Russell's attempt to settle the matter once and for all in 1913 with an appeal to modern science. "Oddly enough, in advanced sciences such as gravitational astronomy, the word 'cause' never occurs," he wrote. Time for philosophers to get with the program. "The reason why physics has ceased to look for causes is that, in fact, there are no such things. The law of causality, I believe, like much that passes muster among philosophers, is a relic of a bygone age, surviving, like the monarchy, only because it is erroneously supposed to do no harm."

Russell had in mind the hyper-Newtonian view of science described a century earlier by Laplace—the universe rigid—in which all that exists is locked together in a machinery of physical laws. Laplace spoke of the past as the *cause* of the future, but if the whole machine chugs along in lockstep, why should we imagine any particular gear or lever to be more causal than any other piece? We may consider the horse to be the cause of the carriage’s motion, but that is mere prejudice. Like it or not, the horse, too, is fully determined. Russell had noticed, and he was not the first, that when physicists write down their laws in mathematical language, time has no inherent directionality. “The law makes no difference between past and future,” he wrote. “The future ‘determines’ the past in exactly the same sense in which the past ‘determines’ the future.”

“But,” we are told, “you cannot alter the past, while you can to some extent alter the future.” This view seems to me to rest upon just those errors in regard to causation which it has been my object to remove. You cannot make the past other than it was—true ... If you already know what the past was, obviously it is useless to wish it different. But also you cannot make the future other than it will be ... If you happen to know the future—e.g. in the case of a forthcoming eclipse—it is just as useless to wish it different as to wish the past different.

Time Travel

Can you imagine a time before we dreamed about time travel? It seems hard to believe now, but before H.G. Wells’ *The Time Traveller*, in 1895, the theoretical concept was wispy, carrying very little cultural import. Wells’ thrilling tale of adventure, Eloi, and Morlocks catapulted time travel into the popular imagination.

Because Wells popularized the concept, his description of the actual act is allowed to be blurry; he was exploring brand-new territory, after all. Stories since then have had to be just as inventive, and most opt to take the concept in a new theoretical direction. From the physics-challenging to the paradox-inviting, here are some of our favorites.



A WRINKLE IN TIME **BY MADELEINE L'ENGLE**

Intrepid young universe travelers Meg and Charles Wallace fold, or “wrinkle,” space-time. L’Engle calls this ‘tessering’ or performing a ‘tesseract’—a concept loosely borrowed from the cosmological construct of the same name, a four-dimensional cube.



A SOUND OF THUNDER **BY RAY BRADBURY**

A character traveling to the Jurassic Era crushes a butterfly under his boot. Upon returning to the present he notices subtle changes in his world; funky word spellings, altered election outcomes, strange behavior. This is widely recognized as the first instance of the “butterfly effect,” in which seemingly small alterations in space-time can have massive, universe-altering ripple effects.

And yet, Russell notwithstanding, scientists can no more abandon causation than anyone else. Cigarette smoking causes cancer, whether or not any particular cigarette causes any particular cancer. The burning of oil and coal in the air causes climate change. A mutation in a single gene causes phenylketonuria. The collapse of a burned-out star causes a supernova. Hume was right: “All reasonings concerning matters of fact seem to be founded on the relation of *Cause and Effect*.” Sometimes it’s all we talk about. The lines of causality are everywhere, some short and some long, some firm and others tenuous, invisible, interwoven, and inescapable. They all do run in one direction, from past to future.

Let’s say that one day in 1811, in the town of Teplice, northwestern Bohemia, a man named Ludwig inks a note on a stave in his sketchbook. On an evening in 2011, a woman named Rachel blows a horn in Boston Symphony Hall, with a measurable effect: the air in that room vibrates with a predominant wavelength of 444 cycles per second. Who can deny that, at least in part, the note on paper caused the atmospheric vibrations two centuries later? Using the laws of physics, the path of influence from those molecules in Bohemia to the molecules in Boston would be challenging to compute, even given Laplace’s mythical “intelligence which could comprehend all the forces.” Yet we can see an unbroken causal chain.



DR. WHO

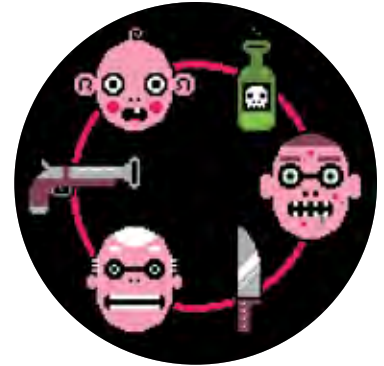
If you’ve seen the show, you’re familiar with the TARDIS, an organic phone booth that allows the Doctor and his pals to hop anywhere in time and space. Sounds like fantasy, right? Maybe—but, according to Benjamin K. Tippett and David Tsang, and their “blue box white paper,” a TARDIS could exist—provided a few new, gravitationally radical types of matter popped up in the universe for physicists to splice and dice.



KINDRED

BY OCTAVIA BUTLER

Kindred’s structure forces its readers out of linear time. Modeled after traditional antebellum slave narratives, Butler cuts and pastes past and future events together until they seem interchangeable, making it impossible for readers to interpret events according to cause-and-effect. In doing so, she challenges the notion of linear progress, questioning how far humans have come when many fundamental struggles, like racism and sexism, occur cyclically.



RANT

BY CHUCK PALAHNIUK

This temporal whirlpool of a novel vortexes around a dystopian future society and the collisions between its two factions. The book’s epic conclusion involves the grandfather paradox, a twist on the butterfly effect in which changing the past (killing one’s grandparents) alters the future in an impossible way (preventing one’s birth.) *Rant* inverts this idea, suggesting instead that killing—and replacing—one’s grandparents makes one super-strong, perhaps immortal.

A chain of information, if not matter.

Russell did not end the conversation when he declared notions of causality to be relics of a bygone age. Not only do philosophers and physicists continue to wrangle over cause and effect, they add new possibilities to the mix. Retrocausation is now a topic: also known as backward causation or retro-chronal causation. Michael Dummett, a distinguished English logician and philosopher (and reader of science fiction), seems to have given this branch its start with his 1954 paper, “Can an Effect Precede Its Cause?” followed 10 years later with his less tentative, “Bringing About the Past.” Among the questions he raised was this: Suppose he hears on the radio that his son’s ship has sunk in the Atlantic. He prays to God that his son should be among the survivors. Has he blasphemed, by asking God to undo what has been done? Or is this prayer functionally identical to praying in advance for his son’s safe passage?

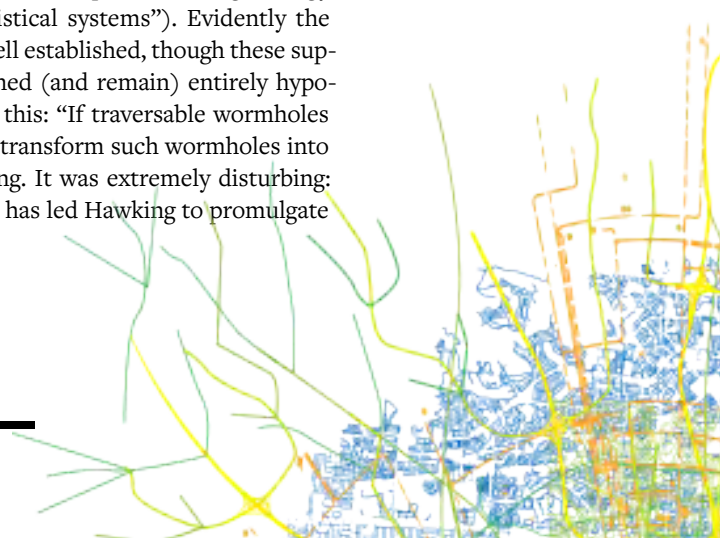
What might inspire modern philosophers, against all precedent and tradition, to consider the possibility that effects might precede causes? *The Stanford Encyclopedia of Philosophy* offers this answer: “Time Travel.” Indeed, all the time-travel paradoxes, births and murders alike, stem from retro-causality. Effects undo their causes.

The first main argument against the causal order being the temporal order is that temporally backwards causation is possible in cases such as time travel. It seems metaphysically possible that a time traveler enters a time machine at time t_1 , thus causing her to exit the time machine at some earlier time t_0 . Indeed, this looks to be nomologically possible, since Gödel has proved that there are solutions to Einstein’s field equations that permit looping pathways.

Not that time travel settles the matter. “A variety of incoherencies might be alleged here,” the encyclopedia cautions, “including the incoherency of changing what is already fixed (causing the past), of being both able and unable to kill one’s own ancestors, or of generating a causal loop ...” Brave writers are willing to risk an incoherency or two. Philip K. Dick ran the clocks backward (as it were) in *Counter-Clock World*, and so did Martin Amis in *Time’s Arrow*.

We do seem to be traveling in circles.

“The recent renaissance of wormhole physics has led to a very disturbing observation,” wrote Matt Visser, a mathematician and cosmologist in New Zealand in 1994 in *Nuclear Physics B* (the branch of *Nuclear Physics* devoted to “theoretical, phenomenological, and experimental high energy physics, quantum field theory, and statistical systems”). Evidently the “renaissance” of wormhole physics was well established, though these supposed tunnels through spacetime remained (and remain) entirely hypothetical. The disturbing observation was this: “If traversable wormholes exist then it appears to be rather easy to transform such wormholes into time machines.” It was not just disturbing. It was extremely disturbing: “This extremely disturbing state of affairs has led Hawking to promulgate his chronology protection conjecture.”



Hawking is, of course, Stephen Hawking, the Cambridge physicist who by then had become the world's most famous living scientist, in part because of his dramatic decades-long struggle with an inexorably paralyzing motor neuron disease and in part because of his flair for popularizing the knottiest problems of cosmology. No wonder he was attracted to time travel.

The “chronology protection conjecture” was the title of a paper he wrote in 1991 for *Physical Review D*. He explained the motivation as fol-

People have always wondered whether they can escape destiny.

lows: “It has been suggested that an advanced civilization might have the technology to warp spacetime so that closed timelike curves would appear, allowing travel into the past.” Suggested by whom? An army of science-fiction writers, of course, but Hawking cited the physicist Kip Thorne (yet another Wheeler protégé) of the California Institute of Technology, who had been working with his graduate students on “wormholes and time machines.”

At some point the term “sufficiently advanced civilization” became a trope. As in: Even if we humans can't do it, could a sufficiently advanced civilization? This is useful not just for SF writers but for physicists, too. So Thorne and Mike Morris and Ulvi Yurtsever wrote in *Physical Review Letters* in 1988, “We begin by asking whether the laws of physics permit an arbitrarily advanced civilization to construct and maintain wormholes for interstellar travel.” Not coincidentally, 26 years later, Thorne served as executive producer and science advisor for the 2014 big-budget movie *Interstellar*. “One can imagine an advanced civilization pulling a wormhole out of the quantum foam,” they wrote in the 1988 paper, and they included an illustration captioned: “Spacetime diagram for conversion of a wormhole into a time machine.” They were contemplating wormholes with mouths in motion: A space ship might enter one mouth and exit another mouth in the past. Fittingly, they concluded by posing a paradox, only this time it isn't the grandfather who dies:

Can an advanced being measure Schrödinger's cat to be alive at an event *P* (thereby “collapsing its wave function” onto a “live” state), then go backward

in time via the wormhole and kill the cat (collapse its wave function onto a “dead” state) before it reaches *P*?

They left that question unanswered.

Hawking stepped in. He analyzed the wormhole physics as well as the paradoxes (“all sorts of logical problems, if you were able to change history”). He considered the possibility of evading the paradoxes “by some modification of the concept of free will,” but free will is seldom a happy topic for a physicist, and Hawking saw a better approach: what he proposed to call the Chronology Protection Conjecture. A great deal of calculation was required, and when the calculating was done, Hawking was convinced: The *laws of physics* would protect history from the supposed time travelers. Notwithstanding Kurt Gödel, they must forbid the appearance of closed time-like curves. “It seems there is a chronology protection agency,” he wrote sci-fi-ishly, “which prevents the appearance of closed timelike curves and so makes the universe safe for historians.” And he concluded with a flourish—the kind of thing Hawking could get away with in the *Physical Review*. He had more than a theory. He had “evidence”:

There is also strong experimental evidence in favor of the conjecture from the fact that we have not been invaded by hordes of tourists from the future.

“Time *steps aside*. Like an airplane hitting an air pocket.”

Hawking is one of those physicists who knows that time travel is impossible but also knows it’s fun to talk about. He points out that we are all traveling through time, one second at a time. He describes black holes as time machines, reminding us that gravitation slows the passage of time locally. And he often tells the story of the party he threw for time travelers—invitations sent only after the fact: “I sat there a long time, but no one came.”

In fact, the Chronology Protection Conjecture had been floating about long before Stephen Hawking gave it a name. Ray Bradbury, for example, stated it in his 1952 story about time-traveling dinosaur hunters: “Time *doesn’t permit* that sort of mess—a man meeting himself. When such occasions threaten, Time *steps aside*. Like an airplane hitting an air pocket.” Notice that Time has agency here: Time doesn’t permit, and time steps

aside. Douglas Adams offered his own version: “Paradoxes are just the scar tissue. Time and space heal themselves up around them and people simply remember a version of events which makes as much sense as they require it to make.”

Perhaps that seems a bit magical. Scientists prefer to credit *the laws of physics*. Gödel thought a robust, paradox-free universe was simply a matter of logic. “Time travel is possible, but no person will ever manage to kill his past self,” he told a young visitor in 1972. “The *a priori* is greatly neglected. Logic is very powerful.”⁷ At some point chronological protection became part of the ground rules. It even became a cliché. In her 2008 story, “The Region of Unlikeness,” Rivka Galchen can take all that old stage business for granted:

Science fiction writers have arrived at analogous solutions to the grandfather paradox: murderous grandchildren are inevitably stopped by something—faulty pistols, slippery banana peels, their own consciences—before the impossible deed can be carried out.

Region of unlikeness comes from Augustine: “I perceived myself to be far off from Thee, in the region of unlikeness”—in *regione dissimilitudinis*. He is not fully realized. Nor are any of us, bound as we are in time and space. “I beheld the other things below Thee, and I perceived that they neither altogether are, nor altogether are not.” God is eternity, remember, and we are not, much to our sorrow.

Galchen’s narrator falls into a friendship with two older men, philosophers maybe, scientists, it’s all a bit vague. The relationships are not well defined. The narrator feels that she is a bit undefined herself. The men speak in riddles. “Oh, time will tell,” one of them says. And: “Time is our tragedy, the substance we have to wade through as we try to move closer to God.” They vanish from her life for a while. She watches the obituary pages. An envelope appears mysteriously in her mailbox—diagram, billiard balls, equations. She thinks of an old joke: “Time flies like an arrow and fruit flies like a banana.” One thing becomes clear: Everyone in this story knows a lot about time travel. A fateful loop—the same paradox as ever—begins to emerge from the shadows. Some rules are explained: that “contrary to popular movies, travel into the past didn’t alter the future, or, rather, that the future was already altered, or, rather, that it was all far more complicated than that.” Fate seems to be tugging at her, in a gentle way. Can anyone evade destiny? Look what happened to Laius. All she can say is, “Surely our world obeys rules still alien to our imagination.” ☺

7. Rudy Rucker, a mathematician and, later, an author of science fiction.

JAMES GLEICK is an award-winning science writer and best-selling author of *Chaos: Making a New Science*, *Genius: The Life and Science of Richard Feynman*, and *The Information: A History, a Theory, a Flood*. His books have been translated into thirty languages.



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THEY CALL HIM 007, probably because he's smart, but probably also because that's a fun name for a crow. 007 became famous for solving an 8-step puzzle involving sticks, stones, and ropes. The video of the feat was seen more than 11 million times on YouTube. One of its top comments is from a viewer who said he or she probably could not have solved the puzzle.

I watched the video more than a few times myself. Suddenly the subjective world of the crow—of animals—admitted a complexity I hadn't considered. I couldn't help but imagine a human consciousness looking out through the crow's eyes, and to connect that kind of intelligence to personhood.

Whether this is instinct or chauvinism, I'm not alone. This year saw Go grandmaster Lee Sedol lose to Google's AlphaGo computer program. Sedol's wife says that at one point he called out a name in his sleep: not AlphaGo, or Google, but the name of the human engineer who moved the pieces on the program's behalf.

As we discover and build new learning systems, the biggest lessons may be about how we fit into the landscape emerging around us.

Welcome to "Learning."

—MS

"Humans have robots beat in the sheer efficiency with which we can learn."

TOM VANDERBILT

"Why We Love How-to Videos" p.62

Learning

NEW LESSONS



How Much More Can We Learn About the Universe?

These are the few limits on our ability to know

BY LAWRENCE M. KRAUSS

AS A COSMOLOGIST, some of the questions I hear most frequently after a lecture include: What lies beyond our universe? What is our universe expanding into? Will our universe expand forever? These are natural questions to ask. But there is an even deeper question at play here. Fundamentally what we really want to know is: Is there a boundary to our knowledge? Are there fundamental limits to science?

The answer, of course, is that we don't know in advance. We won't know if there is a limit to knowledge unless we try to get past it. At the moment, we have no sign of one. We may be facing roadblocks, but those give every indication of being temporary. Some people say to me: "We will never know how the universe began." "We can never know what happened before the Big Bang." These statements demonstrate a remarkable conceit, by suggesting we can know in advance the locus of all those things that we cannot know. This is not only unsubstantiated, but the

history of science so far has demonstrated no such limits. And in my own field, cosmology, our knowledge has increased in ways that no one foresaw even 50 years ago.

This is not to say that nature doesn't impose limits on what we can observe and how we can observe it. For example, the Heisenberg uncertainty principle constrains what we can know about the motion of a particle at any time, and the speed of light restricts how far we can see or travel in a given interval. But these limits merely tell us what we cannot observe, not what we cannot eventually learn. The uncertainty principle hasn't gotten in the way of learning the rules of quantum mechanics, understanding the behavior of atoms, or discovering that so-called virtual particles, which we can never see directly, nevertheless exist.

The observation that the universe is expanding does imply a beginning, because if we extrapolate backward, then at some point in the distant past, everything in our observable universe was co-located at a single point.

ILLUSTRATION BY JACKIE FERRENTINO

Cosmic inflation erased aspects of our past.

At that instant, which now goes by the name of the Big Bang, the laws of physics as we know them break down, because general relativity, which describes gravity, cannot be successfully integrated with quantum mechanics, which describes physics on microscopic length scales. But most scientists do not view this as a fundamental boundary to knowledge, because we expect that general relativity will have to be modified as part of a consistent quantum theory. String theory is one of the major ongoing efforts to do so.

Given such a theory, we might be able to answer the question of what, if anything, came before the Big Bang. The simplest possible answer is perhaps also the least satisfying. Both special and general relativity tie together space and time into a single entity: spacetime. If space was created in the Big Bang, then perhaps time was as well. In that case, there was no “before.” It simply wouldn’t be a good question. This is not the only possible answer, though, and we will need to await a quantum theory of gravity and its experimental confirmation before we will have any confidence in our reply.

Then there is the question of whether we can know what lies beyond our own universe, spatially. What are the boundaries of our universe? Again, we can hazard a guess. If our spacetime arose spontaneously—which, as I argued at length in my last book, *A Universe from Nothing*, seems the most likely possibility—then it probably has zero total energy: The energy represented by matter is exactly offset by the energy represented

by gravitational fields. Put simply, something can arise from nothing if the something amounts to nothing. Right now, the only universe that we can verify has zero total energy is a closed universe. Such a universe is finite yet unbounded. Just like you can move around the surface of a sphere forever without encountering any boundaries, the same may be true of our universe. If we look far enough in one direction, we would see the back of our heads.

In practice, we cannot do that, probably because our visible universe is only part of a much larger volume. The reason has to do with something called inflation. Most universes that arise spontaneously with microscopic size will re-collapse in a microscopic time, rather than endure for billions of years. But, in some, empty space will be endowed with energy, and that will cause the universe to expand exponentially fast, at least for a brief period. We think that such a period of inflation occurred during the earliest moments of our Big Bang expansion and prevented the universe from re-collapsing immediately. In the process, the universe puffed up in size to become so great in extent that, for all intents and purposes, it would now appear flat and infinite—like a cornfield in Kansas that looks infinite despite being located on the huge sphere we call Earth. This is why we don’t see the backs of our heads when we look up in space, even though our universe may be closed on its largest scales. In principle, though, we could see the whole thing if we waited long enough, as



ON A CLEAR DAY YOU CAN'T SEE FOREVER The farthest you see, in principle, is 45.3 billion light-years. Although that represents a direct limitation on our knowledge, it doesn't keep us from grasping the basic workings of nature.

long as inflation hadn't resumed in our visible universe, and is not occurring elsewhere in regions of space we cannot observe.

As for the possibility that regions we cannot yet observe, or may never observe, may be inflating, in fact our current theories suggest that this is the most likely possibility. If we consider the phrase “our universe” to refer to that region of space with which we once could have communicated or with which we one day may communicate, then inflation generally creates other universes beyond ours. Inflation may have been brief within our volume of space, but the rest of space expands exponentially forever, with isolated regions like ours occasionally decoupling from the expansion, just as isolated ice patches can form on the surface of fast-moving water when the temperature is below freezing. Each such universe had a beginning, pegged

to the time when inflation ended within its spatial volume. In this case, the beginning of our universe may not have been the beginning of time itself—further reason to doubt whether the Big Bang represents an ultimate limit to our knowledge.

Depending on the processes that cause each universe to decouple from the background space, the laws of physics might be different in each one. We have come to call this collection of possible universes a “multiverse.” The idea of a multiverse has gained traction in the scientific community not only because it is motivated by phenomena like inflation, but also because the possibility of many different universes, each with its own laws of physics, might explain various seemingly inexplicable fundamental parameters of our universe. Those parameters are simply the values that randomly arose when our universe was born.



COLLIDING GALAXIES Such cosmic commotion will one day cease to occur, and observers in the distant future may never realize how dynamic our universe once was.

If other universes are out there, they are separated from ours by huge distances and recede at super-light relative velocities, so we can never detect them directly. Is the multiverse then just metaphysics? Does verifying the possible existence of a multiverse thus represent a fundamental boundary to our knowledge? The answer is: not necessarily. Although we may never see another universe directly, we can still test the theory that may have produced it empirically—for example, by observing gravitational waves that inflation would produce. This would allow us in principle to test the detailed nature of the inflationary process that resulted in our universe. These waves are similar to the gravitational waves recently discovered by LIGO, but differ in their origin. They come not from cataclysmic events such as the collisions of massive black holes in distant galaxies, but from the earliest moments of the Big Bang, during the putative period of inflation. If we can detect them directly—as we might be able to do in a variety of experiments that are now looking for the signature they would leave in the cosmic microwave background radiation left over from the Big Bang—we can probe the physics of inflation and then determine whether

eternal inflation is a consequence of this physics. Thus, indirectly, we could test whether other universes must exist, even if we cannot detect them directly.

In short, we have discovered that even the very deepest metaphysical questions—which previously we might have imagined would never be empirically addressable, including the possible existence of other universes—may in fact be accessible, if we are clever enough. No limits to what we may learn from the application of reason combined with experimental observation are yet known.

A universe without limits is appealing and motivates us to continue searching. But can we be confident there will be no limits to our knowledge, ever? Not quite.

Inflation does place a fundamental limit on knowledge—specifically, knowledge of the past. It essentially resets the universe, destroying potentially all the information about the dynamical processes that preceded it. The rapid expansion of space during inflation severely dilutes the contents of any region. So it may have wiped out traces of, for example, magnetic monopoles, a type of particle that theory suggests the very early

If we look far enough in one direction, we would see the back of our heads.

universe produced in profusion. That was one of the original virtues of inflation: It reconciled the fact we have never seen such particles with predictions of their production. But in getting rid of a discrepancy, inflation erased aspects of our past.

Worse, the erasure may not be over. We are apparently living in another period of inflation right now. Measurements of the recession of distant galaxies indicates that the expansion of our universe is currently speeding up, not slowing down, as it would be if the dominant gravitational energy resided in matter or radiation, and not in empty space. We currently have no understanding of the origin of this energy. Each of the potential explanations suggests fundamental limits to the progress of knowledge and even to our very existence.

The energy of empty space could suddenly disappear if the universe undergoes some kind of phase transition, a cosmic version of steam condensing into liquid water. If that were to happen, the nature of fundamental forces might change, and all the structures we see in the universe, from atoms on up, might become unstable or disappear. We would disappear along with everything else.

But even if the expansion continues, the future is still rather dismal. Within about 2 trillion years—which may seem like a long time on human scales, but is not so long on cosmic scales—the rest of the universe will disappear from our view. Any observers who evolve on planets around stars in this distant future will imagine that they live on a single galaxy surrounded by an eternal empty space, with no signs of acceleration or even any evidence of an earlier Big Bang. Just as we have lost sight of monopoles, they will be blind to the history that we readily see. (To be sure, they may have access to observable phenomenon we do not yet have access to, so we shouldn't feel too superior.)

Either way, we should enjoy our brief moment in the sun and learn what we can, while we can. Work harder, graduate students! ☺

LAWRENCE M. KRAUSS is a theoretical physicist and cosmologist, the director of the Origins Project and the foundation professor in the School of Earth and Space Exploration at Arizona State University. He is also the author of bestselling books including *A Universe from Nothing* and *The Physics of Star Trek*.



Cursive Handwriting and Other Education Myths

Teaching cursive handwriting doesn't have nearly the value we think it does

BY PHILIP BALL

A RECENT NEWCOMER at one of the home-education groups my family attends explained that one of the frustrations that led her to take her son out of the school system was that he wasn't being allowed to write stories. It's something he loves to do, and it seems strange that a school should obstruct that enthusiasm. But the teachers declared he wasn't ready because he can't yet write in cursive.

To me this symbolizes all that is wrong with the strange obsession shared in many countries about how children learn to write. Often we teach them how to form letters based on the ones they see in their earliest reading books. And then we tell them that they must learn this hard-won skill all over again, using "joined-up" script. Yet there is no evidence that cursive has any benefits over other handwriting styles, such as manuscript, where the letters aren't joined, for the majority of children with normal development.

I should make it clear I'm not referring to handwriting itself, often seen as synonymous with cursive.

There is ample evidence that writing by hand aids cognition in ways that typing does not: It's well worth teaching. And I confess I'm old-fashioned enough to think that, regardless of proven cognitive benefits, a good handwriting style is an important and valuable skill, not only when your laptop batteries run out but as an expression of personality and character. I should also say that cursive is a perfectly respectable, and occasionally lovely, style of writing, and children should have the opportunity to learn it if they have the time and inclination. My eldest child loves cursive and has the most elegant handwriting, in which I take great pride. And I love a good Victorian copperplate as much as anyone.

But imposing cursive from an early age is another matter. There should be a sound reason for it, as there should be reasons for teaching anything to children. Yet the grip that cursive exerts on much of teaching practice is sustained only by a disturbing blend of traditionalism, institutional inertia, folklore, prejudice, and bribery. It suggests that what teachers "know"

about how children learn is sometimes more a product of the culture in which they're immersed than a result of research and data. It seems unlikely, in this regard, that teaching cursive is unique in educational practice. Which forces us to wonder: What happened to evidence?

SOMETHING LIKE MODERN CURSIVE emerged from Renaissance Italy, perhaps partly because lifting a delicate quill off and on the paper was apt to damage it and spatter ink. By the 19th century cursive handwriting was considered a mark of good education and character. Teaching of manuscript lettering (not joined up) only began in the United States in the 1920s, to some controversy. In many countries today, including the U.S. and Canada, children are generally taught to write in manuscript in the first grade and are then taught cursive from second or third grade. In France, children are expected to use it as soon as they start to write in kindergarten, but in Mexico only manuscript is taught. The U.S. and United Kingdom leave some discretion for when cursive is taught, but there is the assumption that it will become the pupil's normal mode of writing. When cursive is taught, it may become compulsory, so children may be marked down if they don't write this way. In France, the cursive form is virtually universal and highly standardized, and children are discouraged from developing their own handwriting style.

Despite this diversity, the teaching of cursive is often accompanied by a strong sense of propriety. It's simply the right thing to do. If you ask teachers why (I've tried), they'll probably look at you oddly before offering a variety of answers, which will probably include these:

- It's faster.
- It helps with spelling.
- It helps with dyslexia.

What does research say on these issues? It has consistently failed to find any real advantage of cursive over other forms of handwriting. "There is no conclusive evidence that there is a benefit for learning cursive for a child's cognitive development," says Karin Harman James, an associate professor in the Department of Psychological and Brain Sciences at Indiana

University, who studies early brain development as a function of learning experiences.

James cautions that the issue is difficult to study because it's hard to find children whose educational situation differs only in the style of handwriting. What's more, a lot of the "evidence" that does get quoted is rather old and of questionable quality, and some of the findings are contradictory. Simply put, our real understanding of how children respond to different writing styles is surprisingly patchy and woefully inadequate.

Let's take a closer look, though, at what we *do* know. Many people (including teachers) swear that cursive is faster, and cite not only the fact that there is less lifting of pen from paper but also their own experience. Needless to say, the latter point is like me saying that English is a faster language than French because I can speak and read it more quickly. Of course that's true for something you've done all your life.

Tests on writing speed have been fairly inconclusive in the past. But one of the best and most recent was conducted in 2013 by Florence Bara, now at the University of Toulouse in France, and Marie-France Morin of the University of Sherbrooke in Canada. They compared writing speeds for French-speaking primary pupils in their respective countries. While cursive is quite rigidly enforced in France, teachers in Canada are more free to decide which style to teach, and when. Some Canadians teach manuscript first and cursive later; some introduce cursive straight away in first grade.

So was cursive faster than manuscript? No, it was slower. But fastest of all was a personalized mixture of cursive and manuscript developed spontaneously by pupils around the fourth to fifth grade. Even in France, a quarter of the French pupils who were taught cursive exclusively and were still mostly using it in the fourth grade, had largely abandoned it for a mixed style by the fifth grade. They had apparently imbibed manuscript style from their reading experience (it more closely resembles print), even without being taught it explicitly.

While pupils writing in cursive were slower on average, their handwriting was also typically more legible than that of pupils taught only manuscript. But the mixed style allowed for greater speed with barely any deficit in legibility.

The grip that cursive
has on teaching is
sustained by folklore
and prejudice.

On the strength of these findings, Bara and Morin hesitated to make any recommendation for teaching a particular style except to say that it's unwise to demand strict adherence to any of them—contrary to the French tradition. That idea is supported by Virginia Berninger, a professor of education psychology at the University of Washington. “Evidence supports teaching both formats of handwriting and then letting each student choose which works best for him or her,” she writes in a 2012 paper.

Does cursive help with writing and reading disorders such as dyslexia? There's some evidence that it might. “Some children who have trouble printing letters do benefit from learning cursive because they do not have to take their pencil off of the paper as much,” says James. But, she adds, “these children are the exception, and the results cannot be generalized to all children learning to write.”

In fact, for typical children, there's some reason to think manuscript has advantages. Because cursive writing is more challenging for motor coordination and for sheer complexity of the letters, some early research from the 1930s to the 1960s indicated that children develop their writing skills sooner and more legibly with manuscript. Because they have to lift pen from paper between each letter, children prepare better for the next letter. Some recent studies suggest that freeing up cognitive resources that are otherwise devoted to the challenge of simply making the more elaborate cursive forms on paper will leave children more articulate and accurate in what they write.

There's also some suggestion that the difference in appearance between cursive and manuscript could inhibit the acquisition of reading skills, making it harder for children to transfer skills between learning to read and learning to write because they simply don't see cursive in books. Reading and literacy expert Randall Wallace, of Missouri State University, says “it seems odd and perhaps distracting that early readers, just getting used to decoding manuscript, would be asked to learn another writing style.”

It's not clear, however, how much such difficulties truly show up. In a 2009 study in Quebec, Bara and Morin found no reading difficulties in primary-school children that correlated with learning cursive. Yet a more recent study by the pair and their colleagues,

How many of us have great-grandmother's letters in the attic, written in beautiful cursive?

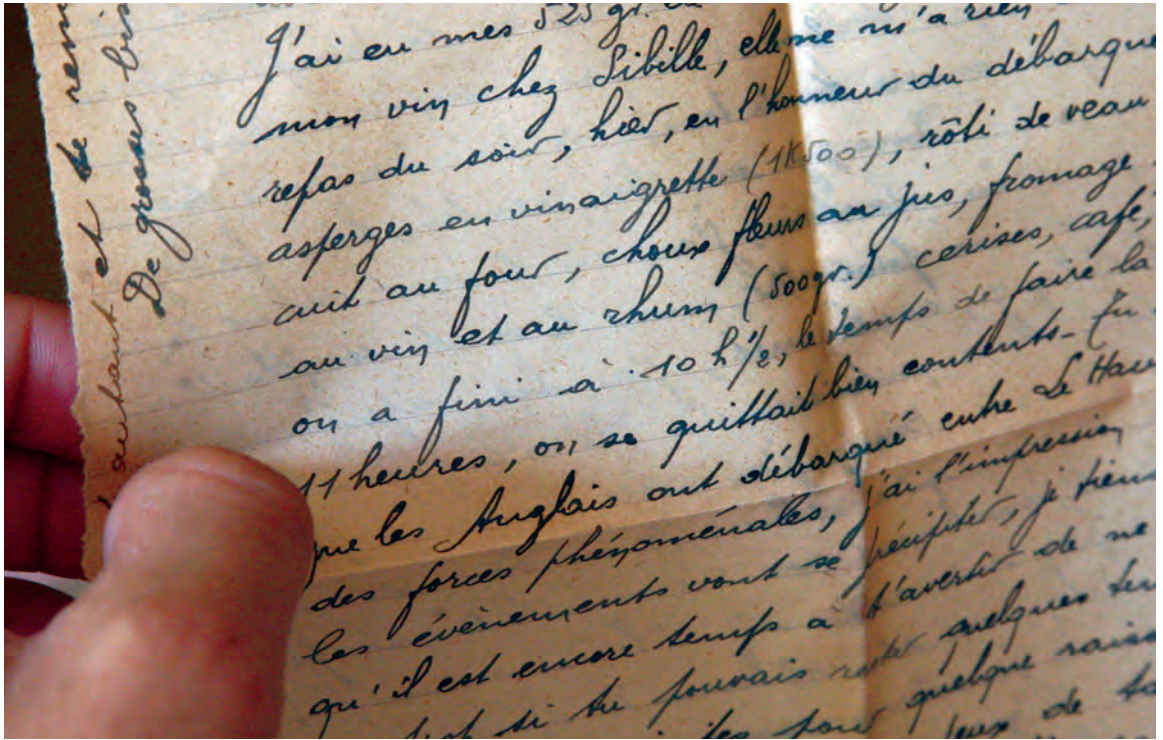
comparing Canadian and French primary schoolers, showed that those who learned only cursive handwriting performed more poorly than those who learned manuscript, or both styles, in recognizing and identifying the sound and name of individual letters.

Regardless of how significant or lasting these differences are, it makes sense that they should exist. There's good evidence, both behavioral and neurological, that a “haptic” (touch-related) sense of letter shapes can aid early reading skills, indicating a cognitive interaction between motor production and visual recognition of letters. That's one reason, incidentally, why it's valuable to train children to write by hand at all, not just to use a keyboard.

But whether it makes any difference, in this regard, which form of handwriting is taught is less clear. In a brain-imaging study on older children, James says that she observed “no brain differences between the two styles of writing.” The type of handwriting doesn't matter to such haptic feedback and reinforcement, she says, as long as children are creating the letter by hand and not tracing it.

In short, the jury is out over whether it is better to learn manuscript, cursive, or both forms of handwriting. There may be pros and cons in all cases. And even if being taught both styles might have some advantages, it's not clear that those cognitive resources and classroom hours couldn't be better deployed in other ways.

WHY THEN DO SOME educational systems place such importance on learning cursive? How, if not by



HANDWRITING MATTERS Nobody questions the value of a handwritten love letter, like this one in French from WWII. The problem is that evidence for cursive's value over other forms of handwriting is missing in action.

consulting the evidence, are educational policy and teaching practices formed?

"My impression is that cursive is still taught primarily because of parental demand and tradition, rather than because there is any scientific basis for its superiority in learning," says Wallace. What's particularly troubling, though, is how inertia and preconceptions seem to distort perception and policy at the expense of the scientific evidence.

In 2011, Bara and Morin decided to take a close look at why teachers do what they do. They and their coworkers interviewed 45 primary-school teachers in Quebec and France about how and why they teach handwriting.

The results were sobering. Teachers had only sketchy knowledge, at best, of what research showed on the subject, especially when it came to the

motor-function aspects of forming letters. Their views were, it seemed, formed primarily by the culture and institutional setting in which they worked.

While Canadian teachers were fairly mixed in their opinions about whether cursive was harder to learn than manuscript, and which should be taught when, French teachers were fairly unanimous. Four-fifths of them insisted that cursive was no more complex than manuscript, and three-quarters said that cursive is faster—a belief contradicted by Bara and Morin's studies. More than half of the Quebec teachers thought that learning manuscript first assists learning to read, while only 10 percent of French teachers thought so.

In other words, teachers who are recommended by their education ministry to teach cursive, as in France, seem to become convinced that there are sound reasons for doing so, despite the lack of evidence. And teachers

in Canada who decide for themselves to introduce cursive as soon as possible seem likewise to believe that there are advantages that justify this decision.

Just because the French situation is probably one of the least sinister or harmful examples of state brainwashing doesn't mean we should shy away from calling it by its real name. Even in the more relaxed teaching practices in Quebec there's a clear sign of the well attested psychological phenomenon in which we "find" evidence to support the decision we have already made anyway, and apply less rigorous judgment when our preconceptions are apparently confirmed.

Indeed, the way rational argument on the question of cursive handwriting so often evaporates suggests that there's some kind of deep emotional investment at stake. When I wrote previously for a British magazine challenging the hegemony of cursive, it received one of the biggest responses the magazine had experienced. Here are just a couple of the popular defenses offered for cursive:

Imagine the frustration your kids will feel when they discover great-grandmother's letters in the attic and can't read them! Without cursive, you're divorcing them from the past.

Cursive is beautiful, whereas manuscript looks childish.

But cursive is not another language. If you need to learn to read it, that takes an hour at most. Besides, how many of us have great-grandmother's letters in the attic, written in beautiful cursive? (In the U.S. there are even suggestions that learning cursive is somehow patriotic and that without it people would not be able to read the Declaration of Independence.) And while I relish the elegance of Jane Austen's original manuscripts, it's plain that many people's cursive is rather far from lovely, or indeed from legible. Manuscript, meanwhile, is only as childish as you decree it to be.

Beliefs about cursive are something of a hydra: You cut off one head, and another sprouts. These beliefs propagate through both the popular and the scientific literature, in a strange mixture of uncritical reporting and outright invention, which depends on myths often impossible to track to a reliable source.

Take a 2014 article in *The New York Times* about the pros and cons of handwriting. This alluded to a 2012 study allegedly demonstrating that cursive may benefit children with developmental dysgraphia—motor-control difficulties in forming letters—and that it may aid

How much else in education is determined by "what's right" rather than what's supported by evidence?

in preventing the reversal and inversion of letters. It's a common claim, and so I began to delve into it.

I was taken to a paper by education researcher Diane Montgomery, describing a study that used an approach called the Cognitive Process Strategies for Spelling (CPSS) to try to help pupils with spelling difficulties, generally diagnosed as dyslexic. This method involves teaching these children cursive, with no comparison to other handwriting styles.

Cursive was chosen for use with CPSS, says Montgomery, because "experiments in teaching cursive ... have proved highly successful in achieving writing targets earlier and for a larger number of children." In support of that claim she cites two studies in journals from the early 1990s so obscure that even the British Library doesn't stock them, but which were in any case conducted on non-dyslexic cohorts and so say nothing about benefits for dyslexics.

Montgomery writes that other dyslexia remediation projects have used cursive too, but cites only one "proven" advantage: a 1998 study allegedly reporting that "cursive script appeared to facilitate writing speed." Not only is this claim contradicted by Bara and Morin's work, but the 1998 paper doesn't even make it. It simply reports how, for children taught a new cursive style in Australian schools, faster writing slightly decreases legibility.

Montgomery also cites a 1976 paper that allegedly advocates "the exclusive use of cursive from the beginning." Except that it doesn't do that at all. It describes

a study comparing letter reversals and transpositions for 21 children at one school, taught cursive from the outset, with 27 from another taught first manuscript and then cursive. The first set showed slightly fewer of these mistakes, but the author acknowledged that, given the tiny sample size, “we in no way wish to offer the present data as documenting proof of the superiority of cursive over manuscript writing.”

So there we have it. But how many people will now be convinced that the benefits of cursive have been affirmed by *The New York Times*, based on the findings of academic research? No wonder teachers are confused.

IS THERE, THEN, ANY SCIENTIFIC CASE for making cursive writing a standard component of the primary curriculum? Wallace thinks not. Given the unproven benefits and the demands it places on time and effort, he feels that “the reasons to reject cursive handwriting as a formal part of the curriculum far outweigh the reasons to keep it.”

Others, like Bara, Berninger, and James, are more ambivalent, but find no evidence that cursive is best. Some feel that in certain respects it is worse than manuscript—it is slower, and time is wasted in learning (or sometimes relearning) this difficult skill. On the other hand, pupils differ, and there’s some potential value in giving them the option of finding what style suits them best, as well as exposure to different fonts so that they might generalize their letter-recognition skills. Or perhaps we should trust that children will find their own “hand” naturally, developing shortcuts for speed and so forth without having to be taught these in some rigid, formal, and standardized fashion.

There’s certainly a debate to be had. But it’s not one that seems to be taking place in schools or education ministries. And every time I hear of a young child turned off writing because he lacks the fine motor skills needed to master cursive, or prohibited from expressing herself freely because she’s not using the approved script, I see that our groundless obsession with cursive is not only pointless but can be destructive.

This must surely lead us to wonder how much else in education is determined by a belief in what is “right,” unsupported by evidence. Education and learning are difficult to pin down by research. Teaching practices

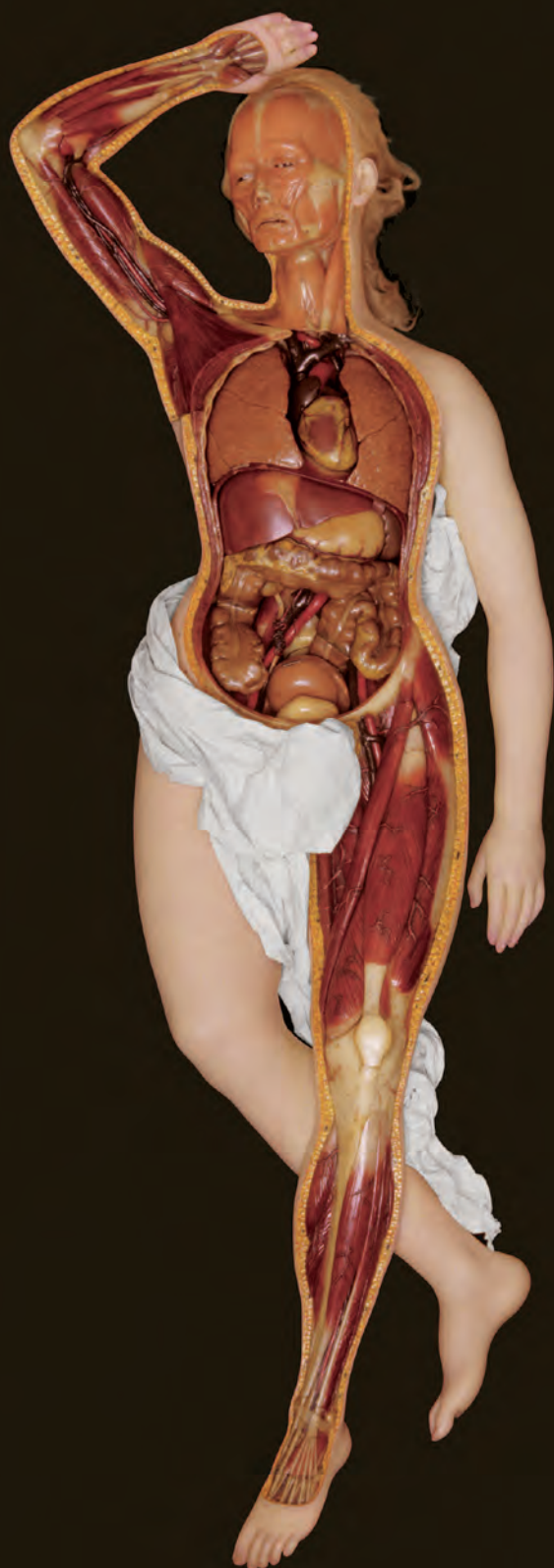
vary, it’s often impossible to identify control groups, and socioeconomic factors play a role. But it’s often the case that the very lack of hard, objective evidence about an issue, especially in the social sciences, encourages a reliance on dogma instead. The danger is greater in education, which, like any issue connected to child rearing and development, is prone to emotive views.

All the same, there is *some* evidence. But it seems little heeded either by teachers or, more significantly, the policymakers who guide their practice. Too often, education is instead a political football. In 2013 in the U.K., the former Secretary of State for Education, conservative politician Michael Gove, became loathed by teachers for instituting changes to the national curriculum based on his own preconceptions about how and what children should learn. Gove’s notoriously dismissive attitude to specialist advice was made explicit in a recent interview, where he said that “people in this country have had enough of experts.” Such blithe disregard of research is not, needless to say, confined to the political right; education and learning are vulnerable to ideologies of all persuasions.

There needs to be wider examination of the extent to which evidence informs education. Do we heed it enough? Or is what children learn determined more by precedent and cultural or institutional norms? To judge from how children learn handwriting, the signs aren’t good. ☹️

PHILIP BALL is a writer based in London. His latest book is *The Water Kingdom: A Secret History of China*. He is a left-hander who does not use cursive. As for what that does to his handwriting, he will let you be the judge:

Schrödinger's Discomfort about the EPR scenario:
 "It is rather discomforting that the theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it."
 Schrödinger, *Proc. Camb. Phil. Soc.* 32, ~~444~~ 555-563, here p556 (1935).
 This and the companion piece preceding it (32, 446-452) were an analysis of EPR in which he introduced "entanglement".



The Brief, Mystical Reign of the Wax Cadaver

Early medical models of human anatomy shrouded death in feminine beauty

BY JOANNA EBENSTEIN

TOWARD THE END of the 18th century, in a wax workshop in Florence, a life-sized, anatomically correct, dissectible goddess of colored wax was created. Artist Clemente Susini took the idealized feminine beauty for which Italian artists had long been renowned in an ambitious new direction, and to hyper-realistic lengths. The result—an Anatomical Venus—is the perfect object: one whose luxuriously bizarre existence challenges belief. It—or better, she—was conceived as a means of teaching human anatomy without the need for constant dissection, which was messy, ethically fraught, and reliant on scarce cadavers. The Anatomical Venus also tacitly communicated the relationship between the human body and a divinely created cosmos, between art and science, and between nature and mankind, as it was then understood.

Often referred to as the “Medici Venus,” this life-sized, dissectible wax woman with gleaming glass eyes and human hair can still be viewed in her original

Venetian glass and rosewood case. She can be disassembled into seven anatomically correct layers, revealing at the final remove a tranquil fetus curled in her womb. She and her sisters, wax women in fixed states of anatomical undress sometimes referred to as Slashed Beauties or Dissected Graces, can still be found in a handful of European museums. Supine in their glass boxes, they beckon with a gentle smile or an ecstatic downcast gaze. One idly toys with a plait of real golden human hair; another clutches at the plush, moth-eaten satin cushions of her case as her torso erupts in a spontaneous, bloodless auto-dissection; another is crowned with a golden tiara, while one further wears a silk ribbon tied in a bow around a dangling entrail.

Since their creation in late-18th-century Florence, these wax women have seduced, intrigued, and instructed. In the 21st century, they also confound, flickering on the edges of medicine and myth, votive and vernacular, fetish and fine art. How can we understand today an object that is at once a seductive

representation of ideal female beauty and an explicit demonstration of the inner workings of the body? How can we make sense of an artifact that was once equally at home in the fairground and the medical museum? How can we comprehend a creature memorably described by Holly Myers in the *Los Angeles Times* as “an Enlightenment-era St. Teresa ravished by communion with the invisible forces of science”?

To the modern eye, the Medici Venus is a perplexing object, one that challenges conventions of scientific visualization and explodes neat, categorical divides between art and science, entertainment and education. In her own day, she was considered the ideal tool to teach anatomy to a general public, and she was so highly regarded by anatomists that copies were commissioned for a variety of museums and teaching collections around Europe. The Medici Venus was a perfect embodiment of the Enlightenment values of her time, in which human anatomy was understood as a reflection of the world and the pinnacle of divine knowledge, and in which to know the human body was to know the mind of God. Although she was neither the first nor the last of her kind, she was the most accomplished Anatomical Venus ever made, setting the standard by which all others are judged.

THE MEDICI VENUS WAS BORN in the workshop of The Museum for Physics and Natural History in Florence, better known as La Specola, a public science museum in Florence. Museum director Felice Fontana’s grand and ambitious aim was to create an encyclopedia of the human body in wax. Fontana hoped that it would end the need for cadavers in the teaching

of anatomy: If we succeeded in reproducing in wax all the marvels of our animal machine, we would no longer need to conduct dissections, and students, physicians, surgeons, and artists would be able to find their desired models in a permanent, odor-free, and incorruptible state.

Supine in their glass boxes,
they beckon with a gentle smile
or an ecstatic downcast gaze.

The wax models produced by the workshop at La Specola were posed as if alive, healthy, and pain-free, in an attempt to distance the study of anatomy from the contemplation of death and bloody internal organs. The Anatomical Venus was further removed from notions of death and the corpse as she drew on the historical and artistic figure of the Roman goddess of love, beauty, and fertility, evoking a long history of paintings and sculptures of placid, idealized nudes.

Each pristine wax model at the museum was the product of the careful study of cadavers that were delivered from the nearby Santa Maria Nuova hospital. Although the collection fell short of its ambition to render all further human dissection unnecessary, today, over 200 years after their creation, La Specola’s



BRINGING UP BABY These painted plaster obstetric models were used for the training of surgeons and midwives in the mid-18th century.



SLEEPING BEAUTY This anatomical Venus, produced at La Specola between 1784 and 1788, is displayed in her original rosewood and Venetian glass case at the Josephinum, Vienna, Austria.

waxworks are still considered remarkably accurate, some of them demonstrating anatomical structures that had yet to be named or described at the time of their making.

Susini was the best known of all the wax artists employed at La Specola's workshop, and it was under Susini's oversight that the museum created its finest and most iconic works, among them the ingenious, dissectible Medici Venus.

The modelers who created the anatomical wax models at La Specola and other wax workshops depended in part for the veracity of their work on the anatomical illustrations featured in anatomical atlases. Real human body parts would then be procured to work from, in order to ensure that all the individual parts were as accurate as possible. An Anatomical Venus was expensive and time-consuming to produce. Over 200 cadavers were sometimes required to craft a single

dissectible figure, owing to the speed with which bodies decayed, especially in the hot weather of the summer months.

The modeler would either take a cast of the prepared specimen or copy it by hand. Once a model of inexpensive wax or clay had been approved, a plaster cast would be taken to serve as a mold, which could then be used repeatedly.

Next, the plaster molds would be coated with soap or oil to ease release of the wax. Wax can look uncannily like flesh; it has a similarly moist appearance, depth of color (due to the even suspension of added pigments), and transparent opacity. The most commonly used waxes were beeswax; white "Virgin wax" from Smyrna or Venice; or that of the Chinese scale insects *Ceroplastes ceriferus* and *Ericerus pela*, which produce a particularly fine, hard, white wax with a high melting point, well suited to modeling skin, though



Fig. 12. *Posterior view of the human back and shoulder, showing the muscles and ribs.* M. D. *Antony, sculp.* J. *Waller, del.*

The ecstatic was understood as an expression of the sacred: a mystical experience.

prohibitively expensive. The wax would be mixed with turpentine and other oils or fats to produce the required texture, as well as a mastic, or plant resin, to fortify and increase its stability, which was important

for sustaining structure and retaining vivid colors. It would then be carefully heated and colored with finely ground pigments, often highly precious or toxic, which had been sifted through cloth and dissolved in oil or turpentine.

Thin layers of tinted wax would then be painted into, cooled, and released from the mold. As most of the pieces were hollow, they were stuffed with rags or woodchips for support, although some, including Susini's Medici Venus, have metal frames. Hair was attached with varnish; eyelashes were individually implanted. Fine blood vessels and nerves were made of silk or linen fibers dipped in wax. The parts would be assembled, while attending to any flaws or damage. Finally, the model would be glazed in order to keep its surfaces free of dust and affect a realistic shine: another anatomical masterwork ready for display.



IN MINIATURE This half-scale wax model is thought to have been a study for the iconic dissectible Medici Venus at La Specola.



PICTURE PERFECT Clemente Susini, depicted here in a wax self-portrait, oversaw the creation of the finest wax models at La Specola.

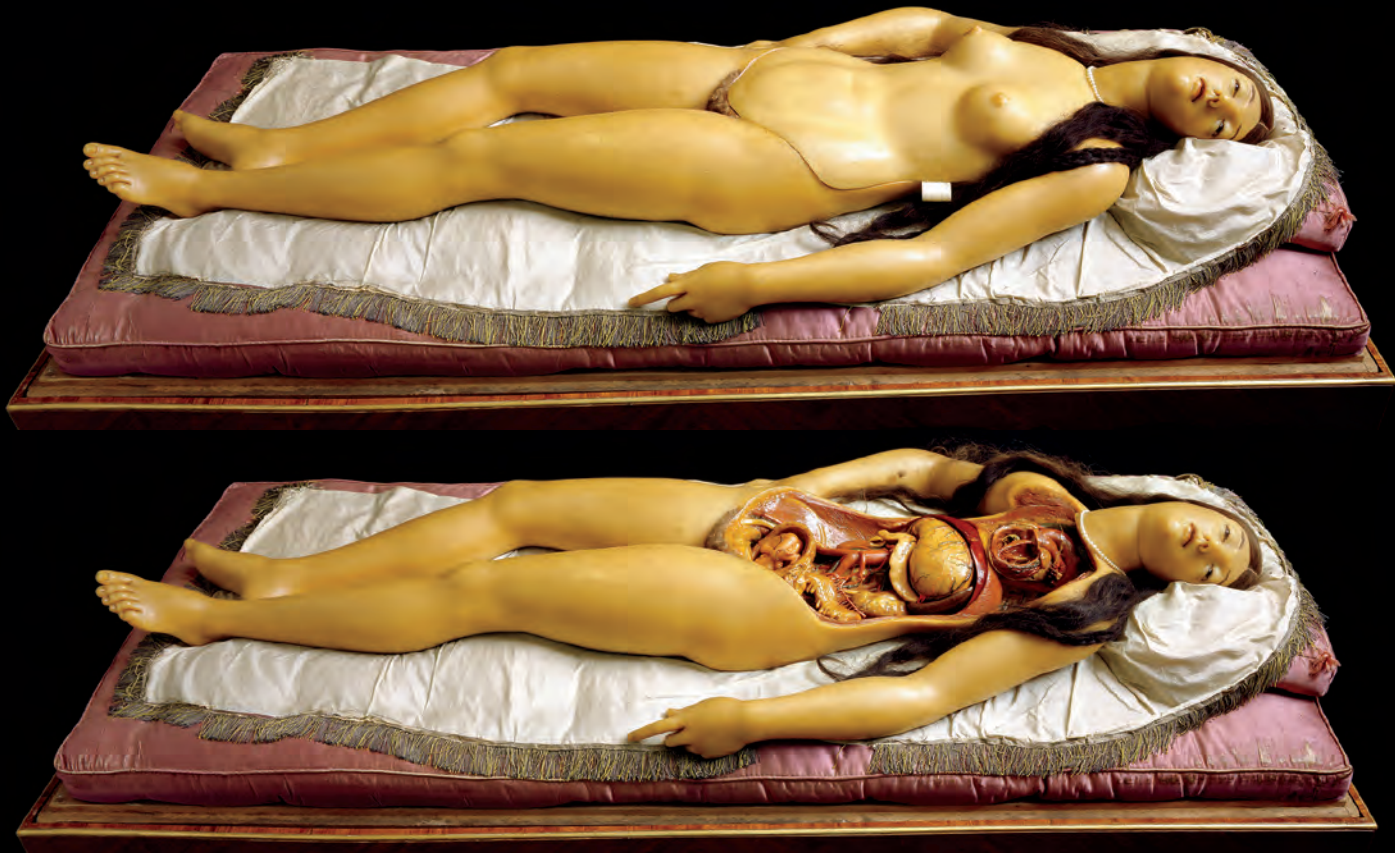
THE MEDICI VENUS LOOKS perplexing and sometimes even troubling to the contemporary eye, a response that is largely due to the startling juxtaposition between the abjectness of her innards and the erotic charge of her hyper-beautiful exterior. This odd sense is heightened by the inclusion of details that, to today's sensibility, seem superfluous to her educational aims: her cascade of lustrous hair, life-like glass eyes, pearl necklace (a memento mori symbol that also covers the seam that attaches her head to her torso), and bed of luxurious silk and satin. Such artful and seductive details seem to undermine her scientific integrity, but it is the intertwining of anatomy, art, and religion that unlocks the meaning of her provocative appeal.

The Medici Venus's enigmatic expression and swooning posture are suggestive of ecstasy, which today is understood as sexual. We can infer that at the time of her creation she was not regarded as particularly indecent from the fact that, upon opening to the general public, including women and children, the wax models were the most popular exhibits, eliciting neither criticism nor public outcry. There are scores of comments by visitors to the museum who spoke

highly of the collection, and we know that copies were commissioned by a variety of other museums. Clearly, something has changed since the time of Venus's creation in such a way as to render her strange and sexually charged. It is likely that a different understanding of the ecstatic than our own influenced Venus's reception. The ecstatic was understood at that time not merely as a profane, sensual experience, but as an expression of the sacred: a mystical experience. Depictions of saints and martyrs in attitudes of ecstatic release fill the churches of Italy and other Catholic countries.

But how are we to understand such ecstatic representations today? Perhaps the heart of the confusion lies in the notion of the ecstatic as either religious or sexual, sacred or profane, where once it was understood to be both. In Georges Bataille's 1957 *Eroticism*, he argues that sexuality itself was a part of religious expression until Christianity banished it from that domain. The very etymology of the word ecstasy lies in the Greek *ek*, meaning "out of," and *stasis*, meaning "standing." This escape from isolated consciousness is experienced as a sort of transcendent bliss beyond the powers of language or description. It is, in Bataille's words, "divine life sought through death of the self" that is at the heart of the ecstatic experience. It is our way of returning to the state of grace that existed before we were banished from the Garden of Eden; before we were divided from the universe by our self-awareness, our language and propensity for abstraction, our sense of shame, and the foreknowledge of our own death—arguably the very thing that separates us from other animals. This is the enlightened epiphany described by mystics of all religious backgrounds. It is no wonder that sexuality retains a touch of the supernatural, if rendered strange by our attempts to focus it squarely in the world of the body and the senses, and to separate it from more mysterious domains.

ONLY A LITTLE OVER 200 YEARS AGO the Medici Venus was the perfect tool to teach human anatomy to the public; today she is bizarre—an alluring, life-like female wax model in a state of ambiguous ecstasy with her inner organs on graphic display. Perhaps she could only be truly understood for a brief period, a time when it was still possible for religion, art, philosophy, and science to coexist peacefully; she is a relic from



A MYSTICAL EXPERIENCE The Medici Venus, displayed intact and dissected. When the exhibit was first displayed to the public, no outcry ensued, despite her pose and ecstatic expression.

an age in which the torch was passed from spirituality to science as the primary arbiter of death, disease, the nature of life, and humanity's place in the universe. But maybe we are drawn today to the Anatomical Venus because of an unspoken, intuited resolution of our own divided nature, an unconscious recognition of another avenue abandoned, in which beauty and science, religion and medicine, soul and body might be one. ☺

JOANNA EBENSTEIN is a multidisciplinary artist, curator, writer, lecturer, and graphic designer. She is also the co-founder and creative director of the Morbid Anatomy Museum in Brooklyn, New York.

Adapted from *The Anatomical Venus* by Joanna Ebenstein, published by Thames & Hudson LTD. Copyright © 2016 Joanna Ebenstein

Why We Love How-to Videos

*Instructional videos can teach us anything—
especially if you watch them this way*

BY TOM VANDERBILT

AN INSISTENT PATTERN HAS quietly taken hold in my household. I will order some consumer product online. The product will arrive. I will open the package, extract the thing from its protective wrappings, and retrieve the instruction manual. I will examine the product briefly, then begin to read the instruction manual. And then I will go to YouTube.

There, I will find, almost invariably, that someone has already done the thing that I am hoping to do. They will have documented the process with varying degrees of professionalism ranging from chirpy, well-captioned professional productions to people in their poorly-lit bedrooms.

Most recently, it was a hitch-mounted bicycle rack for my car giving me trouble. The written instructions were telegraphic, the drawings may well have been ancient cuneiform. I found my salvation on YouTube, and the rack was road-ready in minutes. When I later thanked a friend who had recommended the product, I confessed I had gotten a video assist on the install.

“The guy with the Subaru?” he asked. “In his driveway?” Our path to enlightenment had apparently crossed, along with some 57,000 other viewers.¹

It is not just product assembly. My YouTube search history is filled with moments of fleeting pedagogy: How to best “pop up” on a surfboard, how to play Dinosaur Jr.’s “Get Me” on guitar, how to set up a private server for my daughter’s Minecraft (Minecraft tutorials alone must number in the hundreds of thousands). When a plumber came by to unclog our toilet, he tenderly told me after I could have done the same thing with an auger from the hardware store—and saved \$100. And so I immediately purchased the device. But how to use it properly? To YouTube I went, suddenly realizing I should have looked there first. I was steered to a video of a man patiently demonstrating auger technique on a sample jam. This task, he noted, was a plumber’s “cash cow.” He joked about being forgiven, if any plumbers happened to be watching, for “giving away the secrets.” But he need not have worried: YouTube is rife with auger demonstrations from

ILLUSTRATION BY VINNIE NEUBERG





FLIGHT SCHOOL Searching YouTube for “how to make a paper airplane” returns over 1 million hits. This particular example is from a user called Martin Cecen, who uploads new paper airplanes every week.

plumbers themselves.

Last year, it was estimated that YouTube was home to more than 135 million how-to videos.² In a 2008 survey, “instructional videos” were ranked to be the site’s third most popular content category—albeit a “distant third” behind “performance and exhibition” and “activism and outreach.”³ More recent data suggest that distance may have closed: In 2015, Google noted that “how to” searches on YouTube were increasing 70 percent annually.⁴ The genre is by now so mature that it makes for easy satire.

What are people looking to do? The most popular searches, by one analysis, range from the achingly prosaic to the exceedingly specific—from “how to kiss” to “how to make a rainbow-loom starburst bracelet.” You can learn how to boil water, field strip an AR-15 rifle, or fly a 747. But stories abound of people—usually kids—achieving impressive proficiency in everything from opera singing to dubstep dancing by simply copying what they have seen in YouTube videos.⁵ YouTube pedagogy has swept through—and virtually helped create—fields like competitive cubing (Rubik’s),

where solve times have plummeted, aided largely by the transmission of techniques via YouTube.⁶

There is, to an extent unparalleled in history, the promise that anyone, anywhere in the world, without cost or travel or the embarrassment of public failure, can learn just about anything. Some take it too far: When a Las Vegas man was arrested last year for performing illegal surgical operations—he does not have a medical degree—he noted that while he had long read medical textbooks, his primary educational source was YouTube. “You don’t watch one, you watch like 20 or 25 [videos] like I do,” he said. “Pretty close to anything you want to learn you can learn it off YouTube for free.”⁷

I am not about to attempt open-heart surgery. But as I racked up time looking for people to show me how to do things, I wondered: Why did this seem to be such an effective way to learn, and how could I do it better?

WE HUMANS ARE NOT ALONE in being able to learn through video observation. A 2014 study showed that when a group of marmosets were presented with an

YouTube is catnip for our social brains.

experimental “fruit” apparatus, most of those that watched a video of marmosets successfully opening it were able to replicate the task. They had, in effect, watched a “how to” video.⁸ Of the 12 marmosets who managed to open the box, just one figured it out sans video (in the human world, he might be the one making YouTube videos).

Robots can do it too. The problem, though, is that robots do not learn very effectively from watching one demonstration. Ozan Şener, a researcher at Cornell University, notes that even in object recognition tasks in computer vision, researchers routinely train robots using millions of photos of objects. “There is no way you can collect a million demonstrations of anything,” he says.

So Şener and his fellow AI researchers at Cornell wondered if there was a way to solve this problem. As Şener put it: “What kind of data exists which is already collected, which is scaleable, which spans lots of activities and lots of environments?” The answer, of course, was YouTube. A search for an activity like “How to tie a bow tie,” Şener noted, generates upward of 250,000 hits on YouTube. Using the 100 most popular videos for a given popular task, the team set the robots loose in an unsupervised learning task, leaving it to them to try to figure out what was significant. Even left to their own devices, the robots were able to write text

instructions for the tasks they’d observed.

With robots, as with humans, it may be easier to show them what to do than to tell them. But humans have robots beat in the sheer efficiency with which we can learn. We don’t need 100 videos to learn to tie a bow tie. This, says Luc Proteau, head of the Department of Kinesiology at the University of Montreal, is a defining feature of humans.

“We are built to observe,” as Proteau tells me. There is, in the brain, a host of regions that come together under a name that seems to describe YouTube itself, called the action-observation network. “If you’re looking at someone performing a task,” Proteau says, “you’re in fact activating a bunch of neurons that will be required when you perform the task. That’s why it’s so effective to do observation.”

We are, in effect, simulating doing the task ourselves, warming up the same neurons that will be used when we actually give it a go. “It’s thought that the observation network developed as a means of understanding what the meaning is of actions performed by others,” Proteau says. “If we see someone making a fist, you will be able to understand, if I was doing that, what would be the purpose—to hit someone.”

This ability to learn socially, through mere observation, is most pronounced in humans. In experiments, human children have been shown to “over-imitate” the

problem-solving actions of a demonstrator, even when superfluous steps are included (chimps, by contrast, tend to ignore these).⁹ Susan Blackmore, author of *The Meme Machine*, puts it this way: “Humans are fundamentally unique not because they are especially clever, not just because they have big brains or language, but because they are capable of extensive and generalised imitation.” In some sense, YouTube is catnip for our social brains. We can watch each other all day, every day, and in many cases it doesn’t matter much that there’s not a living creature involved. According to Proteau’s research, learning efficiency is unaffected, at least for simple motor skills, by whether the model being imitated is live or presented on video.¹⁰

AS GOOD A FIT as YouTube is for our social brains, there are ways we can learn from videos even better.

The first has to do with intention. “You need to want to learn,” Proteau says. “If you do not want to learn, then observation is just like watching a lot of basketball on the tube. That will not make you a great free throw shooter.” Indeed, as Emily Cross, a professor of cognitive neuroscience at Bangor University told me, there is evidence—based on studies of people trying to learn to dance or tie knots (two subjects well covered by YouTube videos)—that the action-observation network is “more strongly engaged when you’re watching to learn, as opposed to just passively speculating.” In one study, participants in an fMRI scanner asked to watch a task being performed with the goal of learning how to do it showed greater brain activity in the parietofrontal mirror system, cerebellum and hippocampus than those simply being asked to watch it. And one region, the pre-SMA (for “supplementary motor area”), a region thought to be linked with the “internal generation of complex movements,” was activated *only* in the learning condition—as if, knowing they were going to have to execute the task themselves, participants began internally rehearsing it.¹¹

It also helps to arrange for the kind of feedback that makes a real classroom work so well. If you were trying to learn one of Beyoncé’s dance routines, for example, Cross suggests using a mirror, “to see if you’re getting it right.” When trying to learn something in which we do not have direct visual access to how well we are doing—like a tennis serve or a golf swing—learning

by YouTube may be less effective. You might be able to learn the chords of your favorite song through simple mirroring, but at least one guitarist notes some problems in the idea of “learning by copying from YouTube.” While self-taught guitarists can often “spit back” notes, robot-like, he suggests that only a teacher in the room can help develop more intangible (but no less important) factors like “tone” and “groove.”

On the other hand, Justin Sandercoe, a longtime guitar player and teacher in the United Kingdom, who has famously built up a massive library of online lessons (even before YouTube), thinks people can largely tell if they are getting better or not at playing a piece of music by comparing their performance to the online version they are trying to emulate. Whatever might be lacking in terms of a person not being in the room with the student, he suggests, is made up for by the sheer convenience of online learning. “If you learn something one on one, and forget about it later when you’re at home, you can’t really rewind it.” On YouTube, a student can endlessly rewind—and the teacher won’t get frustrated.

The final piece of advice is to look at both experts and amateurs. Work by Proteau and others has shown that subjects seemed to learn sample tasks more effectively when they were shown videos of both experts performing the task effortlessly, and the error-filled efforts of novices (as opposed to simply watching experts or novices alone).¹² It may be, Proteau suggests, that in the “mixed” model, we learn what to strive for as well as what to avoid.¹³ Watching Roger Federer is not enough—we need to see the average duffer flailing about on the court. As Daniel Lametti and Kate Watkins, professors at the University of Oxford, note, “observing someone failing to learn—such as someone who is already an expert (e.g. Federer)—provides no benefit to observers when they actually go to learn the task.”¹⁴

In other words, seeing learning happening actually helps us learn. Although, admittedly, sometimes we do not want to learn plumbing—we just want to fix the damned toilet. ☺

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Is Artificial Intelligence Permanently Inscrutable?

Despite new biology-like tools, some insist interpretation is impossible

BY AARON M. BORNSTEIN

DMITRY MALIOUTOV CAN'T SAY much about what he built.

As a research scientist at IBM, Malioutov spends part of his time building machine learning systems that solve difficult problems faced by IBM's corporate clients. One such program was meant for a large insurance corporation. It was a challenging assignment, requiring a sophisticated algorithm. When it came time to describe the results to his client, though, there was a wrinkle. "We couldn't explain the model to them because they didn't have the training in machine learning," says Malioutov.

In fact, it may not have helped even if they were machine learning experts. That's because the model was an artificial neural network, a program that takes in a given type of data—in this case, the insurance company's customer records—and finds patterns in them. These networks have been in practical use for over half a century, but lately they've seen a resurgence, powering breakthroughs in everything from speech

recognition and language translation to Go-playing robots and self-driving cars.

As exciting as their performance gains have been, though, there's a troubling fact about modern neural networks: Nobody knows quite how they work. And that means no one can predict when they might fail.

Take, for example, an episode recently reported by machine learning researcher Rich Caruana and his colleagues. They described the experiences of a team at the University of Pittsburgh Medical Center who were using machine learning to predict whether pneumonia patients might develop severe complications. The goal was to send patients at low risk for complications to outpatient treatment, preserving hospital beds and the attention of medical staff. The team tried several different methods, including various kinds of neural networks, as well as software-generated decision trees that produced clear, human-readable rules.

The neural networks were right more often than any of the other methods. But when the researchers

ILLUSTRATION BY EMMANUEL POLANCO

and doctors took a look at the human-readable rules, they noticed something disturbing: One of the rules instructed doctors to send home pneumonia patients who already had asthma, despite the fact that asthma sufferers are known to be extremely vulnerable to complications.

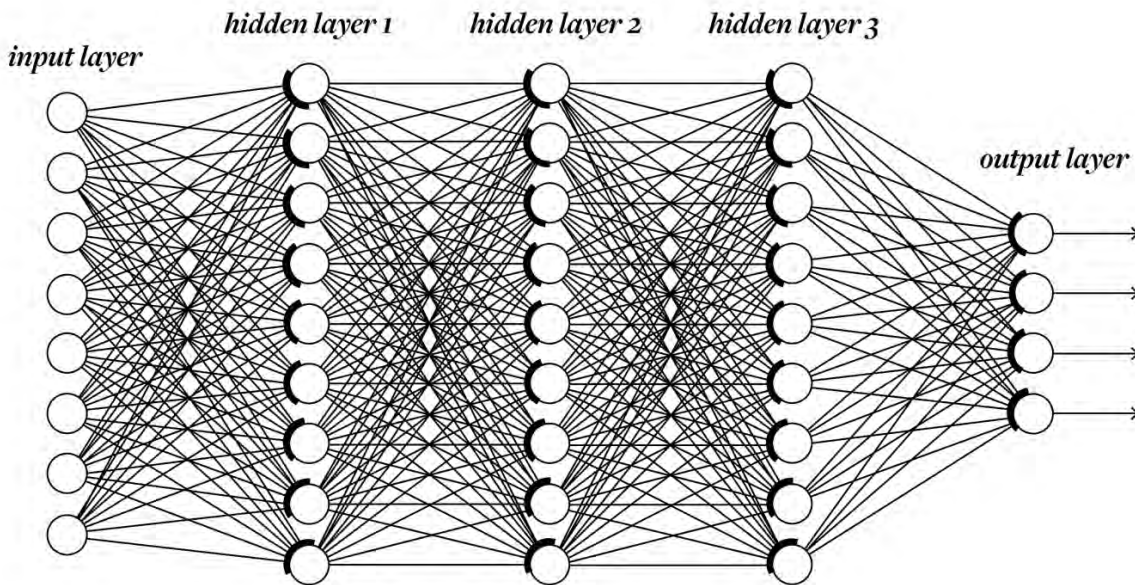
The model did what it was told to do: Discover a true pattern in the data. The poor advice it produced was the result of a quirk in that data. It was hospital policy to send asthma sufferers with pneumonia to intensive care, and this policy worked so well that asthma sufferers almost never developed severe complications. Without the extra care that had shaped the hospital's patient records, outcomes could have been dramatically different.

The hospital anecdote makes clear the practical value of interpretability. "If the rule-based system had learned that asthma lowers risk, certainly the neural nets had learned it, too," wrote Caruana and colleagues—but the neural net wasn't

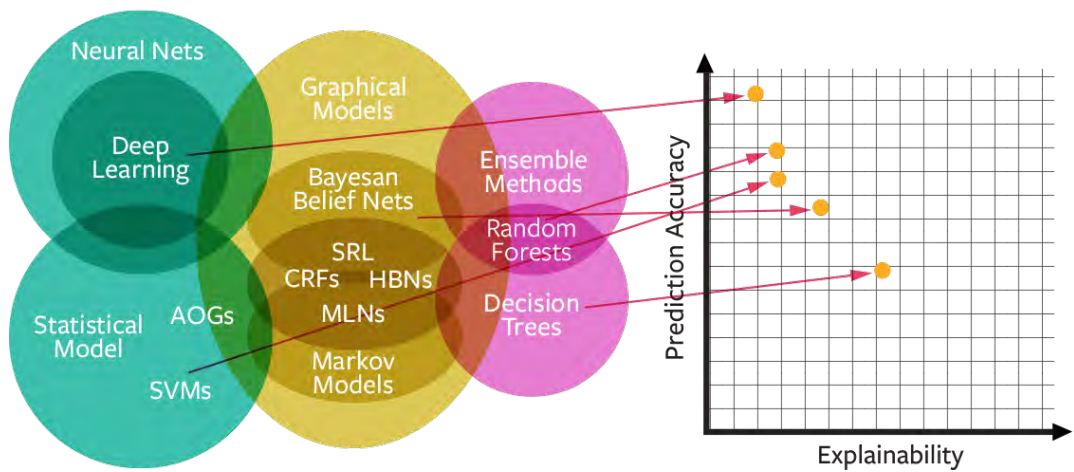
human-interpretable, and its bizarre conclusions about asthma patients might have been difficult to diagnose.¹ If there hadn't been an interpretable model, Malioutov cautions, "you could accidentally kill people."

This is why so many are reluctant to gamble on the mysteries of neural networks. When Malioutov presented his accurate but inscrutable neural network model to his own corporate client, he also offered them an alternative, rule-based model whose workings he could communicate in simple terms. This second, interpretable, model was less accurate than the first, but the client decided to use it anyway—despite being a mathematically sophisticated insurance company for which every percentage point of accuracy mattered. "They could relate to [it] more," Malioutov says. "They really value intuition highly."

Even governments are starting to show concern about the increasing influence of inscrutable neural-network oracles. The European Union recently proposed to establish a "right to explanation," which



HIDDEN MEANINGS In neural networks, data is passed from layer to layer, undergoing simple transformations at each step. Between the input and output layers are hidden layers, groups of nodes and connections that often bear no human-interpretable patterns or obvious connections to either input or output. "Deep" networks are those with many hidden layers.



WHAT VS WHY Modern learning algorithms show a tradeoff between human interpretability and accuracy. Deep learning is both the most accurate and the least interpretable.

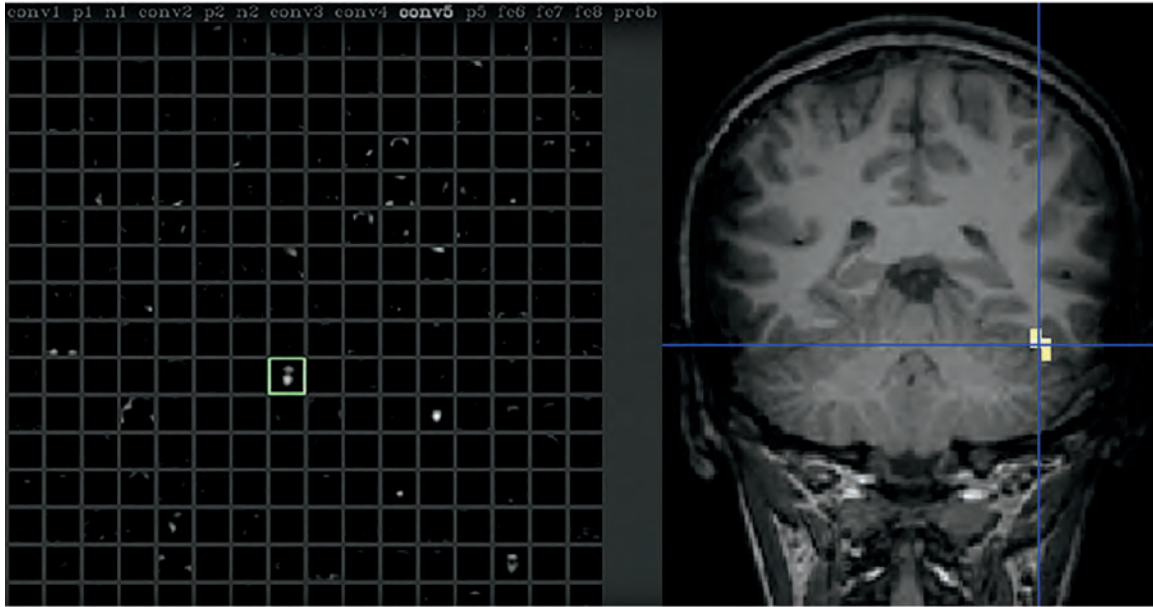
allows citizens to demand transparency for algorithmic decisions.² The legislation may be difficult to implement, however, because the legislators didn't specify exactly what "transparency" means. It's unclear whether this omission stemmed from ignorance of the problem, or an appreciation of its complexity.

In fact, some believe that such a definition might be impossible. At the moment, though we can know everything there is to know about what neural networks are doing—they are, after all, just computer programs—we can discern very little about how or why they are doing it. The networks are made up of many, sometimes millions, of individual units, called neurons. Each neuron converts many numerical inputs into a single numerical output, which is then passed on to one or more other neurons. As in brains, these neurons are divided into "layers," groups of cells that take input from the layer below and send their output to the layer above.

Neural networks are trained by feeding in data, then adjusting the connections between layers until the network's calculated output matches the known output (which usually consists of categories) as closely as possible. The incredible results of the past few years are

thanks to a series of new techniques that make it possible to quickly train deep networks, with many layers between the first input and the final output. One popular deep network called AlexNet is used to categorize photographs—labeling them according to such fine distinctions as whether they contain a Shih Tzu or a Pomeranian. It consists of over 60 million "weights," each of which tell each neuron how much attention to pay to each of its inputs. "In order to say you have some understanding of the network," says Jason Yosinski, a computer scientist affiliated with Cornell University and machine learning startup Geometric Intelligence, "you'd have to have some understanding of these 60 million numbers."

Even if it were possible to impose this kind of interpretability, it may not always be desirable. The requirement for interpretability can be seen as another set of constraints, preventing a model from a "pure" solution that pays attention only to the input and output data it is given, and potentially reducing accuracy. At a Defense Advanced Research Projects Agency (DARPA) conference early this year, program manager David Gunning summarized the trade-off in a chart that shows deep networks as the least understandable of



BRIAN ACTIVITY A single neuron in a deep neural net (highlighted by a green box) responds to Yosinski's face,³ just as a distinct part of the human brain reliably responds to faces (highlighted in yellow).

modern methods. At the other end of the spectrum are decision trees, rule-based systems that tend to prize explanation over efficacy.

The result is that modern machine learning offers a choice among oracles: Would we like to know what will happen with high accuracy, or why something will happen, at the expense of accuracy? The “why” helps us strategize, adapt, and know when our model is about to break. The “what” helps us act appropriately in the immediate future.

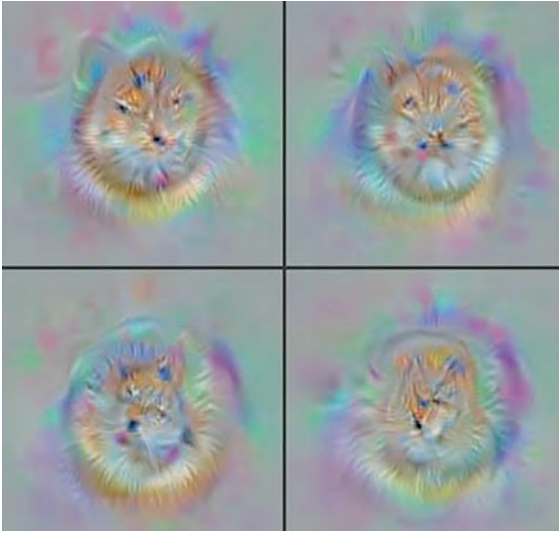
It can be a difficult choice to make. But some researchers hope to eliminate the need to choose—to allow us to have our many-layered cake, and understand it, too. Surprisingly, some of the most promising avenues of research treat neural networks as experimental objects—after the fashion of the biological science that inspired them to begin with—rather than analytical, purely mathematical objects. Yosinski, for example, says he is trying to understand deep networks “in the way we understand animals, or maybe even humans.” He and other computer scientists are importing techniques from biological research that

peer inside networks after the fashion of neuroscientists peering into brains: probing individual components, cataloguing how their internals respond to small changes in inputs, and even removing pieces to see how others compensate.

Having built a new intelligence from scratch, scientists are now taking it apart, applying to these virtual organisms the digital equivalents of a microscope and scalpel.

YOSINSKI SITS AT A COMPUTER TERMINAL, talking into a webcam. The data from the webcam is fed into a deep neural net, while the net itself is being analyzed, in real time, using a software toolkit Yosinski and his colleagues developed called the Deep Visualization toolkit. Clicking through several screens, Yosinski zooms in on one neuron in the network. “This neuron seems to respond to faces,” he says in a video record of the interaction.³ Human brains are also known to have such neurons, many of them clustered in a region of the brain called the fusiform face area. This region, discovered over the course of multiple studies beginning

LEFT: COURTESY OF JASON YOSINSKI
RIGHT: MAXIMILIAN RIESENHUBER, GEORGETOWN UNIVERSITY
MEDICAL CENTER



IDEALIZED CATS Examples of synthetic ideal cat faces, generated by the Deep Visualization toolkit.³ These faces are generated by tweaking a generic starting image pixel by pixel, until a maximum response from AlexNet's face neuron is achieved.

in 1992,^{4,5} has become one of the most reliable observations in human neuroscience. But where those studies required advanced techniques like positron emission tomography, Yosinski can peer at his artificial neurons through code alone.

This approach lets him map certain artificial neurons to human-understandable ideas or objects, like faces, which could help turn neural networks into intuitive tools. His program can also highlight which aspects of a picture are most important to stimulating the face neuron. “We can see that it would respond even more strongly if we had darker eyes and rosier lips,” he says.

To Cynthia Rudin, professor of computer science and electrical and computer engineering at Duke University, these “post-hoc” interpretations are by nature problematic. Her research focuses on building rule-based machine learning systems applied to domains like prison sentencing and medical diagnosis, where human-readable interpretations are possible—and critically important. But for problems in areas like vision, she says, “Interpretations are completely within

the eye of the beholder.” We can simplify a network response by identifying a face neuron, but how can we be certain that’s really what it’s looking for? Rudin’s concerns echo the famous dictum that there may be no simpler model of the visual system than the visual system itself. “You could have many explanations for what a complex model is doing,” she says. “Do you just pick the one you ‘want’ to be correct?”

Yosinski’s toolkit can, in part, counter these concerns by working backward, discovering what the network itself “wants” to be correct—a kind of artificial ideal. The program starts with raw static, then adjusts it, pixel by pixel, tinkering with the image using the reverse of the process that trained the network. Eventually it finds a picture that elicits the maximum possible response of a given neuron. When this method is applied to AlexNet neurons, it produces caricatures that, while ghostly, unquestionably evoke the labeled categories.

This seems to support his claim that the face neurons are indeed looking for faces, in some very general sense. But there’s a catch. To generate those pictures, Yosinski’s procedure relies on a statistical constraint (called a natural image prior) that confines it to producing images that match the sorts of structure that one finds in pictures of real-world objects. When he removes those rules, the toolkit still settles on an image that it labels with maximum confidence, but that image is pure static. In fact, Yosinski has shown that in many cases, the majority of images that AlexNet neurons prefer appear to humans as static. He readily admits that “it’s pretty easy to figure out how to make

Some researchers hope to eliminate the need to choose—to let us have our many-layered cake, and understand it, too.

the networks say something extreme.”

To avoid some of these pitfalls, Dhruv Batra, an assistant professor of electrical and computer engineering at Virginia Tech, takes a higher-level experimental approach to interpreting deep networks. Rather than trying to find patterns in their internal structure—“people smarter than me have worked on it,” he demurs—he probes how the networks behave using, essentially, a robotic version of eye tracking. His group, in a project led by graduate students Abhishek Das and Harsh Agrawal, asks a deep net questions about an image, like whether there are drapes on a window in a given picture of a room.⁶ Unlike AlexNet or similar systems, Das’ network is designed to focus on only a small patch of an image at a time. It moves its virtual eyes around the picture until it has decided it has enough information to answer the question. After sufficient training, the deep network performs extremely well, answering about as accurately as the best humans.

Das, Batra, and their colleagues then try to get a sense of how the network makes its decisions by investigating where in the pictures it chooses to look. What they have found surprises them: When answering the question about drapes, the network doesn’t even bother looking for a window. Instead, it first looks to the bottom of the image, and stops looking if it finds a bed. It seems that, in the dataset used to train this neural net, windows with drapes may be found in bedrooms.

While this approach does reveal some of the inner workings of the deep net, it also reinforces the challenge presented by interpretability. “What machines are picking up on are not facts about the world,” Batra says. “They’re facts about the dataset.” That the machines are so tightly tuned to the data they are fed makes it difficult to extract general rules about how they work. More importantly, he cautions, if you don’t know how it works, you don’t know how it will fail. And when they do they fail, in Batra’s experience, “they fail spectacularly disgracefully.”

Some of the obstacles faced by researchers like Yosinski and Batra will be familiar to scientists studying the human brain. Questions over the interpretations of neuroimaging, for example, are common to this day, if not commonly heeded. In a 2014 review of the field, cognitive neuroscientist Martha Farah wrote

“You could have many explanations for what a complex model is doing. Do you just pick the one you ‘want’ to be correct?”

that “the worry ... is that [functional brain] images are more researcher inventions than researcher observations.”⁷ The appearance of these issues in very different realizations of intelligent systems suggests that they could be obstacles, not to the study of this or that kind of brain, but to the study of intelligence itself.

IS CHASING INTERPRETABILITY a fool’s errand? In a 2015 blog post entitled “The Myth of Model Interpretability,” Zachary Lipton, of the University of California, San Diego, offered a critical perspective on both the motivations behind interpreting neural networks, and the value of building interpretable machine learning models for huge datasets in the first place. He submitted a provocative paper on this subject to a workshop (organized by Malioutov and two of his colleagues) on Human Interpretability at this year’s International Conference on Machine Learning (ICML).⁸

Lipton points out that many scholars disagree over the very concept of interpretability, which suggests to him either that interpretability is poorly understood—or that there are many equally valid meanings. In either

case, chasing interpretability may not satisfy our desire for a straightforward, plain-English description of a neural net output. In his blog post, Lipton argued that, when it comes to enormous datasets, researchers have the option to resist the impulse to interpret and could, instead, “place faith in empirical success.” One purpose of the field, he argued, is to “build models which can learn from a greater number of features than any human could consciously account for,” and interpretability could keep such models from reaching their full potential.

But this ability is both feature and failing: If we don’t understand how network output is generated, then we can’t know what aspects of the input were necessary, or even what might be considered input at all. Case in point: In 1996, Adrian Thompson of Sussex University used software to design a circuit by applying techniques similar to those that train deep networks today. The circuit was to perform a straightforward task: discriminate between two audio tones. After thousands of iterations, shuffling and rearranging circuit components, the software found a configuration that performed the task nearly perfectly.

Thompson was surprised, however, to discover that the circuit used fewer components than any human engineer would have used—including several that were not physically connected to the rest, and yet were somehow still necessary for the circuit to work properly.

He took to dissecting the circuit. After several experiments, he learned that its success exploited subtle electromagnetic interference between adjacent components. The disconnected elements influenced the circuit by causing small fluctuations in local electrical fields. Human engineers usually guard against these interactions, because they are unpredictable. Sure enough, when Thompson copied the same circuit layout to another batch of components—or even changed the ambient temperature—it failed completely.

The circuit exhibited a hallmark feature of trained machines: They are as compact and simplified as they can be, exquisitely well suited to their environment—and ill-adapted to any other. They pick up on patterns invisible to their engineers; but can’t know which of those patterns exist nowhere else. Machine learning researchers go to great lengths to avoid this phenomenon, called “overfitting,” but as these algorithms are

used in more and more dynamic situations, their brittleness will inevitably be exposed.

To Sanjeev Arora, a professor of computer science at Princeton University, this fact is the primary motivation to seek interpretable models that allow humans to intervene and adjust the networks. Arora points to two problems that could represent hard limits on the capabilities of machines in the absence of interpretability. One is “composability”—when the task at hand involves many different decisions (as with Go, or self-driving cars), networks can’t efficiently learn which are responsible for a failure. “Usually when we design things, we understand the different components and then we put them together,” he says. This allows humans to adjust components that aren’t appropriate for a given environment.

The other problem with leaving interpretability unsolved is what Arora calls “domain adaptability”—the ability to flexibly apply knowledge learned in one setting to another. This is a task human learners do very well, but machines can fail at in surprising ways. Arora describes how programs can be catastrophically incapable of adjusting to even subtle contextual shifts of the sort that humans handle with ease. For instance, a network trained to parse human language by reading formal documents, like Wikipedia, can fail completely in more vernacular settings, like Twitter.

By this view, interpretability seems essential. But do we understand what we mean by the word? Pioneering computer scientist Marvin Minsky coined the phrase “suitcase word” to describe many of the terms—such as “consciousness” or “emotion”—we use when we talk about our own intelligence.⁹ These words, he proposed, reflect the workings of many different underlying processes, which are locked inside the “suitcase.” As long as we keep investigating these words as stand-ins for the more fundamental concepts, the argument went, our insight will be limited by our language. In the study of intelligence, could interpretability itself be such a suitcase word?

While many of the researchers I spoke to are optimistic that theorists will someday unlock the suitcase and discover a single, unifying set of principles or laws that govern machine (and, perhaps, human) learning, akin to Newton’s *Principia*, others warn that there is little reason to expect this. Massimo Pigliucci, a

professor of philosophy at City University of New York, cautions that “understanding” in the natural sciences—and, by extension, in artificial intelligence—might be what Ludwig Wittgenstein, anticipating Minsky, called a “cluster concept,” one which could admit many, partly distinct, definitions. If “understanding” in this field does come, he says, it could be of the sort found not in physics, but evolutionary biology. Rather than *Principia*, he says, we might expect *Origin of the Species*.

This doesn’t mean, of course, that deep networks are a harbinger of some new kind of autonomous life. But they could turn out to be just as difficult to understand as life. The field’s incremental, experimental approaches and post-hoc interpretations may not be some kind of desperate feeling around in the dark, hoping for theory to shine a light. They could, instead, be the only kind of light we can expect. Interpretability may emerge piecemeal, as a set of prototypic examples of “species” arranged in a taxonomy defined by inference and contingent, context-specific explanations.

At the ICML workshop’s close, some of the presenters appeared on a panel to try and define “interpretability.” There were as many responses as there were panelists. After some discussion the group seemed to find consensus that “simplicity” was necessary for a model to be interpretable. But, when pressed to define simplicity, the group again diverged. Is the “simplest” model the one that relies on the fewest number of features? The one that makes the sharpest distinctions? Is it the smallest program? The workshop closed without an agreed-upon answer, leaving the definition of one inchoate concept replaced by another.

As Malioutov says, “Simplicity is not so simple.” ☺

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ILLUSTRATION BY **AMANDA BAEZA**

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THEY SAY REAL CHOICES are hard to make. Another way to put that is real choice-making is hard to find. Whether we are choosing a breakfast cereal, politician, or life partner, what seem like free choices often follow from unconscious cues and self-confirming biases.

Even Mother Nature can seem reluctant to choose, keeping cats both dead and alive, and running up a large multiverse tab. By some accounts, there is no such thing as time, or events, which means that what we experience as choices are just mathematical solutions to distant boundary value problems.

This is a message we resist. We spend billions on campaign ads that have little effect, and years rationalizing decisions that were not rational. Choice, as we learn in this issue, is both one of our most cherished powers, and one of the most obscure.

Welcome to “Selection.”

—MS

“When you have more options, you tend to put pressure on yourself to make the perfect choice.”

ELIZABETH SVOBODA

“The Problem with Modern Romance Is Too Much Choice” p.88

Selection

CHOOSING TO KNOW

Only Street Dogs



Are Real Dogs

*Purebreds don't satisfy the
biological definition of a species*

BY RAYMOND COPPINGER
& LORNA COPPINGER

ILLUSTRATION BY CHRIS BUZELLI



BUZELLI



CHOW TIME Feral village dogs scavenge for food in a garbage dump.

WHAT IS A DOG? Many people often think of dogs as kennel club creations. The purebred dog is man's best friend, not the street dog. Man's best friends live ubiquitously in the United States, Europe, and other developed countries and, in these countries, are by and large household pets. Man's best friends only live in areas where people have easy access to vaccines against rabies and distemper. They are the results of certain levels of commercial appeal involving pet stores, breeders, dog food companies, veterinary medicine, magazines, and books.

But could it be that breeds represented as working, hunting, or pet groups don't represent real dogs? Could it be that the so-called stray dogs, street dogs, neighborhood dogs, village dogs, and even feral dogs of the world are the real, naturally evolved, self-selected dogs?

When watching the dogs in the Mexico City dump, a number of our students would say, "These dogs are different from real dogs—these are mongrels." The implication is that the kennel club breeds are the ancestors of the village dogs. People seem to believe that if a dog doesn't look like one of the kennel club recognized breeds then it must be a hybrid or mongrel. People think if you let all the pure breeds go and they interbreed

for a few generations, the resulting population of dogs would look like the Mexico City dump dogs.

However, this cannot be true. For instance, dogs on the East African Island of Pemba all look the same, and they have never been anywhere near any breed of dog. Breeds of dogs are a result of what Darwin labeled artificial selection, which he contrasted with natural selection. He was impressed with, even in awe of, people who created breeds of pigeons or dogs or the myriad of farmyard species. Darwinian artificial selection happens when humans select for a particular trait by sexually isolating a male and a female from the general population. Modern humans with their chain-link fences and wire cages find that isolation fairly easy to do, which is why most of the greatest number of breeds of dogs or breeds of anything are relatively recent. Thus, artificial selection enabled the purposeful creation of most of our present breeds of dogs.

Numbering only about 15 percent of the world's population of dogs, the purebreds, if left to mingle with a free-ranging population, are not going to have any effect on the genetic structure of the world population of dogs. If you released those 150 million purebred dogs into the wild all at once, they would not survive for very long. Why? They aren't adapted to any ecological niche, and their numbers would be rapidly swamped by the 850 million village or street dogs, either by not finding adequate food or by crossbreeding with the wild dogs.

Our beautiful village dogs are neither the result of artificial selection nor the result of mongrelization of stray pet dogs. The similarity in size and overall design of all the street dogs and village dogs should give you a clue—a clue about natural selection.

Of the billion dogs in the world, three-quarters of them look as much alike as do the individuals of any other species. A few years ago we asked a Navajo shepherd what a Navajo sheepdog looked like. He said, "A Navajo sheepdog is not too big and not too small." To us the Navajo sheepdogs were identical in size and shape and color variations with the sheepdogs of Sonora and the village dogs in the mountains of Venezuela or the ones we worked with in eastern and South Africa or saw in India and China. That is true of the majority of dogs in the world—they are not too big and they are not too small. One of the most

fascinating details about that 75 percent of the dogs in the world that control their own reproductive life is: They all look similar.

For a biologist, that kind of uniformity implies the process of natural selection. Their size and shape (and even color) indicate an adaptation to a niche. The village dog is not a blending of purebreds that was created by artificial selection. The village dog is the animal that evolved on its own, with no reproductive control by humans, and is adapted to the niche in which it makes its living. The message is, those look-a-like dogs have evolved right there in their niche and are uniquely adapted to this niche. They are not escapees from irresponsible dog owners. They are a natural species that lives close to humans, finds its own food, and mates perfectly well without human control.



OUR TASK HERE is to demonstrate that the dog is a species of mammal that is adapted to its own particular environments. The dog is a shape that has evolved to a new niche that was created when people switched from hunting and gathering to growing grain. The waste products of that activity created a food supply that supports village dogs. Were there dogs before the age of agriculture? Probably not, but if there were, they had adapted to a different niche.

When one shape evolves into another shape, the Darwinian assumption is that the new shape is an adaptation to a new niche. A new niche means a new source of food and nesting places and a good location to raise pups, where the dangers aren't overwhelming.

Darwin pointed out that more animals are born than there is food to feed them. In other words, for

Could it be that breeds represented as working, hunting, or pet groups don't represent real dogs?

most animals, the cost of behaving (searching for, chasing, and killing prey) is going to be greater than the benefit of behaving (calories in the prey). For most animals the costs outweigh the benefits, and therefore most animals are starving and won't reproduce—no pups. Darwin theorized that a few individuals behave so efficiently (they are better fit, or adapted), that the benefit will be greater than the cost. Those animals will survive and reproduce.

Let us run this argument again. The dog evolved, meaning it changed shape from whatever the ancestor looked like. We are assuming that happened because the new shape was an adaptation to a new niche. Adapting to a new niche means the new shape was more efficient in that new niche than the old shape.

Walking or chasing is not the only cost. Add in an energy cost in building the organism from a single-celled egg to the reproductive adult; this is called the design cost. How much does it cost (in calories) to build the dog? It costs much more to build a 100-pound wolf than it does to build a 30-pound dog.

Just for ease of thinking about it, assume that the design of the wolf requires 2,500 calories a day to grow up. It needs less at the beginning and more at the end of the growth period. The average wolf needs 2,500 calories per day until it is nearly 2 years old ($365 \text{ days} \times 2 \text{ years} \times 2,500 \text{ calories} = 1,825,000 \text{ calories}$). It takes close to 2 million calories to grow a wolf pup to the size and shape at which it could efficiently kill its first caribou (not counting the costs to the parents).

The design of the dog, in contrast, requires 1,000 calories per day (less when a tiny pup) for many fewer days to become an efficient acquirer of food than does a wolf pup. A young dog can begin obtaining its own food as early as 10 weeks of age. In the Mexico City dump, pups start scavenging food shortly after they are weaned. We figure $1,000 \text{ calories} \times 70 \text{ days} = 70,000 \text{ calories}$. The dog needs 3.5 percent of the calories a wolf needs to get to the point of collecting their own food. Think about that. If I drop a 70-day-old wolf in the middle of a caribou herd, what are its chances of surviving? Just about zero. If I drop a 7-day-old dog pup in the Mexico City dump, what are its chances of finding enough to live on? Not great—but a lot better than the wolf pup among large robust ruminants.

The wolf pup becomes sexually active in its second

year, taking 2 million calories to get there. The dog can become pregnant at seven months (after consuming 210,000 calories) or 10 percent of what wolves require just to get bred for the first time. Getting the dog to reproductive age costs a small fraction, in terms of calories, of what it takes to get the wolf to that first litter of pups.

In other words, the design of the dog means it is cheaper to build than that of the wolf. Why do we compare the design cost of the dog with that of the wolf and not with the coyote or jackal, which are closer in size to the village dog? The enormous differences in the costs of wolves compared to dogs exaggerate the discussion in order to emphasize the way a behavioral ecologist thinks about the fitness of animals for their niche.

But even if we had used the 25-pound coyote or jackal to illustrate our point, we still would find dogs to be less expensive in comparison by the time they reach hunting and reproductive ages. In part, this is because if the adult shape is the perfectly adapted shape for hunting, then anything different from that shape is not as good and will be out-competed, and therefore the juvenile is always at a disadvantage simply because it doesn't have the adaptive shape until it grows up. Consequently, the design of coyotes and jackals includes help in calories from mom, pop, and often an older sibling, which is not true of the dogs.

Another big calorific cost for any species is finding food. In fact, the evolved shape of any species is almost always a signal about how it feeds and what it feeds on. The size of the animal, the shape of its mouth, and the shape and number of teeth are all clues for how it gets its food. Let us look again at why the 850 million village dogs all look alike, by answering, "What is the cost of behaving compared to the returns on that investment of energy?"



FOR A WOLF OR A DOG, the cost of the transportation to food is measured in calories, plus the cost of acquiring that food (the killing cost for the wolf) measured in calories, and the repair cost measured in calories, divided into the benefit of the food acquired measured



We begin to realize
how well designed the
dog is for its niche.



The reason dogs make good pets is this innate behavior of finding somewhere to sit and wait for food to arrive.

in calories, and the result has to be greater than one.

Let's compare the foraging behavior of the village dogs with that of the wild canids. Every day, the dogs sit in the Mexico City dump and wait for the garbage trucks to arrive. Their transportation cost to food in calories is about zero. Their acquisition cost is about zero. Since the food is dead on arrival, killing cost is about zero, and any repair cost minimal. In our wolf/moose story, for example, the moose doesn't exactly want to be killed and eaten and defends itself, whereas the discarded lamb chop at the dump doesn't care.

What about bottlenecks in the dump if food becomes short for one day? About zero. In other dog studies done in South Africa by Daniel Stewart, the dogs are only eating once every other day or every third day. And, of course, that is true of wolves, which only get a bellyful once every three or more days.

What about seasonal fluctuation? About zero. People access a similar amount of food every day. They create a similar amount of waste from that food supply every day. The bottom line is that the scavenging dogs receive access to a food supply that varies little, every day of

DANIEL STEWART

every month of every year. The garbage collectors have full-time jobs and work steadily every month of the year.

A dump dog has few foraging costs compared with its wild relatives, which must put a huge effort into obtaining food. When one compares the cost with the benefit, dump dogs are way ahead. Getting calories is mostly easier for them.

The reason dogs make good pets is in large part because they have this innate behavior of finding somewhere to sit and wait for food to arrive, which is exactly what our pet dogs do. Their niche is scavenging food from humans. They are like ravens and foxes that scavenge food from wolves or humans. Where is that dog food supply? Look for humans, and there it is. Why are dogs nice to people? They are the source of food. Dogs find some food source that arrives daily and they sit there and wait.

One question we might ask, in order to find any foraging difference between dog and wolf, is whether wolves could scavenge the Mexico City dump as well as dogs do. All of a sudden when we ask the question that way, we begin to realize how well designed the dog is for its niche. Remember the design costs. It takes 1,000 calories a day to maintain a dog, and it takes 2,500 calories for a wolf just to hang around acting doglike.

How about jackals and coyotes that are about the same size as our village dogs? Why aren't they in the dump, reducing their transportation, acquisition, and repair costs? Interestingly enough, wolves, coyotes, dingoes, and jackals quite often scavenge in dumps, but only if the dumps are empty of people.



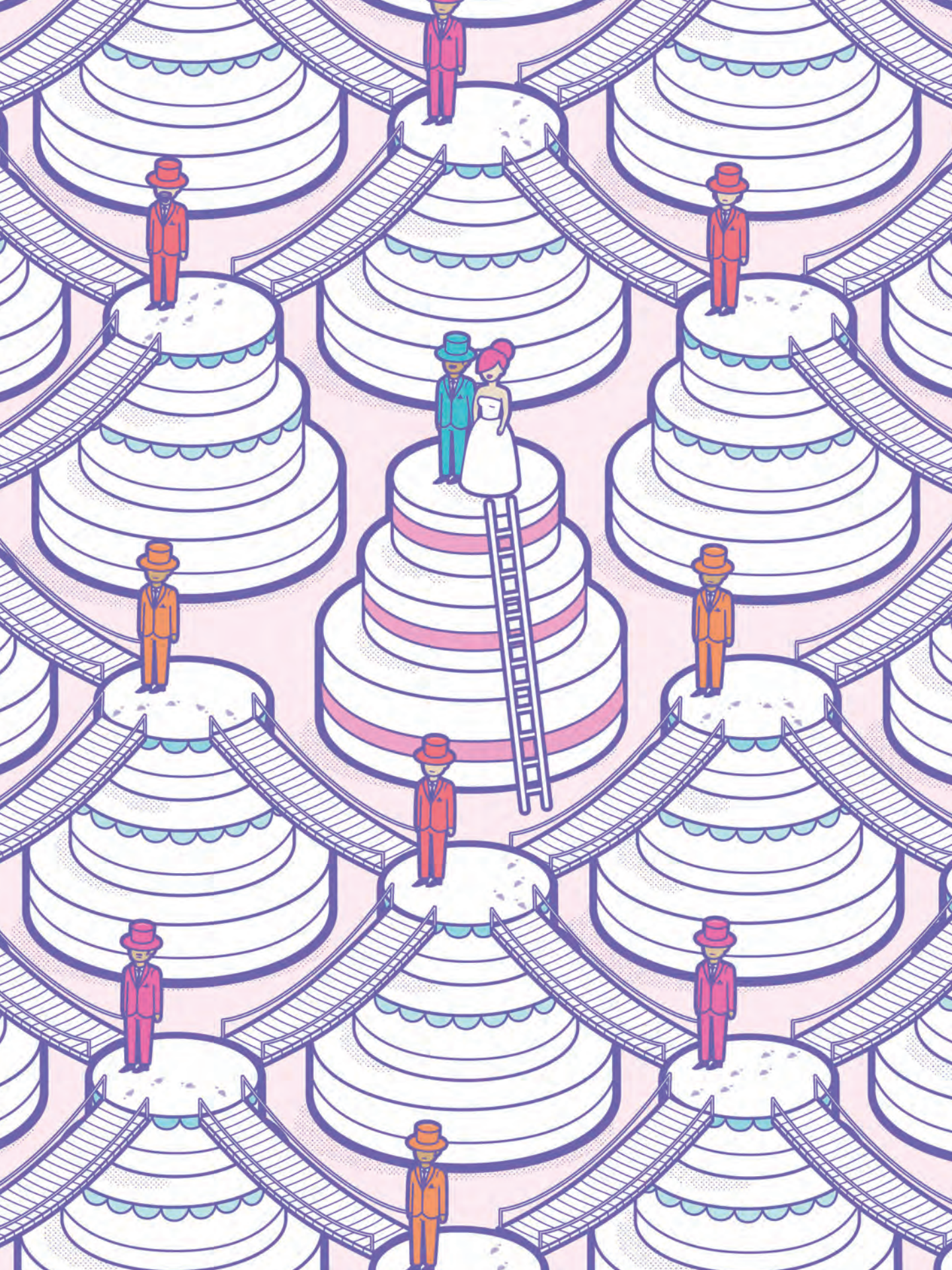
IMAGINE IF TWO PUREBRED DOGS, a male and female St. Bernard, strayed into the Mexico City dump. Would they live happily ever after, rearing big litters of St. Bernards every six months? Of course not. The idea of dog breeds thriving among that enormous dump-dog population goes against the principles of biology. The same selective pressures that influenced the shape and behavior of the village dogs would apply to the purebreds, which would have to compete with the much better adapted village dogs

for resources and space. Although St. Bernards could pass their genes onto the wider population of dogs, their successful offspring would look less like St. Bernards and more like village dogs.

This points us to our original question: What is a dog? It can't be the purebred, artificially selected by humans and constituting a small fraction of the canine population. Rather it's the populous village dog. In fact, we have good reason to think of them as the true purebred. They are not mongrels or stray kennel pups let loose on a village, but a species that over time has become finely, beautifully adapted to its niche. 🐾

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The Problem with Modern Romance Is Too Much Choice

One subject settles the debate over whether we're happier with few or many choices: dating

BY ELIZABETH SVOBODA

IN THE AGE OF online dating there are more romantic options than there are fish in the, well, you know. On the appropriately named site Plenty of Fish, for instance, you can pore over profiles of hundreds or thousands of potential mates before deciding which ones to contact. Such unfettered choice means a better shot at true love—or so many daters believe. The more options you have, the assumption goes, the more likely you are to find the one who truly suits you.

Yet many daters are finding that less romantic choice yields top-notch results without all the angst. My longtime friend Shannon Whitaker, a family-practice physician in the Pittsburgh area, found her husband using eHarmony, which has its customers fill out a detailed compatibility survey, then sends them a restricted number of matches, typically anywhere from a few to a dozen or so at a time. Two weeks after she signed up for the site, Whitaker spotted a guy who intrigued her. They clicked so well that their second

date stretched to 11 hours, and within months, they were starting to talk marriage. Whitaker was shocked—and thrilled—to have found the love of her life with relative ease. On sites with countless options, “there would have been so many people who would not have been good fits,” she says. “I don’t think I would have enjoyed weeding them all out—it would have been way too much work.”

Successes like Whitaker’s are unsurprising to Barry Schwartz, Dorwin Cartwright Professor of Social Theory and Social Action at Swarthmore College. Schwartz has spent years arguing that limiting our options consistently leads to better outcomes. He thinks too much choice overwhelms us and makes us unhappy—a phenomenon he calls the paradox of choice. Endless choices, Schwartz says, are more stultifying than gratifying. In one canonical experiment dubbed “the jam study,” grocery-store shoppers scanning 24 different gourmet jams were less likely to make a purchase than shoppers who looked at only six jams. The shoppers choosing

ILLUSTRATION BY ELLEN PORTEUS

from a wider selection were also unhappier with the jam they'd bought.

The problem, Schwartz explains, is that when you have more options, you tend to put more pressure on yourself to make the perfect choice—and you feel more let down when it doesn't turn out to be perfect, after all. “Even when you choose well, you end up disappointed,” Schwartz says. “You're convinced that even though you did well, you should have done better.” Based on work by psychologists Daniel Kahneman and Amos Tversky, who have shown bad feelings about losses are stronger than good feelings we have about gains, Schwartz argues that as you're presented with countless choices, your pleasure at the prospect of more options is canceled out by the anticipated loss of making a wrong choice.

Since 2004, when Schwartz published *The Paradox of Choice*, researchers have quibbled with the idea

that lots of choices are bound to overtax our mental resources, leading to decision paralysis and unhappiness. When Benjamin Scheibehenne, a professor of cognition and consumer behavior at the University of Geneva, set out to replicate the jam study, he found no evidence that people were less satisfied with their choices when they had a larger array to select from. “It seems to be fairly difficult to overload or confuse or frustrate people just based on the number of options,” Scheibehenne says. “In most situations, people are quite good at coping.” He points out that if abundant choice were really as paralyzing as Schwartz and others have proposed, people would constantly get stymied in everyday situations like deciding which shirt to wear or what to have for lunch.

Instead, Scheibehenne argues that people generally avoid being overwhelmed by practicing a kind of quick-and-dirty mental judo, using some kind of shortcut to



SPEED KILLS LOVE Studies find speed daters often choose partners on the basis of appearance. When presented with fewer choices, daters are likely to spend time reflecting on a person's deeper qualities.

limit their choices—whether that means giving certain factors more weight or simply skipping some of the presented choices. “If there are more initial options available, all decision-makers have to do is tune their filtering procedure,” he says. Scheibehenne thinks it’s smart to use some sort of conscious method to narrow your sights—whether that means relying on a web site’s compatibility formula or concocting your own instinctive rule of thumb. People who do this, he says, “usually end up with a set of reasonably good options that fit their needs, and they’re not overwhelmed anymore.”

Both Scheibehenne and Schwartz agree that limiting choices is a natural human drive. Where they differ is on whether having a large number of initial choices breeds dissatisfaction. Scheibehenne’s research indicates it doesn’t. But Schwartz counters that while we often like the idea of unrestricted choice, the satisfaction we think it will bring doesn’t always materialize. “We always think we want choice,” Schwartz writes, “but when we actually get it, we may not like it.”

The debate over the paradox of choice has often revolved around the mundane: what digital camera to buy, which tropical vacation spot to book, what to watch on Netflix. Now independent research reveals that when it comes to helping people obtain what they truly need—a romantic partner, someone with whom to share life’s traumas and triumphs—less is indeed more. Nowhere are the benefits of choice-limiting more profound than in the quintessentially human realm of love.

THE BRAIN’S ARCHITECTURE HELPS explain why a choice free-for-all can burn us out so easily. While the logic- and reason-guided prefrontal cortex is a key player in the decision-making process, it can get overwhelmed under duress. Research at Temple University’s Center for Neural Decision Making has shown that when people were bombarded with complex information, brain activity in the dorsolateral prefrontal cortex (DLPFC) ramped up—but only to a point. Faced with too much input, the DLPFC responded by decreasing its activity, much like an overloaded circuit switching itself off.

Plus, navigating difficult choices may make you want to pop a Xanax. In a Harvard study where people

were presented with a series of similar options, brain areas responsible for anxiety lit up on their functional MRI scans as they struggled to make a decision. Since the Internet, social media, and crafty marketers present us with so many more similar choices now than we had even 20 years ago, our brains are likely churning out this anxious response on a regular basis. Over time, such constant indecision can darken your mood

When you have a lot of options, you put pressure on yourself to make the perfect choice.



and outlook. The dopamine system, involving brain chemicals and neural actions involved in reward and punishment, is working overtime. “Under continued stress, the dopamine system tends to get depleted, and you might fall into feelings of continual despair,” says biological anthropologist Helen Fisher, author of *The Anatomy of Love*, revised and updated this year. “This sort of thing could happen to the brain when you get too many choices.”

Seasoned online daters can testify to the way their eyes glaze over after they’ve clicked through a few dozen profiles. And when you don’t have any clear way to rank your options—when you dredge up a bunch of prospects who are all brunette, funny, and into rock-climbing—you’ll probably start to feel like the donkey who starved in a hayfield because he couldn’t decide which hay pile to eat. “The more people you look at, the less likely you are to choose anybody,” says Fisher. Humans lived in small hunter-gatherer groups for many thousands of years and often chose their mates from within those groups. So it makes perfect sense, Fisher says, that we’re not biologically equipped to process the mate-choice bonanza of the Internet age. (Fisher is Chief Scientific Advisor at Match.com, where

she has designed a personality test for users.)

When you try to surpass your mental limitations, you may get caught up in your fear of making a wrong choice, just as Schwartz would predict. A 2016 University of Wisconsin study of online daters found that daters who chose from a pool of 24 possible partners were less satisfied with who they picked than daters who chose from a pool of only six. On top of that, the daters who had more options were more likely to want to reverse their decisions. Perhaps they just couldn't shake the thought that they were missing out on something better.

Faced with too much input, the brain functions like an overloaded circuit.

If you do persist in choosing someone from a large array, not only will you come away less satisfied—you'll probably make a worse choice. When online daters had more search options in a University of Taiwan study, they spent less time considering each possibility and found it harder to sort the good prospects from the bad ones. Stretching your cognitive capacity too thinly, the researchers explain, tends to hamstring you on irrelevant details and distract you from the criteria you consider most important. That suggests that in order to assess the qualities that matter—which, for most people, are things like a partner's honesty, his dependability, her sense of humor—you need to go deeper in your search, not wider.

Does that mean you should opt for the expert-guided, custom-flight approach proffered by vendors like eHarmony? Quite a few daters appreciate curated selection enough to be willing to pay extra for it, and Hanna Halaburda, a visiting professor at New York University and senior economist at the Bank of Canada, conducted a study (independent of eHarmony) to figure out why. For starters, Halaburda says, you face less competition in a restricted-choice scenario. You'll be one of the few options that appears in other

daters' lists, meaning they'll consider you more seriously than they would if you were one of thousands. And when your own choice is curtailed, you'll evaluate your options differently, too. "Having less choice forces you to look more carefully at the person," Halaburda says. "You don't dismiss them as much." That means you might hit the romantic jackpot with someone you'd once have shunned for a superficial reason (their cartilage piercing, say, or their love for the Oakland Raiders).

Most sites focused on curation also ask users to jump through some hoops to participate. The eHarmony compatibility questionnaire, for instance, can take people hours to complete, and that creates a different, smaller user pool from the beginning. "You know that once you are on this platform, your potential partner has also invested a lot to be on this platform," Halaburda says. That commitment signifies the seriousness of your would-be paramour's intentions, a big plus for many busy professionals. Whitaker, who was preparing to start her residency when she signed up for eHarmony, didn't have time for flaky or commitment-shy beaux. "I'm so lucky that I found someone right away," she says.

What's more, a choice-narrowing computer program that takes a range of factors into account—personality quirks, religious beliefs, professed values—can save you from your own worst romantic impulses. Left to face too many choices on your own, you might revert to superficial preferences without even realizing it. In one study of speed daters, women chose their partners mostly on the basis of appearance, giving deeper qualities more weight only when they had fewer partner choices. "You're likelier to make bad decisions when there are lots of options," Schwartz says, "especially if it's a complicated decision." With a smaller pool, you can devote your mental resources to making sure your potential partners have the vital qualities most important to you in a relationship.

The less-is-more calculus changes a bit if you expect your future partner to fit very specific criteria. Northwestern marketing professor Alexander Chernev has found that people who have strong ideas about what they want relish choosing from a larger assortment. Ruthless filtering may help explain this result: If you only want to date a Sikh like yourself, or a vegan, your

set of serious options will end up being manageable post-filter, even if your initial pool of options is large. For those whose preferences aren't so specific, though, the filtering process isn't as easy or straightforward, and the threat of overwhelming choices looms larger.

But whether the choosing process is simple or protracted, it's no easy feat to banish the grass-is-greener thoughts that always seem to pop up later on, telling you to widen your horizons, keep your options open, bail out when things get rough. Still, Schwartz says, familiarity with the pain of too many choices—losing a true soul mate, perhaps, because you had one eye on other prospects—may help temper the anxiety of limiting your options. “The way you learn this is by suffering with the problem of choice,” he says.

Even if limiting your dating choices brings practical and emotional benefits, it's worth asking whether those benefits justify giving up a certain amount of individual agency. Signing up for a choice-limiting site involves trusting a computer algorithm to make key calls for you—like deciding which handful of people, out of a potential pool of thousands, you'll be able to get to know more deeply. The algorithm is a black box, the contents of which remain in flux as programmers tweak this or that line of code or re-weight one personality variable against another. Even outside the online-dating realm, some might argue that any option-limiting shortcut is a copout—that you need to take the full measure of a choice like who your life partner should be, even when choosing is tedious or uncomfortable.

It's a compelling argument, one born of the same impulse that drives Western cultural resistance to arranged marriage. And importantly, it's clear that we really don't like to bail out of the choice process entirely. In Tulane University experiments where people were only given one DVD player option to buy, they were less likely to make a purchase than they were if they had two or more options—a reaction researcher Daniel Mochon calls “single-option aversion.” The paradox of choice may be alive and well, but our choices, romantic and otherwise, must also be numerous enough to be meaningful.

So is there an ideally sized choice set when it comes to dating—one large enough to include variety and depth, yet small enough that you can fairly weigh each prospect's potential without tripping your brain's

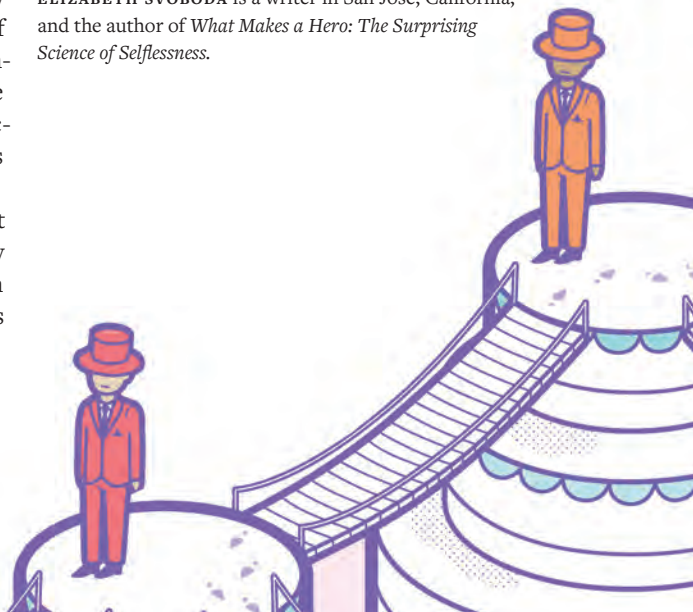
overload switch? “People are trying to make a hard problem easy by suggesting there's a magic number,” Schwartz says. In experiments involving consumer products, he points out, the optimal number of choices seems to be between 8 and 12.

Fisher puts people somewhere in the middle of that range. “Once you've met nine people who are vaguely in the ballpark, choose one and get to know that person better. If nothing works in that nine, go for another nine,” she says. “But stop going out with a million different people. The human brain has never been built to have 20,000 choices for a partner.” Until recently in human history, most people only would have had a handful of mate choices. Yet most partners stayed together for life, and real-life stories of deathless love—Shah Jahan and Mumtaz Mahal, Marie and Pierre Curie—still echo through the generations.

What forms and cements lasting partnerships, then as today, is not unfettered choice that serial daters imagine will usher in the perfect match. It's finding someone who feels like home, in the truest sense of the word, and settling in. “Often, you don't find out about the things that matter until you get to know somebody pretty well,” Schwartz says. “With a million options, you're less likely to persevere.”

In the realm of relationships, then, keeping choice in check is what frees you to forge the thoughtful connections that make for lasting love. Mulling a manageable number of options with care and depth is a strategy more exhaustive—and, ultimately, more effective—than scanning every single profile on dating sites. Paradoxically enough, narrowing your sights might end up being the most liberating romantic choice of all. ☺

ELIZABETH SVOBODA is a writer in San Jose, California, and the author of *What Makes a Hero: The Surprising Science of Selflessness*.





To Rescue Democracy, Go Outside

Real spaces, not digital ones, will fix our politics

BY ALEX PENTLAND

WHEN I SEE a liberal writer's description of Donald Trump, or a conservative writer's views of Hillary Clinton, I am embarrassed for them both. I wouldn't let a 5-year-old child make such impolite and obviously extreme statements—and yet, today, extreme views are often applauded. They are a sign of an increase in polarization and political fragmentation that is happening across the United States.

The Pew Research Center has documented this shift over the last two decades, and shown that Democrats and Republicans have less and less in common with one another (see *Drifting Apart*, on page 97).

These changes are visible in the social media sphere, too. There, fragmentation can be measured by identifying the political alignment of users and postings by how much they draw from familiar left-wing and right-wing sources (like Fox News on the right or *The New York Times* on the left), and then looking at how ideas and facts are shared across the ideological divide.

Facebook researchers have found that most of their users are quite polarized, and don't have many Facebook friends with opposing political views. Politically aligned users of the site also share very little in the way of news or opinion with those of opposite persuasion (see *Let's Not Talk*, on page 97).

In this way, social media makes it easier for users to develop a virtual peer community that supports unusual identity, beliefs, and behavior, and for extreme views to find support. This changes how we form our sacred beliefs, which are those beliefs that include “core constructs of national and ethnic identities and moral norms.”¹ Such beliefs are the basis of our social identity—regardless of whether we are right or left leaning—and so are hard to change. Functional magnetic resonance imaging studies have shown that we process these sorts of beliefs in a region of the brain that is separate from those regions that handle our normal rational way of thinking, and without particular regard for utility.¹

ILLUSTRATION BY JAMES YANG

We self-identify and seek out like opinions.



As a consequence, sacred beliefs are resistant to logic or evidence, because to question them is to damage our peer group membership, and undermine the social benefits we receive from it. The ability to maintain unusual identities leads to a fragmentation of our sacred beliefs and our political sphere, and increases the difficulty of obtaining consensual change.^{2, 3} The result is what Harvard law professor Cass Sunstein and his colleagues call a digital “echo chamber.”⁴

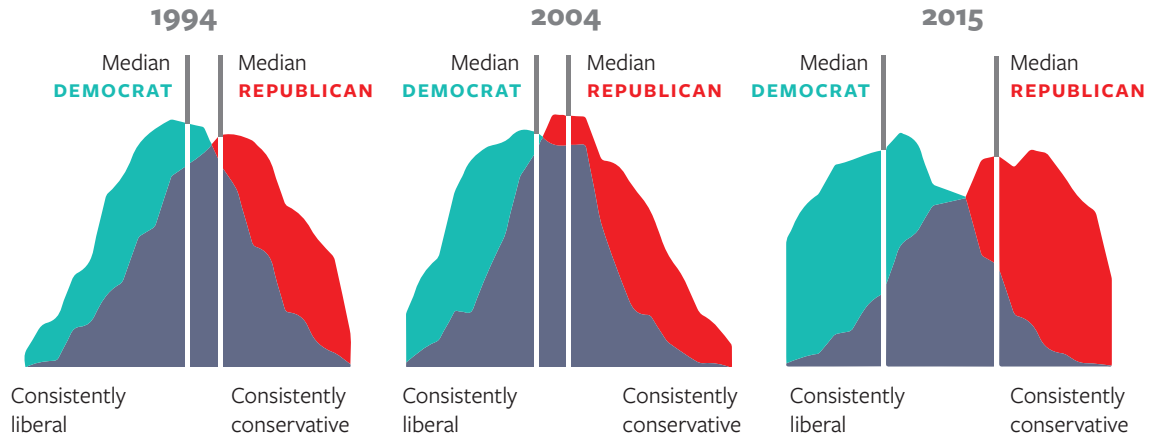
All of which sounds rather bleak. But there is another dimension to our segregated society that we sometimes forget about: where we physically live, and whom we move past on a day-to-day basis. It shouldn’t be a surprise that the physical world, too, is becoming increasingly segregated. But it also might offer a solution.

IN RECENT DECADES, U.S. neighborhoods have become significantly more segregated by income. Data shows that more and more American families are living in neighborhoods where the majority is just like them: Poor families live in poor neighborhoods, and rich families live in rich ones (see *Like with Like*, on page 98).

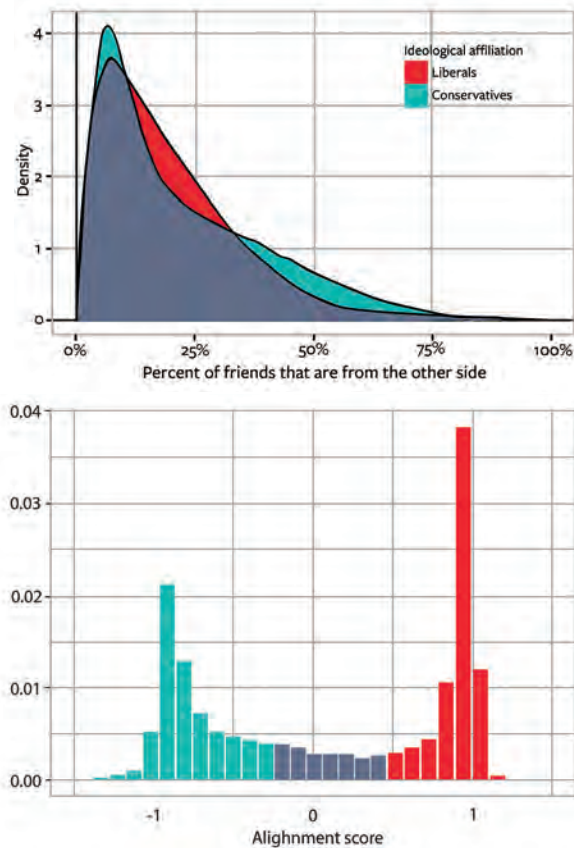
This is particularly problematic because our physical networks are a powerful influence on our beliefs. In 2008, my research group at the Massachusetts Institute of Technology studied interactions among a group of voters. We used cell-phone based Bluetooth proximity detection, WLAN location approximation and communication, and call records to put together an account of subjects’ face-to-face interactions, gathering 132,000 hours of social interaction data.

We found that face-to-face social exposure features explained individual political opinions on election day better than self-reported social ties or the views of people with whom they had political discussions. The best predictor of subject attitudes was not their friends, parents, or political discussants, but rather the attitudes of the peers who shared the same physical environment.

We have recently shown similar results in Europe and the Middle East.⁵ The voting behavior of people who work in the same area and shop at the same stores is more uniform than those of a given age, gender, or socioeconomic status. Not only do we seek out environments that have people like us (birds of a feather really do flock together!), but we unconsciously pick



DRIFTING APART The Pew Research Center used a 10-item scale of political values to show how Democrats and Republicans are increasingly at odds with one another.⁶



LET'S NOT TALK On Facebook, users of a given persuasion have few friends of the opposite persuasion (top panel), and share little content with them (bottom panel).⁷

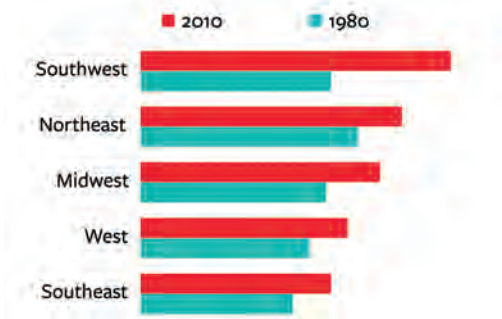
Ideas are shaped more by face-to-face interaction.

up attitudes and beliefs from the people we identify as peers. When in Rome, we begin to do as the Romans do—often without even being conscious of it. This runs counter to the common assumption in economics that people are independent and autonomous. The evidence is that people's beliefs and actions are overwhelmingly determined through social learning from peers, whether we know it or not.

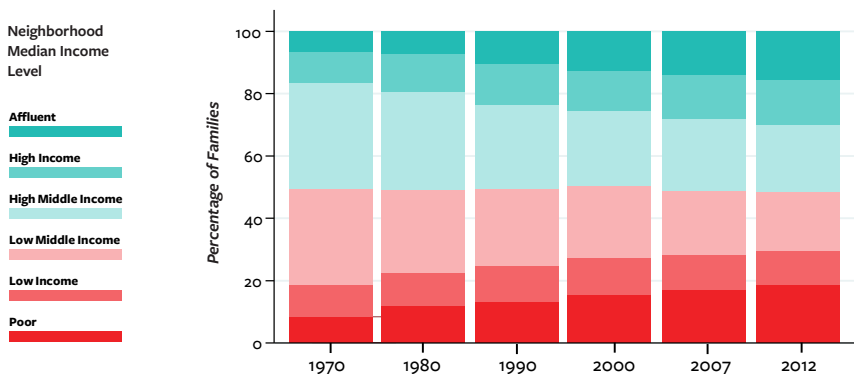
While in one sense this is just another facet of today's increasingly polarized world, it also provides us with an opportunity. When we interact through social media, we self-identify and seek out like opinions. In real life, we have less control over that selection—we never know who we'll run into. Physical interactions are also very powerful. They are much better at changing opinions than digital media. Studies show such interactions produce better learning outcomes,⁸ a greater chance of reaching consensus,⁹ and greater satisfaction in workplace teams.¹⁰

So what would happen if the way we interacted with each other forced us to mix with people of different groups? If we didn't allow ourselves to dive ever deeper into self-reinforcing groups? What would happen if we mixed primarily through that quaint and old-fashioned technique, namely moving about in our physical environment, encountering opinions and perspectives that we did not pre-select? Could we counter the devil's

Residential Income Segregation Index (RISI) by region, 1980 and 2010



Percentage of Families Living in High-, Middle-, and Low-Income Neighborhoods
Metropolitan Areas with Population > 500,000, 1970-2007



LIKE WITH LIKE Data from the Pew Center (top)¹¹ and Stanford University (bottom)¹² show that the physical space Americans inhabit is increasingly segregated by socioeconomic status.

brew of single-community media combined with physical segregation? My research at MIT strongly suggests that the answer is yes. In businesses, on the street, and in peer groups, ideas are shaped more by face-to-face interaction than by digital media.^{13, 14}

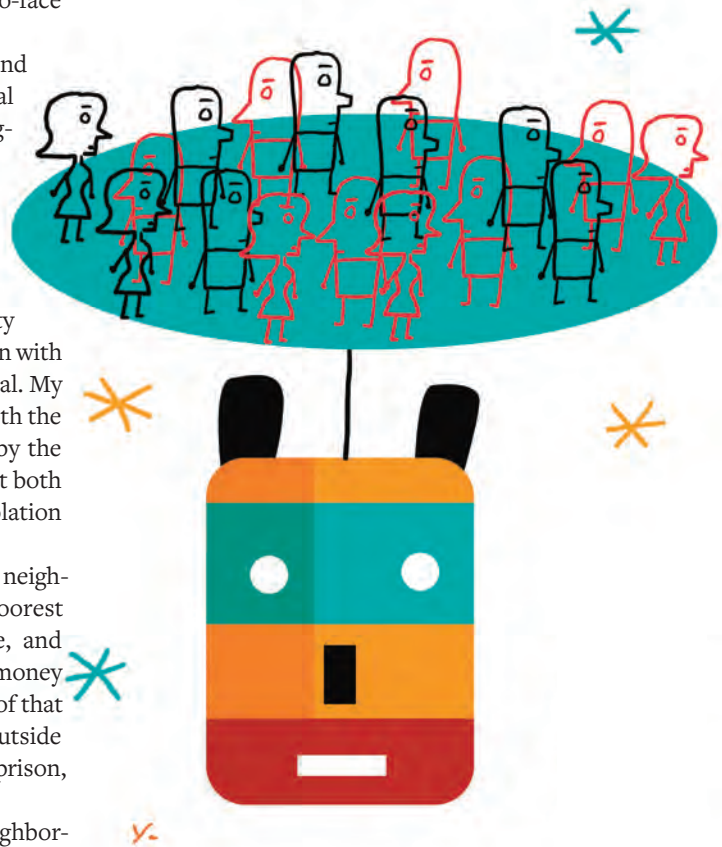
The benefits of physical mixing extend beyond reducing political fragmentation. The National Economics Review Board has noted that the segregation of poverty has a very strong negative association with upward mobility, whereas segregation of affluence does not. The National Bureau of Economic Research has also shown that in the U.S. the correlation between such spatial factors and upward mobility is two to three times stronger than the correlation with income inequality, school quality, or social capital. My own research group at MIT has shown that in both the U.S. and European Union, wealth is predicted by the diversity of face-to-face communication and that both poverty and crime levels are predicted by the isolation of a community.

As a case example, consider the Brownsville neighborhood of Brooklyn, which is one of the poorest neighborhoods in America. The federal, state, and city governments spend enormous amounts of money managing the effects of poverty there, but most of that money goes to middle-class workers who live outside of the neighborhood and operate the relevant prison, shelter, foster care, and hospital systems.

We could take a different approach to neighborhoods like Brownsville, one that targets mixing populations. The government could employ locals for services, improve transportation into and out of the neighborhood, and create tax breaks for industries that employ locals. With enough mixing, the old factions, with their conflicting sacred beliefs, might fade away and a more productive community dialogue could emerge.

So the next time you get mad at a tweet, or are upset by a news item about the growing inequality in our country, turn off your computer or TV, get up, and go talk to someone. For real. ☺

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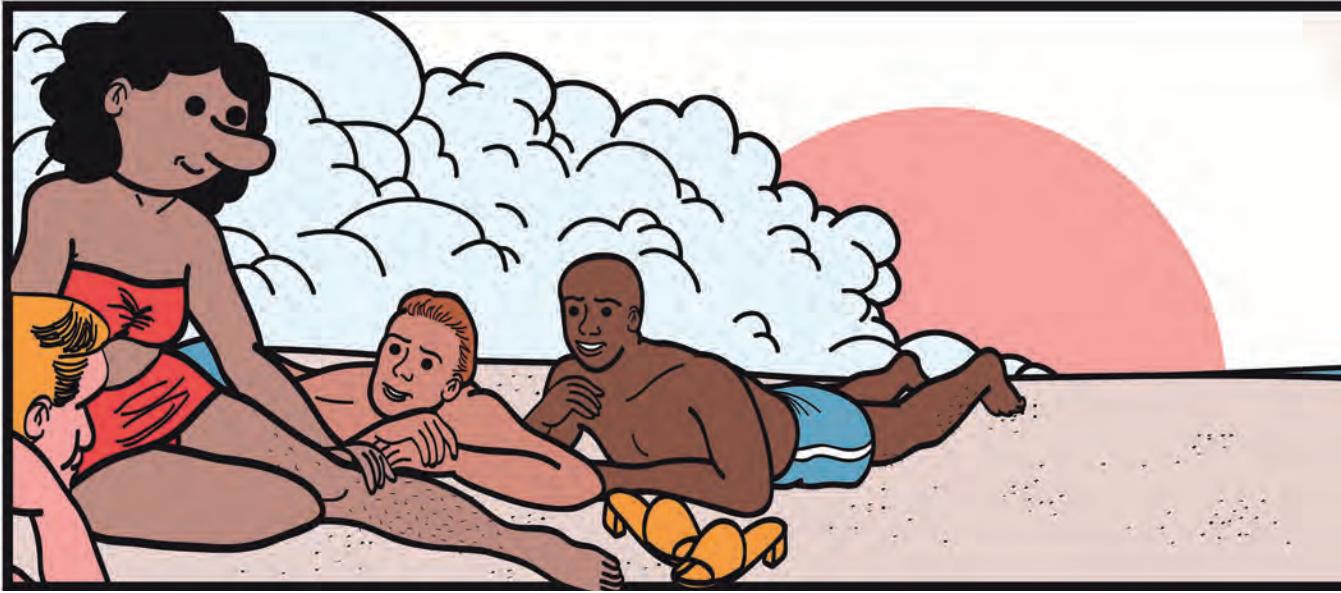


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ILLUSTRATION BY **JIA SUNG**



Beyond Sexual Orientation

Sexual fluidity is a fundamental challenge to both traditional and alternative sexual narratives

BY ANKUR PALIWAL

LISA DIAMOND'S SEVENTH INTERVIEW is the one that she remembers best. She had recruited "subject 007" at Cornell University, where she was studying how women who express attraction to other women come to understand their sexual identity. One early evening in 1995, in a conference room on the university campus, she settled down to ask the first question of her subject.

How did 007 currently identify herself on the spectrum of sexual identities? The woman answered that she didn't know. She told Diamond that she had been heterosexual all her life until just that last week, when she suddenly found herself falling in love with her best friend—a woman. They had had sex a couple of times,

something she described as very satisfying. Part of Diamond's work was to categorize her subjects based on how they self-identified, but 007 wasn't sure—so Diamond put her into the "unlabeled" category.

By the time 007 left after the two hour interview, Diamond had tentatively concluded that the woman would come out as bisexual in her follow-up interview. But 007 never did. The interaction marked the beginning of Diamond's gradual realization that her assumptions about sexuality needed to change. In addition to the static orientations that most of us think about, like heterosexual, gay, and bisexual, some people experience shifts in their attractions that don't fit into static orientations. In Diamond's group, in fact, most did.

ILLUSTRATIONS BY KAYLA E.



As she made her way through her 88 other subjects, Diamond asked each woman to fill out a pie chart indicating, in percentages, how much of her sexual attraction was directed to women, and how much to men. When Diamond followed up with 007 and her other subjects in 1997, she found something interesting: The make-up of their pie charts had shifted, and about 32 percent had changed their sexual identity labels.

It was on a flight to Los Angeles to visit her parents, in the middle of reading interview transcripts and making notes, that Diamond had an “aha” moment. She realized that she had been expecting, and imposing, conventional “coming out” stories: a falsification of sexual identity followed by a revealing of the true self. But “that’s not actually what people [were] saying,” Diamond recalls.

Re-reading her transcripts, Diamond realized that many of her subjects had not been misrepresenting their previous identities at all. Instead, they were moving from one genuine, persistent identity (and label) to another.

As Diamond followed up every two years with the women she was studying, her hypothesis found new support. “They were moving in all possible directions,” says Diamond. In 2005, 10 years after she began her

study, the pie charts continued to change, and about 67 percent of the women had changed their sexual identity labels at least once. Many self-labeled lesbians had unlabeled themselves. Most of the women who had initially preferred not to have a label had taken on the bisexual label. Some unlabeled women became lesbian, and others heterosexual.

These changes were often provoked by a single relationship. After two years of being in a same-sex relationship, subject 007 identified as heterosexual. Some women said that they were attracted to just one person of the same sex (“it’s only her”), but were otherwise straight. Some women fell in love with their best female friends later in life, around 40, and started sexual relationships. Some longtime lesbians began heterosexual relationships.

So were these women straight or gay? The question may be the wrong one to ask, says Diamond. “[Women] over time tended to move toward an identity that allowed for more flexibility. Labels sometimes negate the more complicated experiences they have had.” Diamond referred to these women as sexually fluid.

Sexual fluidity is different from homosexuality or heterosexuality, which are single orientations. “Fluidity allows people to go outside their orientation,”



Diamond says. Some individuals have steady patterns of attraction their entire lives that are consistent with their orientation. But for the sexually fluid, their orientation is not the last word on their attraction.

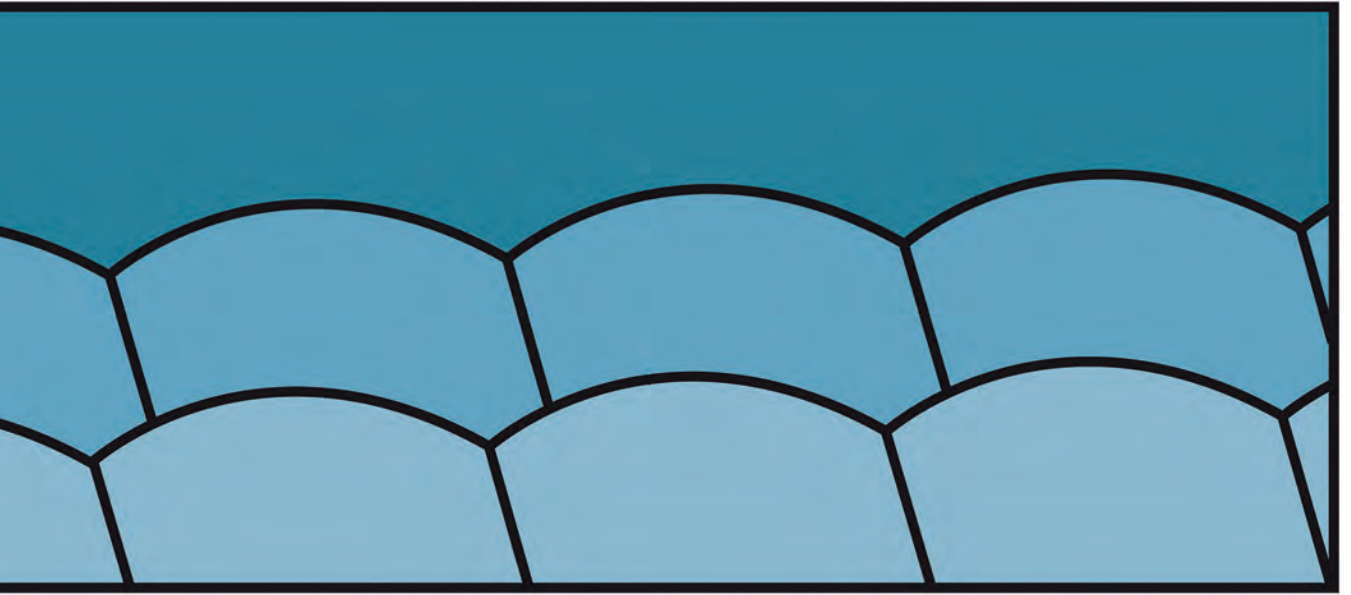
Sexual fluidity is also not the same thing as bisexuality, which is another sexual orientation. “Bisexuality refers to an attraction to both males and females,” explains Leila Rupp, a social scientist at the University of California, Santa Barbara, “while sexual fluidity refers to shifting attractions and desires.” Bisexuals who are consistently attracted to males and females over their entire lives are not sexually fluid. Fluid bisexuals, on the other hand, can be attracted only to males or only to females for periods of time.

In her 2008 book *Sexual Fluidity*, Diamond says sexual fluidity is actually relatively common. It’s not a conclusion that everyone agrees with: Qazi Rahman, a senior lecturer of cognitive neuropsychology at King’s College London, for example, suggests that her study was too small to “tell us much about women in general.” But Charlotte Tate, a gender and sexuality psychologist at San Francisco State University, says that Diamond’s sample size is larger than the recommended sample size for qualitative research, and considers Diamond’s findings significant. “Sexual fluidity is a real

phenomenon,” says Tate. “It is a part of the human experience.”

In the riot of sexual orientations that have become recognized only in the last decade or so (Facebook famously has about 70), sexual fluidity may be one of the more difficult to understand, and one of the more neglected. It is, after all, not really an orientation at all.

IN 1950, THE GAY RIGHTS activist Harry Hay founded America’s first national gay rights organization, the Mattachine Society in Los Angeles. Its aim was to eliminate discrimination against homosexuals, assimilate them into mainstream society, and create an “ethical homosexual culture.” It did not, however, quite speak for bisexuals. The first American pro-gay magazine, *One*, emerged from the Mattachine Society and launched in 1953 with the tagline “the homosexual viewpoint.” Bisexuals were not a major part of the vocabulary in the gay movement. There were even statements from within the non-heterosexual community against bisexuality. One 1974 academic study found that “the lesbian community cannot deny the existence of bisexual behavior but its members do not encourage it, and they do not easily accept women with bisexual identification.”



Robyn Ochs, who came out as bisexual in 1982 and has been campaigning for bisexual rights ever since, remembers some gay marches before the mid-1990s as unwelcoming. “Lesbian women thought that we were sleeping with the enemy,” says Ochs. Dawne Moon, a sociologist at Marquette University, explains that some gay people felt that bisexuals were watering down their message. Any kind of sexual variability outside of homosexuality would threaten the narrative of the gay movement, says Moon. That narrative revolved around same-sex attraction being as authentic and fixed an orientation as heterosexuality.

The scientific practice of the 1960s through the early 1990s reinforced this message. Some researchers blatantly denied the existence of bisexuals. In 1956, the American psychoanalyst Edmund Bergler described bisexuality as “a state that has no existence

beyond the word itself” and an “out-and-out fraud.” Other researchers used terms like “true homosexuals” in their studies. It was common for academics to lump bisexuals and homosexuals together.

Even many school and college textbooks did not quite recognize bisexuality as a possible sexual orientation until about a decade ago. Bisexuality was seen to be a phase some people go through before identifying as heterosexual or homosexual. Kenji Yoshino, professor of constitutional law at New York University School of Law famously called this phenomenon “bisexual erasure” in an essay he wrote in the *Stanford Law Review* in 2000. “It is as if self-identified straights and self-identified gays have concluded that whatever their other disagreements, they will agree that bisexuals do not exist,” Yoshino says.

If the narrative departure represented by bisexuality was discouraged, sexual fluidity—which denied the very idea of static orientation—was an even more remote afterthought, even though it had been observed in the academic literature by the late 1970s. “The notion of sexual fluidity is not a new one,” writes Diamond in *Sexual Fluidity*. A 1977 study of 156 bisexual male and female college students found that some had consistent patterns of attraction over time while

Sexual fluidity was dismissed as “inconvenient noise cluttering the real data.”



others did not.¹ The authors proposed that sexuality is not fixed at a young age, but could vary over a lifetime. A few other studies over the next decade made similar insights, underscoring the importance of time in measuring human attraction. At one point, some researchers devised a new model for quantifying sexuality that included the element of time.² Yet the model, along with these early studies, failed to have much of an impact.

Diamond says that when the early studies on sexual fluidity came out, many researchers still did not recognize bisexuality as a valid orientation. And that posed a special challenge for sexual fluidity. If researchers were not convinced of a person's ability to be attracted to both sexes, it was that much harder for them to recognize a person's temporally segregated attraction to both sexes. And so, says Diamond, sexual fluidity suffered a similar fate as bisexuality, and was dismissed as "inconvenient noise cluttering the real data on sexual orientation."

Tate agrees that scientists were under the sway of an alternative interpretation of sexuality. "Sexual fluidity has probably always existed," she says, but most scientists were committed to an incompatible narrative, in which sexuality is fixed at a young age.

"Scientists tried to erase or deny everything that did not fit into that narrow story," she says. "Even in 2016, only some of us in behavioral science are able to see through this pretense."

By the time Diamond met subjects like 007, the idea of sexual fluidity was still inchoate. But she was drawn to the marginal studies on bisexuality and sexual fluidity, which ultimately gave her the groundwork to distinguish orientation from attraction over time. Many researchers consider Diamond's work to be definitive, providing the first systematic evidence of fluidity in a longitudinal study, and likely the first to use the term sexual fluidity.

Even today only a few people study sexual fluidity. But researchers believe it has the potential to improve

People now associate sexual fluidity with freedom and self-determination.



lives, just like the recognition and acceptance of homosexuality did. In the words of Erin Davis, a sociologist at Cornell College, recognition of sexual fluidity can mean that “[people] do not have to discount past experiences or limit future options.”

I MET STEPH ONE AFTERNOON early this year in her Brooklyn apartment, where she lives with her partner Marissa (which is not her real name) and their two cats. A wind chime Steph’s father made hangs in the kitchen, and a blanket her mother hand knit for the couple is on a living room chair. Around the apartment are many photographs of Steph and Marissa on hiking and road trips.

Steph’s earliest memory of same-sex attraction dates to when she was 13, and devastated after her sister had died in a train-car collision. Steph found solace in her friend, Jill. They hung out together, and had a lot of sleepovers. At one point while on a vacation, they had a conversation about what it would mean if they kissed, which they never did. Later their friendship became awkward and ended on its own. “I always had some attractions toward women but didn’t acknowledge them,” says Steph. “I come from a small town in the Midwest where that [same-sex attraction] might

be inappropriate. I never questioned it.”

At 16, she fell in love with a guy. “He was cute and very smart, and also an athlete,” says Steph. She describes the relationship as happy—until he became depressed and abusive in the fifth year of their relationship. Steph decided to call it off. They were about to get married. “I really loved him,” she says.

While she was recovering from the heartbreak, Steph left her home in Michigan and went to Ecuador on a study abroad program. There, she developed an attraction to a close friend, Christine, who had just come out as a lesbian. A kiss between them would confirm to Steph that she was experiencing a real same-sex attraction. “It felt really good,” says Steph. But she also says that moment was scary. A part of her did not want it to feel good. “It would have been easier to not feel gay,” she tells me. So she told herself that maybe it could just be Christine. “I was in that bubble for a while,” she says.

After Steph came back to Michigan, she and Christine hung out for a while, but their relationship did not work out because Steph was still struggling with her sexual identity, while Christine was un-closeted. Then a chance meeting with Diamond changed how Steph viewed her sexual self.

In 2005, as a senior in psychology at Michigan's Kalamazoo College, Steph was looking for internship opportunities in the field of sexual identity development and came across some research papers written by Diamond. Steph wrote to her asking if she needed any help. At that time, Diamond had just completed the final interviews for her 10-year longitudinal study following women and was working on her book manuscript. She wrote back to Steph saying that she needed another set of eyes to go through the data and transcripts.

A couple months later, Steph flew to Salt Lake City to work with Diamond. When she started flipping through the tables and pie charts she said to herself, "Oh! Alright! Me too!" She felt validated to see other women whose sexual attractions changed over time, and who didn't adhere to a single sexual identity label. Until that point, she didn't know many people like her. She was amazed to see the sexual transitions in the study's women. "I was like, that shit is crazy. This is complex," Steph laughs, throwing her hands in the air. She found herself in those stories, she says.

Coming back to Kalamazoo, Steph became a little more open about her sexuality. She came out as bisexual to her parents over dinner. She called herself bisexual because at that time she was still sleeping with men. Her dad said that he was not shocked but a little surprised. Steph's mother was also accepting, and she and Steph later had several conversations about how Steph could embrace her sexuality.

Steph is quick to clarify that her story is "not a coming out" story. "My five years of relationship with my boyfriend were not false. I actually make a point of telling people that. I loved him very much and I was very much attracted to him," she says. Over time, Steph started identifying as queer because that category recognizes that her gender and sexuality are more fluid. Today if you ask Steph to draw her sexual attraction pie chart, she would assign 80 percent to women and 20 percent to men. She finds men's bodies sexually attractive but with women her connection is both emotional and sexual.

Steph's story shows how impactful the recognition of fluidity can be: Diamond's work served as a catalyst for her recognition and acceptance of her own type of sexual attraction. But it isn't known how many

Steph's story shows how impactful the recognition of fluidity can be.

others like Steph are out there. The U.S. Department of Health and Human Services published a survey in 2016 of over 10,000 American adults, in which 17 percent of women and 6 percent of men reported they'd had at least some kind of same-sex contact in their lifetime. There were more self-identified bisexuals (5.5 percent of women and 2 percent of men) than those who identified as exclusively homosexual (1.3 percent of women and 1.9 percent of men). About 92 percent of women and 95 percent of men called themselves straight. The survey did not include sexual fluidity as an option. It also did not track adults through time to see how their patterns of sexual attraction may have changed. "There are likely to be sexually fluid people embedded in all of the categories represented in the study," says Diamond.

A few recent studies of large populations, however, have identified change in attractions over time. One study of about 1,000 New Zealanders between ages 21 and 38 found that a significant number of them experienced variability in their sexual attraction over time. Among 21-year-old women, up to 9 percent had same-sex attractions, which increased to 16 percent by age 28, and then fell to 12 percent by age 38. Among the 21-year old men, 4.2 percent had homosexual attractions, which went up to 6.5 percent by age 38.³ There is evidence that these changes can continue well into middle age. A 2012 meta-study of data from the National Survey of Midlife Development in the United States found that over a 10-year period, adults (with a mean age of 47 at the beginning of the study) exhibited variability in their sexual identity. Almost 3 percent of

women and 2 percent of men changed their identity over the 10-year period.⁴

Diamond explains that it's possible that some of these changes are the result of individuals coming out, or indications that sexual orientation takes longer to develop than scientists originally thought. But sexual fluidity could also be a cause: "Sexual fluidity helps explain why there are so many changes at the population level," she says.

DIAMOND IS HAPPILY SURPRISED by the proliferation of artists and celebrities who have identified as sexually fluid, and associate it with a kind of liberation. Model Cara Delevingne, musician St. Vincent, and actor Nico Tortorella are just a few of the high-profile individuals who resist traditional labels and describe their sexuality as fluid. Although it's not clear if these celebrities fit Diamond's strict definition of sexually fluid, Diamond is clearly moved by the fact that the term has cultural resonance. "It is very exciting. It blows my mind. I never expected it to happen," Diamond says. "People now associate [sexual fluidity] with freedom and self-determination."

Inspired by Diamond's work herself, Steph moved to New York in 2007 to do her Ph.D. in social psychology, with a focus on gender discrimination, at City University of New York, and met Marissa, her current partner, in a gay basketball league. This spring, during a hike to the top of a mountain with a view of the New York City skyline, Steph reached into her pocket and took out a tiny plastic packet containing a wooden ring. Marissa said yes. That night, in a Brooklyn backyard filled with candles and food catered from a local BBQ restaurant, they celebrated with their families.

As for 007? She married a man and had kids, and has not told anyone, not even her husband, about her sexually fluid past. ☺

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ANKUR PALIWAL is a journalist who writes on science, health, and the environment.



The Parallel Universes of a Woman in Science

In physics and in life, choice and possibility play against each other

BY KATE MARVEL

SPENT YEARS IN GRADUATE SCHOOL where terrified students would desperately try to make small talk with Stephen Hawking in the corridors.

There were few other women and no one else who was not brilliant, or at least capable of convincingly acting the part. When we walk by one professor he averts his eyes and, facing the wall, mutters fervently and kneads his sweaty palms. We assume he is religious. As it turns out, he is simply frightened of women.

It is fortunate for him that there are so few of us. Another professor is reluctant to advise girls who will only get married and leave the field. Another refers to all women as Anna, what, in physics, we call a simplifying assumption. It doesn't matter anyway.

The women speak to the department chairman, a litany of small complaints: An elderly Fellow tried to kiss me. Someone grabbed me, I don't know who, they all laughed about it. Do we belong here? He sits back and shakes his head and says, helplessly, *what do you want me to do?*

In another universe we are terrifying and brazen, Amazons with steel breastplates. In this one, though, we are scared and tired and wary of wandering hands. The other girls are brilliant: They are required to be. I am stupid and 22 and in love with the famous young professor. He loves me too, until he doesn't.

The equations I study are like old friends to me; you can think of them as illustrations, maybe, or small, restful breaks between recognizable words. Here is one:

$$S^n = \{x \in \mathbb{R} : ||x|| = r\}$$

This is fairness in geometric form, the shape formed when everything is the same distance from the center. Mathematics liberates us from physical space. Increase n to add dimensions: point, line, circle, sphere. Go further: Embed curved hyperspheres in higher dimensional space. We can simplify complicated things, then complicate them further.

But sometimes things are simple. Look closely

enough at a curved surface and it appears flat. You move in straight lines down simple paths. Our everyday experiences are described by simple, familiar laws: inertia, force, reaction, $f = ma$.

So I show up every day, unwanted but noticed. There are simple narratives for girls like me: tried, used, found wanting. I feel like a white rabbit after the snow retreats in early spring. There is a gentlemen's agreement between us: Leave, and we will let you go. I graduate, barely, and go back to California. The sun shines, I am happy, and the universe goes on without me. Examined closely enough, everything is mundane.

He shakes his head and says, helplessly, *what do you want me to do?*

NATURE ABHORS A VACUUM; physicists love one. We have rich vocabularies to describe different flavors of emptiness. There are false vacuums, classically stable but subject to the strangeness of quantum mechanics. These are universes ever prone to decay. The rot proceeds by bubble: True vacuum nucleates inside the false one, making a sphere of baby universe. Inside the bubble the constants of nature take new values. The laws are the same inside and out, but followed differently. We create worlds inside worlds, let others fall away.

Here is a fundamental law: We cannot go backward in time. And why would I? Sixteen, too skinny, angry at the world, and hoping not to be called to the board to solve equations. Refusing to learn times tables to 12. Dreams that do not require competence in basic algebra.

But the world is not lacking in teenage aspiring actresses, and there is no shortage of prettier women hungry to play Wife, Girlfriend, Hot Girl 2. In drama class, we wait to be noticed. In astronomy class, we discuss the origin and fate of the universe. I can know more, if I am willing to learn to love the frightening grammar of equations. I have never felt stage fright, but math makes me nervous.

Slowly, though, I learn quantum mechanics and particle physics and turn in problem sets at the last minute. My grades are C's, then A's, then top in the class. This is who I am now. I win a scholarship, a prestigious one, to graduate school. I stumble.

IT MAY BE TIME for another equation:

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$

It's named after a dead white man, Austrian enough to merit an umlaut. Schrödinger's equation: Is it a particle or a wave, neither or both? ψ is the wave function that exists everywhere and nowhere, in all possible universes and some impossible ones too. It takes no form and has no character until it is observed and forced to collapse into reality. There are many worlds and everything we know exists in them all.

There are many universes in which my husband and I never meet, but it's hard to think of one in which I love him as much as here. In some bubble universe, the worst one, his face merges with that of the young professor, so different from him, and they look in opposite directions like a god on a Roman coin. In this one he is kind, likes animals, and makes joyful art that no one wants to pay for.

He comes with me when I leave graduate school. I take a job back home in California, and the shame and guilt at leaving physics dissipate like midday fog. I cling to the edges of science, dabbling in arms control, energy policy, network modeling, before finding work in the physics of climate change. There is something beautiful in the mess of air and water moving together and apart on a rotating sphere. There are useful and interesting problems to solve. There is a French woman in the office next door who is brilliant and friendly and pregnant with her second child, and we are all happy for her.

We are not geniuses, although the kindly man in the office down the hall has a MacArthur grant. There is no Einstein or Feynman, just petabytes of data and rapidly melting ice caps. I make mistakes and say stupid things and am allowed second, third, fourth chances.

After four years I start to forget the nasal whine of a hostile question and the blood sport of talks to aggressive audiences. I tell stories, funny ones, from

grad school: the Fellow who ate only pickles, the night we got drunk and threw breadcrumbs at the Holbein portrait of Henry VIII. I laugh with my new colleagues and feel secure, protected, worth listening to. The sun streams through the double glazed windows onto the cheap gray-white desks and particleboard walls, and I believe I am happy.

And then we get married, and my husband is offered his dream job.

HERE IS NOETHER'S THEOREM, named for the woman who discovered it:

$$\sum_{\alpha=1}^n \frac{\partial \mathcal{L}}{\partial \dot{q}_{\alpha}} \gamma_{\alpha} = \text{constant}$$

It tells us that physics rests on symmetries: The sameness of a perfect sphere viewed from every vantage point means something fundamental is preserved on it. Conservation laws of energy, momentum, and charge all arise from fundamental symmetries of nature. It is tempting to impose moral dimensions on this: Invariance means fairness, fairness means the preservation of important things. Symmetries are beautiful. But they are not eternal.

I stand on a hill between two identical valleys. Both possibilities are equally open to me so long as I remain undecided. Choice destroys this: Moving downward toward one valley means moving away from the other. Possibilities are closed. The symmetry is broken.

When my husband is offered a position at an art college far away he does not hesitate. We go. I quit my job, pack the car, sweep the bougainvillea petals from the porch for the last time. New York City is a morass of garbage and sweating, hostile flesh. It feels strange, a different flavor of unhappiness. I talk to senior scientists, angling for a job, feeling awkward and uncomfortable. Anna, says the voice in my head, you got married and left. What a waste. What a shame.

In another universe my anger expands, dark enough to counteract gravity. Planets are blown into dust. We choose to stay. Or we go, and the snow piles thrown up by the New York cars are dazzlingly white and sweet as spun marzipan. There is no winter. There are days where I don't cry.

There are worse things, of course, in this world and

others. He deserves happiness, and has it. I find work eventually. I like my new colleagues. What does it matter that I feel precarious, awkward, always neglecting something important? Here, I am a wife, and I will do what my mother and grandmothers and all other wives do. He worries, fusses, is helpful around the house. *What do you want me to do?*

I SAVED THE BEST EQUATION for last. It's my favorite, probably everyone else's too. Here it is:

$$R_{\mu\nu} - \frac{1}{2}R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

These (and I'm afraid there are many of them contained in one elegant package) are the Einstein field equations, the core of general relativity. Force equals mass times acceleration, but mass itself is now situated in the universe, all universes, and warps space and time by its very existence. We can go backward in time to a singular point, where all symmetries are unbroken. We can determine the trajectories, pasts, and futures of objects, of planets, of this universe and others, almost exactly. Almost.

Something accelerates the expansion of the universe, ripping space apart faster, again, than the speed of light. We name it and do not know what it is. We describe it, prosaically perhaps, as Dark Energy, and it is as mysterious as it is powerful. It feels wrong, a cheat that exists only in an equation. What do we understand it to be? Intrusive gravity, perhaps, from another universe, or the decayed remnants of someone else's vacuum. It creates new horizons, new curtains beyond which we cannot see. It carries us further and further away from our neighbors, from each other, from what we know. We will never see each other again. We are never apart. ☹

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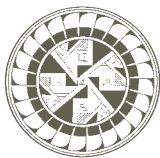
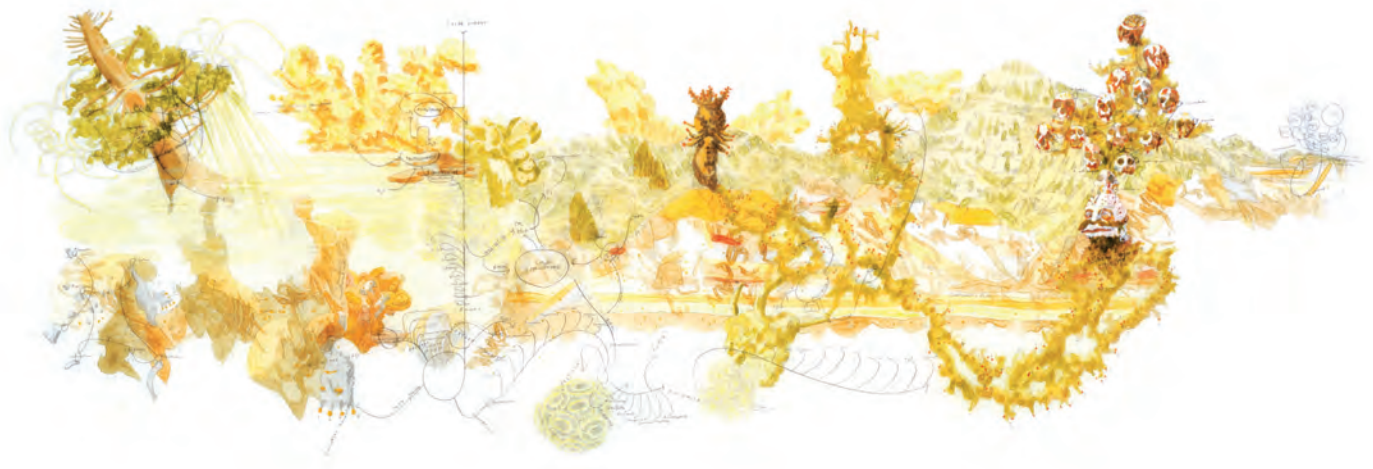
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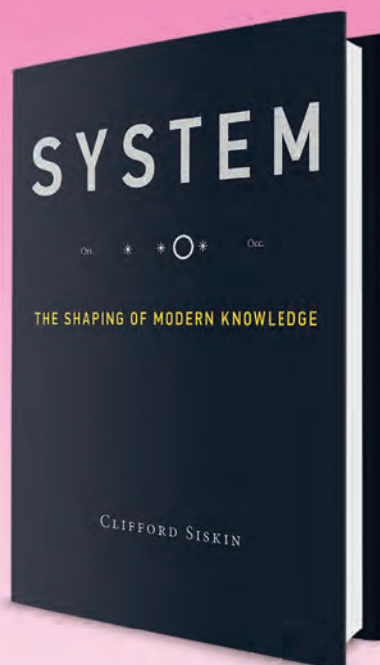


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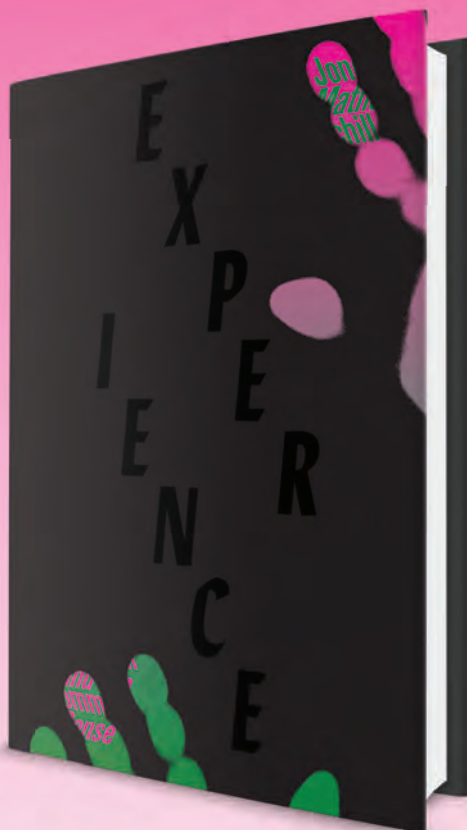


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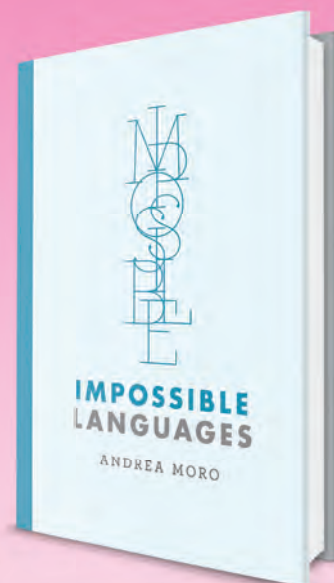
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edited by **Caroline A. Jones,**
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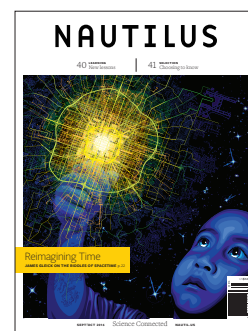
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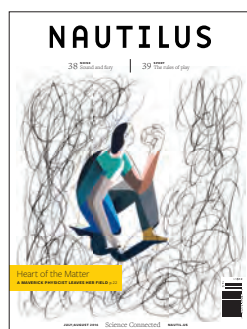
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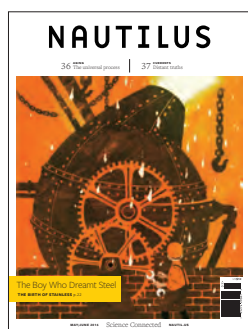
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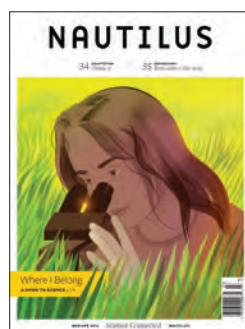
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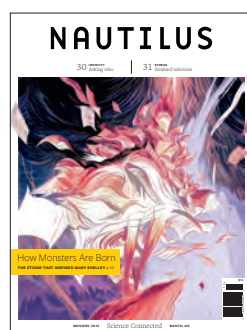
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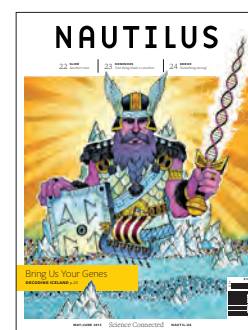
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France A. Córdova

The astrophysicist and director of the National Science Foundation reflects on the themes in Nautilus

INTERVIEW BY CLAUDIA GEIB

SELECTION

In my younger days, I was a rock climber. After work on long summer days, and weekends, this was how I experienced “the freedom of the hills.” This sport requires carefully choosing your route on a wall of rock—sometimes, the wall has its own surprises to challenge you. It requires experience, choice, and commitment. Matching your experience to the technical degree of the route matters, and the experience to accept a surprise now and then also matters. When I was growing up, girls had limited opportunities to learn physics. My decision to go into the sciences made for a demanding and unconventional, big wall to climb. So it’s gratifying for me to see NSF actively work to broaden STEM opportunities for women and minorities. If life is about choices, it’s important to have a broad range to select from when choosing your path. And sometimes, the challenge chooses you. Your choices and commitment lead you to experience the highs of discovery, and ultimately define your own brilliant life.

LEARNING

The fascinating thing about learning is that it doesn’t have to start in a rote way. So much discovery happens almost accidentally. We humans are curious by nature, and just tapping into our curiosity can lead us toward discovery. We also learn through experiences. Einstein once said that “the most beautiful experience we can have is the mysterious.” I began with a seventh-grade science project, where I was delighted by the mystery of atomic structure, and I am now the Director of NSF. But between those points I took a winding road that involved graduating with an English degree; I learned a valuable amount along the way that only aided my journey.

It’s important to widen opportunities for all students, so they can be exposed to a range of experiences that build their knowledge base. Creative methods of engaging students in STEM learning, including through art and design, can broaden horizons. There is a special joy in learning, and discovering new knowledge. ☺



ILLUSTRATION BY ANDY FRIEDMAN

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Top: Matthew Shlian, *Enneagon*.
Left: Matthew Shlian, *Telemetry*.
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