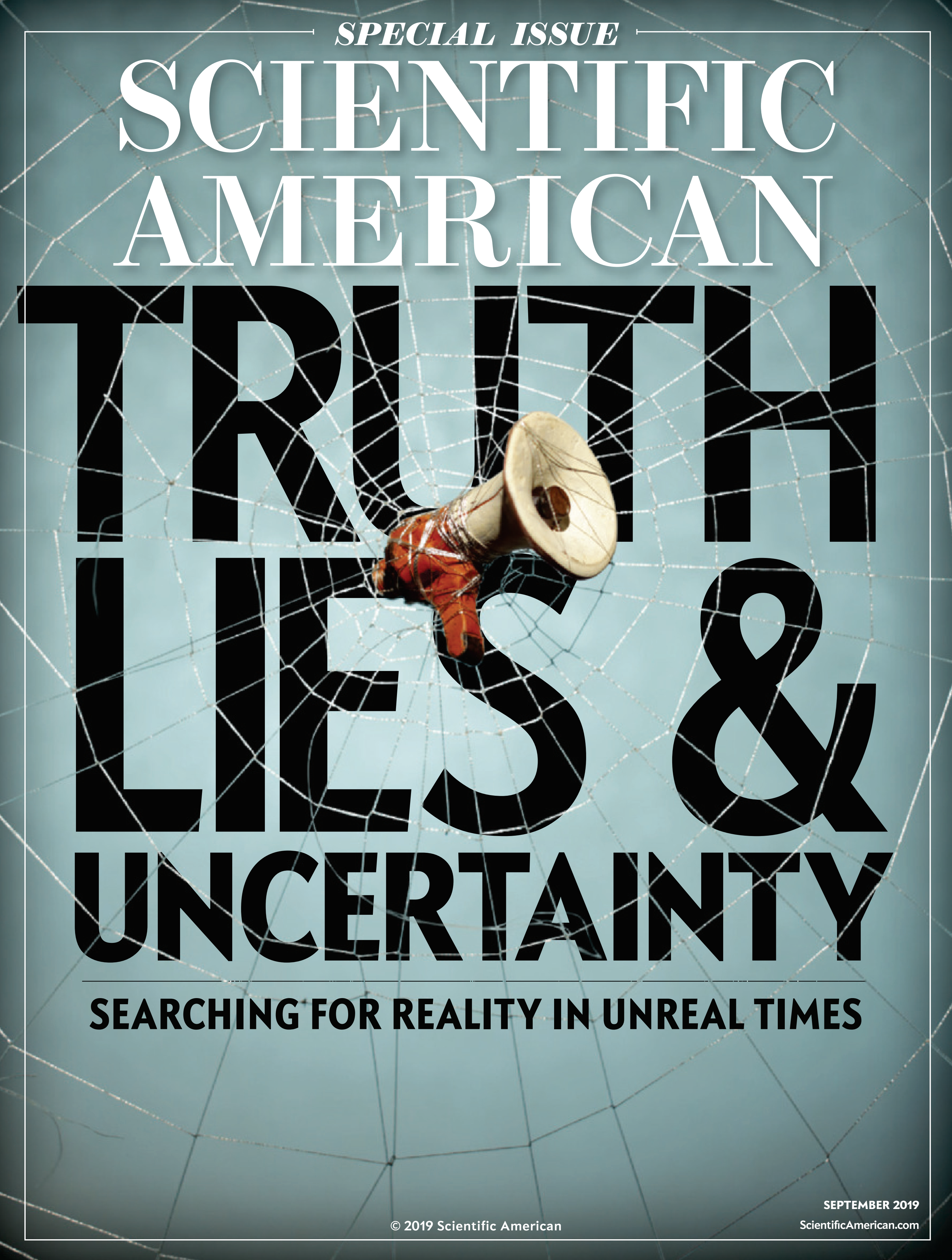

SPECIAL ISSUE

SCIENTIFIC AMERICAN

TRUTH LIES & UNCERTAINTY

SEARCHING FOR REALITY IN UNREAL TIMES

SEPTEMBER 2019

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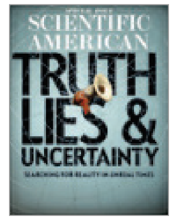

ON THE COVER

For the cover and inside pages of this special issue, we asked the artists at Red Nose Studio to find concrete ways to illustrate the abstract themes of truth, lies and uncertainty. For the illustrations on pages 28, 48 and 72, the artists took inspiration from the saying that only "fools and children tell the truth." **Illustration by Red Nose Studio.**

ON THE WEB

Lonely Planets

It has been 30 years since the Voyager 2 spacecraft flew by Neptune, which like its planetary sibling Uranus is an "ice giant" world in the outer solar system. Now some scientists are contemplating a return. *Go to www.ScientificAmerican.com/sep2019/lonely-planets*

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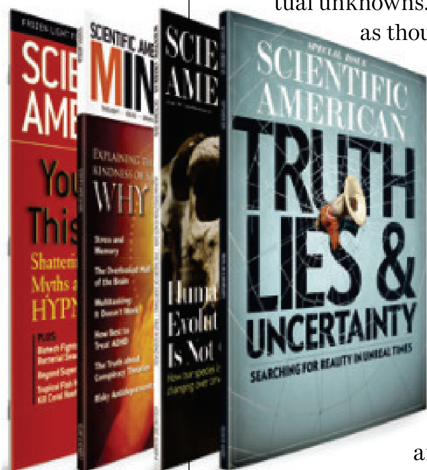
Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Science Communication 101

The scientific process, as I have often said, is an engine of human prosperity. For centuries it has been a driving force behind the advances in knowledge and well-being that we've enjoyed as a species. But none of us can benefit from that evidence-based engine if we don't first communicate well with one another. We need to be able to share new ideas and the products of research. The recipients need to be able to trust that the information is true and to understand an innovation's possible advantages or drawbacks so that we can make sound decisions as a society about what to do with it. If we cannot impart what we are learning to one another in this foundational way, we simply won't continue to progress.



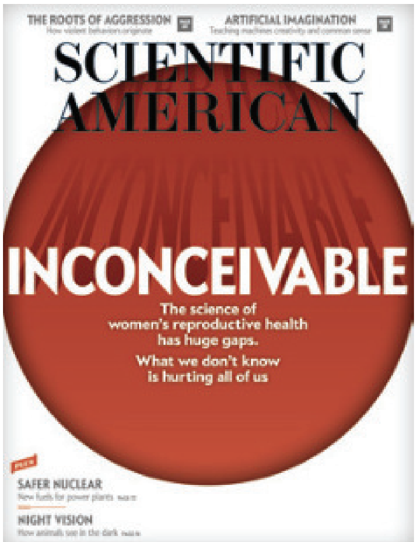
Today, unfortunately, we live in a world where this exchange of information can be fraught. Opinions based on false claims, misunderstandings and actual scientific uncertainties sweep over social media unremittingly. Countering the miasma of dreck feels more important than ever. Fortunately, research can provide helpful insights on that effort, too, as you'll learn in this single-topic issue on "Truth, Lies and Uncertainty."

The stories in the feature well run from what physics can tell us (and not tell us) about the reality and the fundamental laws of the universe to the innate deceptions of a wide variety of animals (not just humans) to how we can productively confront actual unknowns. We hope you will find this special edition as thought-provoking and fascinating to read as we found it while creating it.

Supporting better communication isn't just something that's nice to do. It's vital to ensure a better future for humanity. And it seems fitting that this issue's theme should be my last, after 18 years on staff at *Scientific American,* the past 10 as its editor in chief. By the time you read this, I will be just starting my new role as dean of the College of Communication at Boston University, my alma mater. If I am successful at all in supporting my new colleagues—and, more important, the students who will form the next generation of communicators—it will be because of my good fortune in having served at the 174-year-old national treasure that is *Scientific American*.

Working with the editorial and business teams, collaborating with our researcher and journalist authors and board of advisers on articles, and interacting with all of you—our readers—has been amazing. You've all taught me so much, and I thank you. SA

Illustration by Nick Higgins



May 2019

"Not mentioning menopause reinforces the cultural message to women that their value lies in their reproductive capabilities."

SASHA DAVIES *VIA E-MAIL*

MENOPAUSE AND HEALTH

I appreciate that *Scientific American* is working to bring attention to the issue of female reproductive health in its "Future of Medicine" report. But I am disappointed by the absence of any information about menopause, which means you do not address the full cycle of the female reproductive experience in this series of articles. Further, not mentioning menopause reinforces the cultural message to women that their value, even in the realm of scientific research, lies in their reproductive capabilities.

If the reason for excluding it is a lack of research or meaningful data, that fact alone would be worth sharing.

Sasha Davies *via e-mail*

THE EDITORS REPLY: Davies is right that menopause is an important aspect of women's reproductive health that deserves both more research and more media coverage. According to the AARP, nearly three quarters of women seeking help for menopause symptoms are left untreated. This is an area we will be paying attention to for future coverage.

TREATING AGGRESSION

In "The Roots of Human Aggression," R. Douglas Fields explores the question of whether structural brain abnormalities may be involved in violent behavior. He cites a study by psychiatrist Bernhard Bogerts in Germany that found that more violent prisoners had such abnormalities than nonviolent subjects, yet 58 percent of the violent prisoners Bogerts studied had no organic pathology. And Fields himself allows that "genes and *experience* [my italics] guide the development of neural circuits differently in every individual."

Over the course of human history, antisocial actions were variously tolerated or punished, depending on a community's ability to cope with the aggression. Today, as Fields notes, seven out of 10 violent acts among the mentally ill are reportedly associated with substance abuse, and incarceration has recently become the favored remedy. But association is not the same as causation. Evidence-based research offers some better alternatives, such as improvements in income supports, social infrastructure and peer-to-peer counseling.

It appears that phrenology may be making a comeback in a society crippled by fear.

Karl Dick *Waterloo, Ontario*

Fields has a great article going until he opines, "The prefrontal cortex does not fully develop until the early 20s in humans, pointing to why juveniles should not be held criminally responsible as adults in the U.S." I'm not sure what that even means! Why only in the U.S.? What solution is offered? Should adolescents operate self-guided missiles (aka automobiles)? How about consuming liquor or voting?

And while Fields is certainly entitled to his opinions regarding our legal system, the editors of *Scientific American* should recognize the obvious jump from science writing to op-ed. I would be interested in his thoughts on how society should deal with not fully developed prefrontal cortices but not in the context of science reporting.

Grant Merrill *Evergreen, Colo.*

Fields cites the amygdala, brain stem, hypothalamus, limbic system, pituitary gland and prefrontal cortex as pathways involved in human aggression and provides some reasons as to why we resort to it. I would have enjoyed his fine article even more than I did had he mentioned ways we can limit this capability for violent behavior, which he describes as "engraved in our brain."

Researchers such as I-Ju Hsieh, Yung Y. Chen and Stéphane Paquin have pointed to cognitive reappraisal to regulate negative emotions, conditioning to affect the brain regions that generate emotions, and programs to reduce victimization experiences and emphasize social values. Culture also plays an important role in aggression, and we should be mining environmental areas for more information on controlling it.

Vasilios Vasilounis *Brooklyn, N.Y.*

NUCLEAR ALTERNATIVE

"Reactor Redo," by Rod McCullum, describes new fuels for nuclear power plants that could improve efficiency and safety. Missing from the article is a mention of thorium, which has drawn attention lately because of various purported advantages (safety, nonproliferation, minimal waste, and so on). It also offers a way to escape the political onus of the uranium cycle (whether exaggerated or not, it is a bogeyman to many people).

China, India and others are currently developing thorium reactors. If McCullum deliberately omitted thorium, I wish he would have said why. Otherwise, his article could be construed as special pleading for the current uranium-based industry.

David Ecklein *Rumney, N.H.*

NETWORKING COSTS

In "Turning Off the Emotion Pump" [Ventures], Wade Roush discussed the negative effects of Facebook and questions whether a better social-networking technology can be found. I think there is a simple solution: The problem with Facebook, as well as other Internet platforms, is not the technology itself; it is the company's business model. All the negative ef-

fects that Roush articulates stem from the use of targeted ads, which Facebook depends on to make money because it does not charge users a fee for its services.

So an obvious fix is to have users pay for Facebook. Then there would be no need for it to sell ads or harvest personal information about its users. The users would decide for themselves who they want to connect with and what information to receive, not Facebook. Without the ability or the need to target users, the "emotion pump" Roush describes would be turned off. As a result, social and political polarization would diminish, and voter manipulation would become impossible—or at least much more difficult.

Facebook's annual revenue is about $50 billion, which comes almost entirely from selling ads. With around two billion users, each one would have to pay only $25 a year to replace that revenue, which would be a tiny fraction of what we already pay for Internet access. And the actual cost should be lower because if Facebook stopped selling ads, all the expenses associated with the advertising side of its business would disappear.

PAUL LUKE *via e-mail*

CLARIFICATIONS

"Alzheimer's AI," by Rod McCullom [Advances], describes two brain images as showing PET scans of a normal brain and one with Alzheimer's, respectively. While the agency that provided the images furnished those descriptions, an expert found that they were not the most typical representations for normal and Alzheimer's brains, although they could have come from such patients. *Scientific American* was unable to clarify the original source of the images.

In "Reactor Redo," by Rod McCullum, the opening photograph is described as showing fuel rods. It should have explained that the rods are contained within the visible hexagonal structures.

ERRATUM

"Night Visions," by Amber Dance, incorrectly referred to a shooting star as one point of light at any given moment. A shooting star, or meteor, is a streak of light rather than a single point, created when a meteoroid enters Earth's atmosphere.

LETTERS TO THE EDITOR

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When "Like" Is a Weapon

Everyone is an agent in the new information warfare

By the Editors

No one thinks, *I* am the kind of person who is susceptible to misinformation. It is those *others* (stupid anti-vaxxers! arrogant liberal elites!) who are swayed by propaganda masquerading as news and bot armies pushing partisan agendas on Twitter.

But recent disinformation campaigns—especially ones that originate with coordinated agencies in Russia or China—have been far more sweeping and insidious. Using memes, manipulated videos and impersonations to spark outrage and confusion, their targets transcend any single election or community. Indeed, these efforts aim to engineer volatility to undermine democracy itself. If we're all mentally exhausted and we disagree about what is true, then authoritarian networks can more effectively push their version of reality. Playing into the "us versus them" dynamic makes everyone more vulnerable to false belief.

Instead of surrendering to the idea of a post-truth world, we must recognize this so-called information disorder as an urgent societal crisis and bring rigorous, interdisciplinary scientific research to combat the problem. We need to understand the transmission of knowledge online; the origins, motivations and tactics of disinformation networks, both foreign and domestic; and exactly how even the most educated evidence seekers can unwittingly become part of an influence operation. Little is known, for instance, about the effects of long-term exposure to disinformation or how it affects our brain or voting behavior. To examine these connections, technology behemoths such as Facebook, Twitter and Google must make more of their data available to independent researchers (while protecting user privacy).

The pace of research must try to catch up with the rapidly growing sophistication of disinformation strategies. One positive step will be the launch this winter of *The Misinformation Review,* a multimedia-format journal from Harvard University's John F. Kennedy School of Government that will fast-track its peer-review process and prioritize articles about real-world implications of misinformation in areas such as the media, public health and elections.

Journalists must be trained in how to cover deception so that they don't inadvertently entrench it, and governments should strengthen their information agencies to fight back. Western nations can look to the Baltic states to learn some of the innovative ways their citizens have dealt with disinformation over the past decade: for example, volunteer armies of civilian "elves" expose the methods of Kremlin "trolls." Minority and historically oppressed communities are also familiar with ways to push back on authorities' attempts to overwrite truth. Critically, technologists should collaborate with social scientists to propose interventions—and they would be wise to imagine how attackers might cripple these tools or turn them around to use for their own means.

Ultimately, though, for most disinformation operations to succeed, it is regular users of the social Web who must share the videos, use the hashtags and add to the inflammatory comment threads. That means each one of us is a node on the battlefield for reality. Individuals need to be more aware of how our emotions and biases can be exploited with precision and consider what forces might be provoking us to amplify divisive messages.

So every time you want to "like" or share a piece of content, imagine a tiny "pause" button hovering over the thumbs-up icon on Facebook or the retweet symbol on Twitter. Hit it and ask yourself, Am I responding to a meme meant to brand me as a partisan on a given issue? Have I actually read the article, or am I simply reacting to an amusing or enraging headline? Am I sharing this piece of information only to display my identity for my audience of friends and peers, to get validation through likes? If so, what groups might be microtargeting *me* through my consumer data, political preferences and past behavior to manipulate me with content that resonates strongly?

Even if—especially if—you're passionately aligned with or disgusted by the premise of a meme, ask yourself if sharing it is worth the risk of becoming a messenger for disinformation meant to divide people who might otherwise have much in common.

It is easy to assume that memes are innocuous entertainment, not powerful narrative weapons in a battle between democracy and authoritarianism. But these are among the tools of the new global information wars, and they will only evolve as machine learning advances. If researchers can figure out what would get people to take a reflective pause, it may be one of the most effective ways to safeguard public discourse and reclaim freedom of thought. SA

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Illustration by Aad Goudappel

Gabi Serrato Marks is a Ph.D. candidate in the MIT-WHOI Joint Program in Oceanography and a patient advocate.

Skylar Bayer is an NRC postdoctoral research associate at the NOAA's Northeast Fisheries Science Center.

Disabilities Make Us Better Scientists

But the research world raises barriers to our full participation

By Gabi Serrato Marks and Skylar Bayer

Starting a science graduate degree was one of the most exciting things to happen to each of us. We also knew that graduate school would be particularly difficult. Skylar has a heart condition called polymorphic arrhythmia and has an implantable cardioverter defibrillator that ended her scientific scuba-diving career. Gabi has Ehlers-Danlos syndrome, a disorder that weakens the protein collagen in her body and causes widespread pain.

Although our conditions challenge us in different ways, we are able to cope and function at high levels. But as we have continued in our careers, we have learned that the research world is not designed to accommodate scientists with medical conditions or disabilities. The frequent barriers could be more understandable if we were part of a tiny group, but around 26 percent of U.S. adults have a disability. Scientists with disabilities have creative and unique ideas that are important for pushing research forward, provided we have access to health care, support and institutional backing.

We can be better scientists *because* of our challenges, not in spite of them. When Skylar could not scuba dive anymore, she could still design dive plans. She improved her abilities to carry out laboratory work and do computer modeling. She focused on project management, a skill that will serve her throughout her career. Ehlers-Danlos syndrome is rare, so explaining the condition has honed Gabi's science communication skills. Because of her condition, she is hyperflexible, which comes in handy in caves during fieldwork. We have learned to advocate for ourselves and persevere through challenges, both in our health and in our research.

We are not the only ones who experience benefits from our differences. A research assistant we know who has obsessive-compulsive disorder (OCD) finds that some of her compulsions are useful: Her attention to detail gives her a clear memory and a sharper recall of academic papers than most scientists have. She also is exceptionally careful about procedures—always sure, for instance, that the lab freezer is closed, avoiding a common mistake that has ruined many experiments in numerous institutions.

But we must spend extra time and money taking care of our health, and that can hamper our careers. Richard Mankin, an entomologist at the U.S. Department of Agriculture and president of the Foundation for Science and Disability, has had similar experiences. He was born without some muscles in his legs and arms and uses crutches for mobility. He gravitated toward government work because of the stability it offered. Mankin has traveled widely for fieldwork for more than 40 years, carrying light backpacks and collaborating with other scientists who can transport equipment. Next, he is headed to the Ecuadorian cloud forest to study fruit flies. Mankin says his disability often results in "low expectations from persons who did not know me well and assumed my disability causes reduced levels of productivity." He feels he has to work harder just to show he is equally capable of success.

Although the Americans with Disabilities Act provides legal protections for disabled people, accommodations are just one part of the access puzzle. True access goes beyond legal requirements—it involves a culture of inclusion that allows everyone to perform at the highest level. The researcher with OCD said that part of the challenge of living with a mental illness is the stigma. "I don't want to be viewed as someone who just obsesses over things," she wrote in a private communication. Mankin has been turned down several times for manager positions because he is not viewed as a leader. He wants to be a role model and encourage disabled students to pursue science but worries about how discouraged some folks may be, especially without better support systems.

We work hard to fit into academic culture, so we ask institutional leaders to think beyond legally required accommodations and to support all scientists. We hope that science will become more inclusive and lower barriers against anyone with conditions like ours. Initially we were terrified that we could not be successful scientists because of our health. But now we know that those of us with disabilities, differences in thinking, and medical challenges are well suited for scientific careers—as long as those careers are made as accessible to us as they are to everyone else. SA

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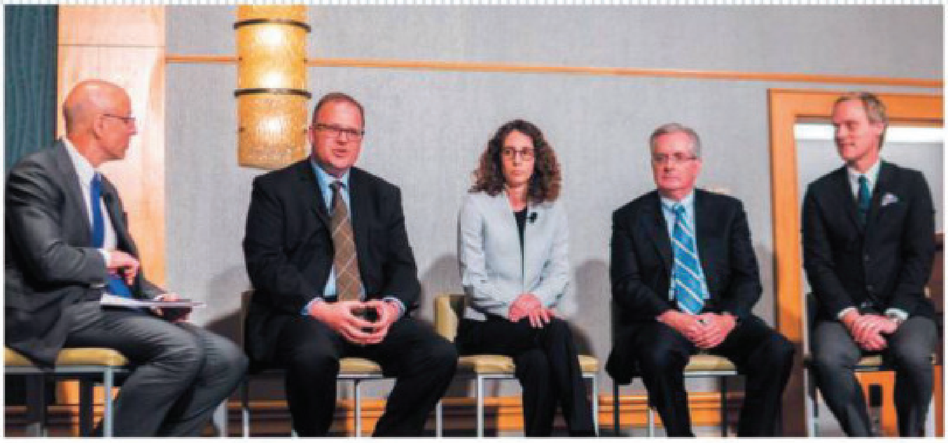
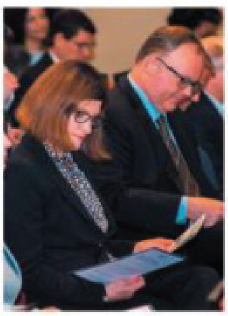
Illustration by Samantha Mash

PROMOTION

The Agenda Setters

Bringing Science to Life





Hot Topics in Oncology

Bethesda North Marriott Hotel & Conference Center | Rockville, MD | May 7th, 2019

SCIENTIFIC AMERICAN'S Custom Media division hosted an engaging, two-panel event in collaboration with Amgen on Tuesday, May 7th in Rockville, MD. The forum, *Hot Topics in Oncology: Getting New Therapies To Patients By Changing The Way We Measure Effectiveness*, attracted a rich audience of opinion leaders in the regulatory, academic, and industry space.

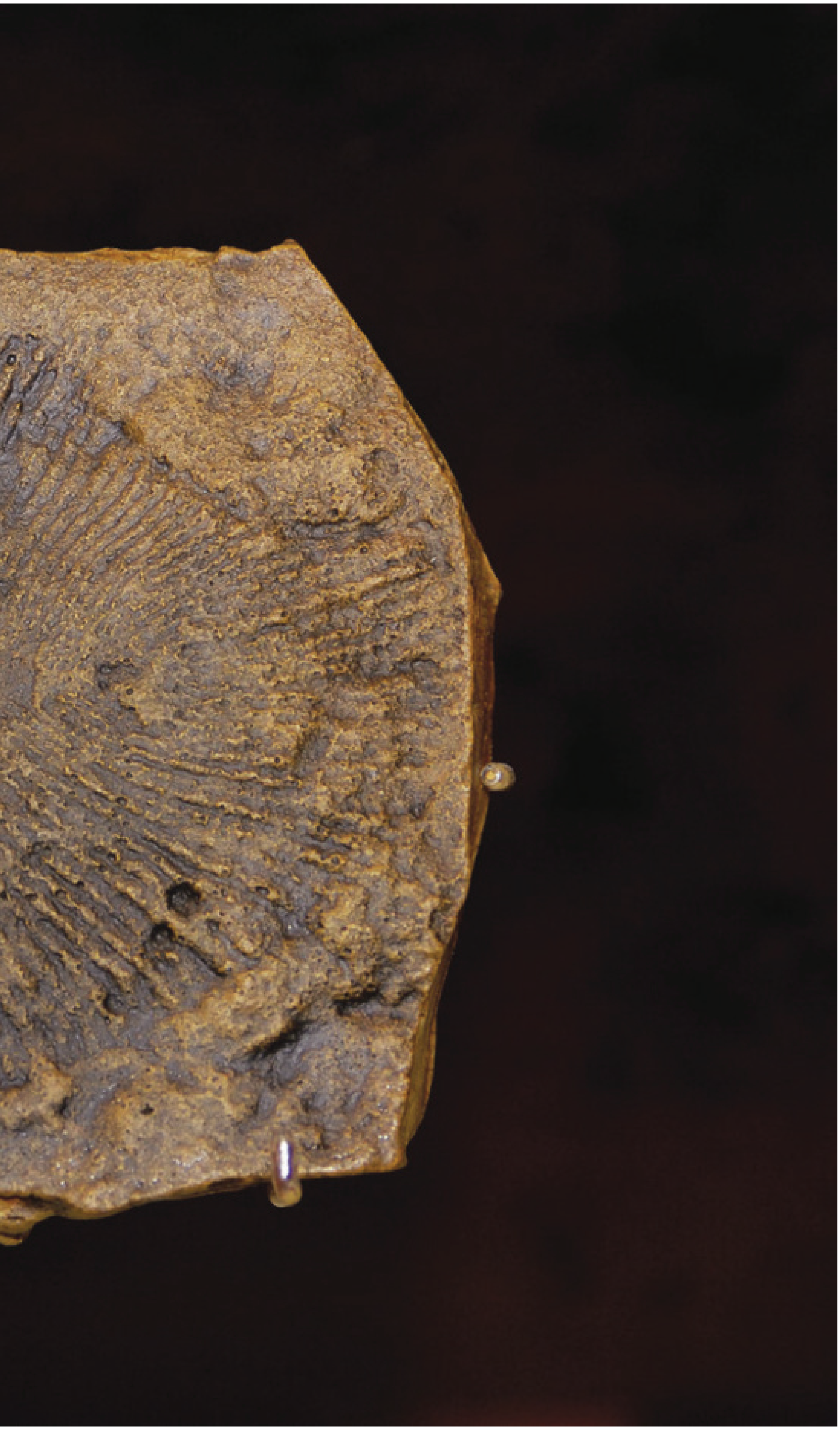
The event opened with remarks by **Jeremy Abbate**, VP and Publisher, Scientific American, followed by keynotes from **Tanisha Carino**, Executive Director, FasterCures and multiple myeloma patient advocate **Yelak Biru**. Moderator **Cliff Goodman** then drove an inspiring and thought-provoking discussion exploring the use of minimal residual disease (MRD) as a surrogate endpoint in clinical trials. Two groups of expert panelists including **Jeff Allen**, Friends of Cancer Research, **Kathy Kross**, Amgen, **Dana Connors**, Foundation for the NIH, **Jon Retzlaff**, American Associate for Cancer Research, **Greg Friberg**, Amgen, **Sarah Holstein**, University of Nebraska Medical Center, ASCO, **John Jenkins**, Greenleaf Health, and **Ola Landgren**, Memorial Sloan Kettering Cancer Center, sought to determine if recent cutting edge technology will allow us to more rapidly deliver new therapies to MRD patients. Attendees were left with an encouraging message that new MRD measurements are already well in effect.

Scientific American's Custom Media division, operating as a separate and distinct unit from its editorial department, develops events, content, and special projects in partnership with corporations, government institutions and academia.

ADVANCES

Fossil from the genus *Dickinsonia* dating back from 571 million to 541 million years ago.

INSIDE



GILBERT S. GRANT *Science Source*

PALEONTOLOGY

Motion in the Ocean

Fossils clarify some of animals' earliest deliberate movements

About 550 million years ago animals were relegated to the seas. Microbes and larger multicellular organisms covered much of the seafloor in an organic mat similar to pond scum. On top of this settled bigger animals, including *Dickinsonia*—a genus of perplexing creatures shaped like dinner plates, round bath mats and flattened coins.

Scientists have long speculated about what Earth's life was like half a billion years ago, during the Ediacaran period, and they are steadily finding more clues. A study published online in June in *Geobiology* reports that *Dickinsonia* may have been some of the first complex animals to move on their own in search of food. This finding, experts say, could help us better understand animals' evolution.

Since *Dickinsonia* were first described in the 1940s, scientists have debated exactly what type of organism they were. "They've been interpreted as everything from a lichen to a worm—a whole variety of things," says Scott Evans, a paleontology researcher at the University of California, Riverside, and one of the study authors. "Recently it has become apparent that this thing was definitely an animal." Based on the fossil evidence, scientists think *Dickinsonia* were soft-bodied and oval-shaped, with multiple body divisions and ribbed upper and lower surfaces. They had a distinct front and back and could grow up to a meter in length but were only several millimeters thick.

Evans and other researchers from U.C.

Riverside and the South Australian Museum in Adelaide analyzed nearly 1,500 *Dickinsonia* fossils to determine whether the animals could move on their own. "People have speculated about [their] being mobile for a while" because of clues in the fossil record, Evans says, "but we wanted to examine the different features we see in *Dickinsonia* to see if we could eliminate all other possible explanations besides mobility."

The record includes body fossils as well as what appear to be "trace fossils"—"footprints" of sorts—that these animals left behind, hinting they were mobile. Some scientists suggested, however, that ancient ocean currents may have picked the creatures up and moved them. Others said the "footprint" fossils may have actually formed from specimens that had decayed and then collapsed when buried in sediment.

But Evans and his team determined that *Dickinsonia* indeed seem to have traveled on their own: possibly tens of meters or more over their lifetime. The fossil record shows that these organisms had all moved in different directions; if ocean currents had shifted them, they would have all been oriented in the same direction, Evans says. The body and trace fossils also reveal specific pathways left by *Dickinsonia.* If these were left by decayed animals, "we would expect them to be sort of random with respect to one another," Evans explains. "And the fact that we're seeing trackways [for a single individual] moving in a preferred direction suggests an organism moving under its own power and moving in a direction related to its internal biology."

The evidence indicates *Dickinsonia* fed in one spot on the seafloor's organic carpet and then actively sought a fresh food source, and they probably did so on relatively short timescales—over hours or days. Some scientists have hypothesized that these animals moved by expanding and contracting their body using muscles, and the new analysis supports this idea. Evans notes that although scientists have found evidence for self-directed animal movement earlier than *Dickinsonia,* those animals likely were smaller and traveled shorter distances. And, he adds, "This is the first time we're seeing an animal move to a new location to feed."

Other researchers say these findings help to resolve some of the debate over *Dickinsonia* and paint a clearer picture of life's history on Earth. "They killed all the other hypotheses" about whether *Dickinsonia* moved or not, says Jakob Vinther, a paleobiologist at the University of Bristol in England, who was not involved in the study. "This provides us with more constraints to understand what [these fossils] tell us about the earliest animals and animal evolution." Paleontologist and mathematician Renee Hoekzema of the University of Copenhagen agrees. "Against all odds we are really starting to resolve fundamental questions about the nature of the enigmatic Ediacara biota and thus gaining insight into the evolution of complex life on the planet," explains Hoekzema, who also was not involved in the study.

Although *Dickinsonia* did not look like any known living things today, there are still some parallels between modern animal life and archaic creatures such as these. "We're seeing very early on the development of complex behaviors of mobility and different feeding styles," Evans says. "These animal communities we find early on in the fossil record are almost as complex as the ones we have today." Perhaps life on ancient Earth was not so alien after all.

—Annie Sneed

PHYSICS

The Perfect Crepe

Exploring the physics behind the delicious dessert

With a little help from computer simulations and fluid dynamics, engineers have finally optimized the craft of crepe making.

So suggests a new study involving these paper-thin, tricky-to-make pancakes, which are often filled with chocolate, cheese or jam. By simulating the behavior of batter poured across a tilting and rotating hot surface, a pair of engineers—separated by half the world but united in their passion for brunch—mathematically determined the pan-angle-and-swirl conditions that give rise to ideal crepes.

The investigation was the brainchild of Mathieu Sellier, an engineer at New Zealand's University of Canterbury, who studies fluid systems at scales from microscopic channels to glacier flows. He also serves as

chief brunch maker in his home and had often wondered: What's the best way to coat the pan thinly and evenly with batter?

In 2016 Sellier mentioned the crepe conundrum to Edouard Boujo, an engineer now at École Polytechnique in France, who studies optimization. They recast the problem in mathematical terms: How does one minimize the difference in thickness between a real-world pancake and an ideal, uniformly flat one? Their results appeared in June in *Physical Review Fluids.*

The optimal technique the duo found—to pour batter into the hot pan, tilt the pan to spread it to the edge and swirl to distribute it evenly—should not come as a surprise to expert crepe cookers. But its implications reach beyond the kitchen.

"This is a really good way of simplifying the problem," says mathematician Matthew Moore of the University of Oxford, who was not involved in the study (but admits to a weakness for savory crepes). He says that probing what happens at the transition between liquid and solid states can often get complicated. Treating crepe making as an optimization problem is a strategy that could be useful for other tasks.

The crepe-making process is similar to techniques for adding thin layers to microchips and evenly applying paint to a car—applications that the engineers say could benefit from their approach. "The connection is that you want to spread your liquid in a thin, uniform layer," Sellier says. "It's the same problem in a lot of cases."

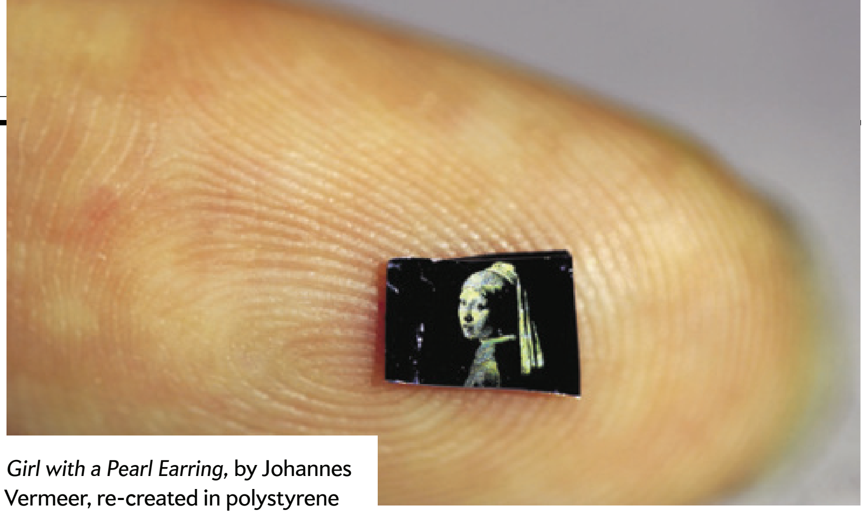
—Stephen Ornes

CLAUDIA TOTIR *Getty Images*

MATERIALS SCIENCE

Cracked Canvases

Microstructures in plastic produce colorful portraits



Girl with a Pearl Earring, by Johannes Vermeer, re-created in polystyrene

ANDREW GIBBONS *Kyoto University*

For millennia humans have created art with pigment-based paints, inks and dyes. Now researchers have produced tiny plastic paintings whose colors come from variations in microscopic surface features instead.

Pigments are chemicals that absorb certain light wavelengths and reflect others to produce specific colors. But some materials—such as those on morpho butterflies' iridescent blue wings and the striking feathers of some hummingbirds—produce colors based on the size and spacing of microstructures on their surfaces, which interact with light wavelengths of different sizes.

Many plastics form minuscule cracks, called crazes, when put under stress. Typically these fractures occur randomly throughout the material. But first exposing some plastics to light beams can selectively weaken them in places, where crazes will appear when the plastic is stressed. "You can actually control where the cracks form," says materials scientist and study co-author Andrew Gibbons of Kyoto University in Japan. Depending on size and configuration, these cracks act as microstructures that produce specific colors.

Gibbons and his colleagues shone powerful LEDs on thin pieces of plastic and then dunked them in acetic acid, generating crazes in the places preweakened by light. These cracks initially reflect the same wavelength of light to which the section of plastic was exposed, according to the study, which was published in June in *Nature.*

If the plastic is soaked longer or exposed to high temperatures, the cracks can expand to reflect longer wavelengths. The size of each region hit by light and the thickness of the plastic also influence how far the cracks expand. To test their method, the researchers produced miniature renderings of classic paintings and even a Queen album cover. (The smallest was 0.25 millimeter across.)

"It's an innovative twist," says polymer scientist Christopher Soles of the National Institute of Standards and Technology, who was not involved in the study. "Usually crazing in materials is a very bad thing," Soles notes, "but here the crazes are useful." He was surprised the process worked with so many different types of plastics, including polystyrene, polycarbonate and acrylic glass—used in food containers, CD cases and bulletproof glass, respectively.

Gibbons says crazing could potentially create a durable plastic coating for currency or high-end merchandise to discourage counterfeiters. And the microstructures can produce more than pretty pictures. Eventually he hopes the technique could be used to create devices that store microscopic amounts of liquid for medical analysis. *—Jennifer Leman*

FIELD BIOLOGY

A Migrating Snack

For young sharks, land-based birds can be easy targets

Songbird from a tiger shark's stomach

MARCUS DRYMON *Field Museum*

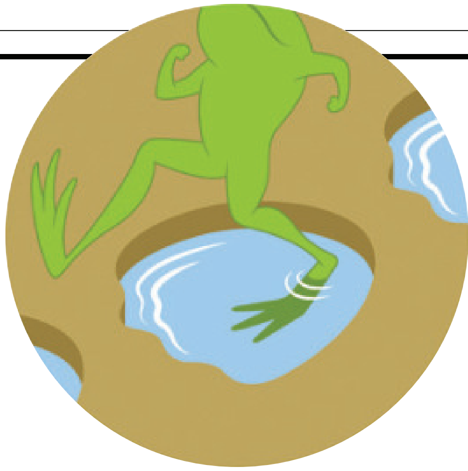
When fisheries biologist James Drymon noticed feathers in the vomit of a tiger shark, he first assumed they belonged to some unfortunate seabird: a gull, perhaps, or a pelican. But when he and his team genetically sequenced the feathers, the results surprised them: the quills came from a land-based songbird called a brown thrasher. So what was it doing in a tiger shark's stomach in the Gulf of Mexico?

Drymon, a researcher at Mississippi State University's Coastal Research and Extension Center, and his colleagues sorted through the stomach contents of 105 juvenile tiger sharks between 2010 and 2018. Nearly 40 percent had recently feasted on birds that hail from dry land. In all, the scientists counted 11 terrestrial bird species showing up on the sharks' menu. The results were published online in May in *Ecology.*

Researchers have known since the 1960s that sharks sometimes eat songbirds, "but what was interesting to us was the prevalence" of the behavior, Drymon says. "This is something that happens every year in a high number" of sharks.

Every fall and spring, songbirds undertake dramatic migrations across the Gulf of Mexico. If bad weather comes along, they can be forced to land on the water—which is effectively a death sentence. "The estimate for the number of migrants that die because of storm-related events is in the billions," Drymon says. He suspects that sharks have long taken advantage of this twice-yearly nutritional bounty raining down from the skies, but scientists have only recently had the genetic tools to confirm this by identifying partially digested feathers.

The results underscore how interconnected marine and terrestrial ecosystems can be, says University of Miami marine ecologist Neil Hammerschlag, who was not involved in the study: "It shows how opportunistic and amazingly generalist these sharks are." *—Jason G. Goldman*



ECOLOGY

Footsteps of Giants

Frog generations thrive in elephants' footprints

As herpetologist Steven Platt trudged through the seasonally flooded Nay Ya Inn wetland in Myanmar (formerly Burma) during a 2016 dry-season expedition, something strange caught his eye: Frisbee-sized pools brimming with clusters of frog eggs and wriggling tadpoles.

The watery pockmarks were old elephant tracks. Platt, who works at the Wildlife Conservation Society, realized that in the parched landscape these puddles may be a lifeline for the next generation of frogs. "It made me wonder how important these tracks—really, tiny little ponds—might be for all the smaller things that are out there," he says.

Elephants are often cited as ecosystem engineers. They knock over trees, trample brush, prune branches and disperse seeds, enhancing biodiversity and helping maintain savannas and forests.

Many researchers focus on these big-picture impacts, but Platt realized other important ones may be right at the elephants' feet. When he returned to the site in 2017, he found tracks in the same spot—and the tadpoles and eggs were back, too. Resembling a series of frog-sized Jacuzzis, the tracks appear to act as small breeding sites linking together larger wetland patches during the dry season, Platt and his co-authors reported in May in *Mammalia.*

Such microcosms of life are probably commonplace, Platt says, but almost "no one bothered to look before." A 2017 paper published in the *African Journal of Ecology*—possibly the only other study that has examined biodiversity in flooded elephant tracks—supports his hunch: its authors found dozens of invertebrate species and tadpoles in elephant footprints and artificially created puddles in Uganda.

According to Chris Thouless, who directs the Elephant Crisis Fund at the Kenya-based nonprofit Save the Elephants and was not involved in the new research, the Myanmar findings are "an amazing demonstration of the interconnectivity in the natural world, between the largest and one of the smallest creatures in the landscape." But habitat loss and poaching threaten elephants throughout their range, Thouless says, and scientists do not know whether frog populations will crash if elephants disappear from the landscape—or whether "new ecological relationships will develop that re-create at least part of the lost complexity of the system."

Platt guesses that at least some of that complexity is irreplaceable. "As the elephants go," he says, "probably a lot of relationships we don't even know anything about at this point go, too."

—Rachel Nuwer

Illustration by Thomas Fuchs

BIOMECHANICS

Falling for Science

A devious treadmill prompts stumbles to study balance

A study participant walks briskly on a treadmill, video cameras recording his every move, when a 35-pound metal block suddenly appears in his path. Special eyeglasses prevent him from seeing it, and he stumbles, lurching forward—until he is caught by a safety harness. One trip down, dozens more to go.

Researchers developed the treacherous treadmill to study how people regain their footing after tripping. They knew this usually means taking an exaggerated step that allows the central nervous system to reorient the body's center of gravity above firm footing, says Michael Goldfarb, a mechanical engineer at Vanderbilt University and co-author of the treadmill study. But "the way you do that changes depending on what your [body's] configuration was when you stumbled," Goldfarb adds.

People with prosthetic legs often struggle to recover from a stumble and thus fall at far higher rates than the general population. Understanding how people trip and recover on two legs could help researchers design better prosthetics.

To trigger genuine tripping, researchers had to deliver the heavy blocks surreptitiously. Goldfarb and his colleagues' apparatus, described in June in the *Journal of NeuroEngineering and Rehabilitation,* works because it can place a heavy block on the treadmill so delicately that participants do not perceive it until they have already tripped. An algorithm determines where to place the block so the researchers can observe stumble responses at different points in a subject's gait.

The surprise is key, but participants in this kind of study know they will eventually be tripped up—which could confound results, says Mark Grabiner, a biomechanicist at the University of Illinois at Chicago, who was not involved in the new work. Researchers have taken various approaches to this problem in the past, sometimes not even telling participants they are in a tripping study, Grabiner says. The new study's stealthy design is "an incremental improvement over existing technologies"—a step in the right direction—he adds.

Researchers successfully triggered 190 stumbles.

SHANE KING AND MAURA EVELD *Vanderbilt University*

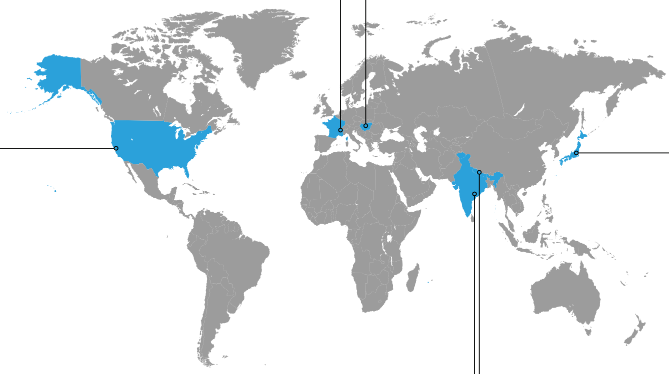
In the next phase of the study, Goldfarb says, his team will use the tripping data to program reflexive stumble responses for a variety of situations in prosthetic limbs.

—Jim Daley

IN THE NEWS

Quick Hits

By Jennifer Leman



FRANCE
Grape seeds found in an ancient refuse pile in the Jura mountains were an exact genetic match with a type of grape harvested there today, meaning local winegrowers have been cultivating the same vintage for roughly 900 years.

HUNGARY
Despite large-scale protests from scientists about academic freedom, the country's Parliament passed a law granting the government control of more than 40 institutes within the Hungarian Academy of Sciences.

U.S.
Officials unanimously voted to ban e-cigarette sales in San Francisco, the first major U.S. city to take this step. Like traditional tobacco, e-cigarettes can cause lung damage and disease, and their use is skyrocketing in young people—in 2018 one in five U.S. high school students reported e-cigarette use.

JAPAN
Japan has withdrawn from the International Whaling Commission and resumed commercial whaling operations after a 31-year hiatus. Two minke whales were killed for their meat in July in the first official hunt.

INDIA
All four reservoirs in Chennai, India's sixth-largest city, have gone dry, forcing more than nine million people in the region to conserve water and rely on government rations. Low rainfall paired with unregulated water use spurred the drought.

NEPAL
Newly declassified cold war–era U.S. satellite images revealed that Himalayan glaciers have lost ice since 2000 at twice the rate that they did during the previous 25 years.

For more details, visit www.ScientificAmerican.com/sep2019/advances

Pteris vittata, a species of brake fern

BOTANY

Arsenic-Eating Fern

The plant's genes hint at ways to clean up soil and water

Arsenic-contaminated groundwater and soil affect millions of people worldwide; the substance can cause skin lesions, cancer and other illnesses if it gets into drinking water and crops. But the Chinese brake fern, *Pteris vittata,* naturally accumulates arsenic levels that would kill most other organisms—and somehow it continues to thrive. The mechanism behind this tolerance has long been a biochemical puzzle.

Now plant researchers Jody Banks and Chao Cai, both at Purdue University, and their colleagues have explained how it happens. By splicing the fern's genes into other plants, Banks says, bioengineers might one day harness its abilities to help clean up contaminated areas.

Banks had noticed that three of the fern's genes become more active when it encounters arsenic. To test whether they are behind its tolerance, she used a common biological technique to turn each gene "off" in several samples—which died when exposed to the poison. Then she and her team used a microscope to track the proteins these genes encode in the species, reconstructing how the proteins work together to collect and neutralize arsenic as it moves through the plant's fronds.

One of the proteins, GAPC1, is found in many organisms and uses phosphate to help break down sugars for energy. Arsenate, the form of arsenic found in soil, is toxic because it replaces phosphate in this process, blocking energy production. But in the fern, GAPC1 has a slightly different structure that allows it to chemically bind arsenate. Another protein called OCT4, encoded by one of the other genes, helps to shuttle the trapped arsenate across membranes into tiny structures called vesicles within the cell. Inside the vesicles the protein GST—encoded by the third gene—transforms arsenate into a form called arsenite. The vesicles transfer this compound to parts of the plant where it safely accumulates as a defense against hungry insects, the researchers found. Their study was published in May in *Current Biology.*

In 2016 biochemist Barry Rosen of Florida International University, who was not involved in the new study, identified a process for trapping and neutralizing the poison in an arsenic-tolerant bacterial species, *Pseudomonas aeruginosa,* that used nearly identical genes. Whereas the fern traps arsenite in specialized cells, the bacteria pump it back out into the environment. "Demonstrating that this very novel mechanism applies to plants as well as bacteria," Rosen says, "shows that organisms have evolved a way to get around the major way that arsenate is toxic." —*Rachel Berkowitz*

PUBLIC HEALTH

Mapping HIV

Toward a more localized picture of the virus's prevalence in Africa

HIV/AIDS is a primary cause of death in sub-Saharan Africa. It is no longer always a death sentence, thanks to lifelong antiretroviral therapy, but getting treatment to patients is a challenge. Now researchers have conducted one of the most geographically specific analyses to date of HIV prevalence in 47 sub-Saharan countries. The study could help authorities better target treatment and prevention efforts.

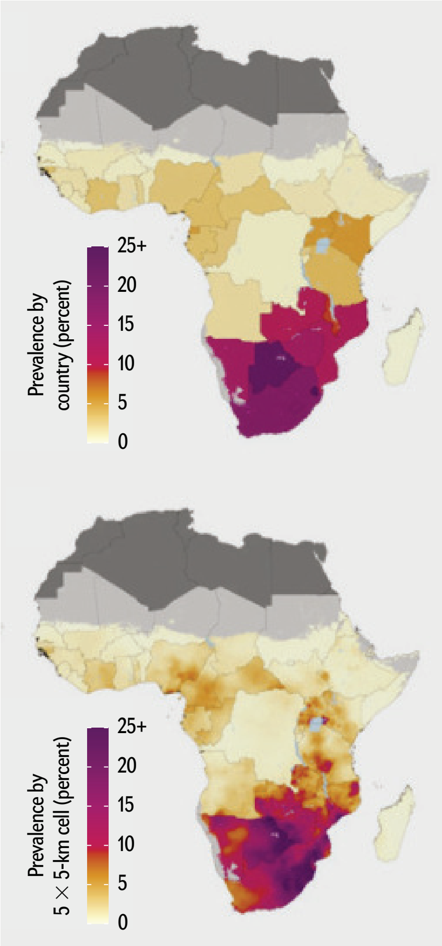
"We hope that it will be useful to people on the ground who are in one particular area and add to what they already know about their community," says lead author Laura Dwyer-Lindgren, an assistant professor of health metrics sciences at the University of Washington. "We also hope it will be useful more centrally, at the country level, for figuring out places where the number of people in need is not matched by the resources."

Dwyer-Lindgren and her colleagues created a database of HIV prevalence based on population surveys and data gathered from clinics where women are seeking prenatal care. They used these data to estimate the proportion of people (aged 15 to 49) with HIV from 2000 to 2017 in five- by five-kilometer geographical grids (*maps*), as well as the number of people living with the virus.

HIV prevalence varied widely from region to region—for example, from 15 percent in Botswana's Ghanzi district to 28 percent in its North-East district in 2017. Prevalence also decreased in some areas, such as Mozambique's Manica district, and increased in others, including its Guijá district.

Having this level of statistical granularity is useful for directing treatment and prevention. "It's a really neat study in that it has synthesized the data over the years that we've been trying to grapple with," says Ayesha Kharsany, a senior scientist at the Center for the AIDS Program of Research in South Africa (CAPRISA), who was not involved in the new work. "We've been very successful making sure that people go on to treatment," she says, but "we need

JODY BANKS *Purdue University*



Prevalence of HIV in adults aged 15 to 49 in 2017, at the country level (*top*) and five- by five-kilometer grid level (*bottom*). The latter provides a more granular picture of the proportion of the population living with the virus.

FROM "MAPPING HIV PREVALENCE IN SUB-SAHARAN AFRICA BETWEEN 2000 AND 2017," BY LAURA DWYER-LINDGREN ET AL., IN *NATURE*, VOL. 570; 2019

to make sure that treatment is scaled up" and targeted to areas that need it most.

The ability to map at this level is "very exciting," adds Sten Vermund, dean of the Yale School of Public Health, also not involved in the new work. He thinks the World Health Organization and the Joint United Nations Program on HIV/AIDS (UNAIDS) should adopt such methodology for their own reports.

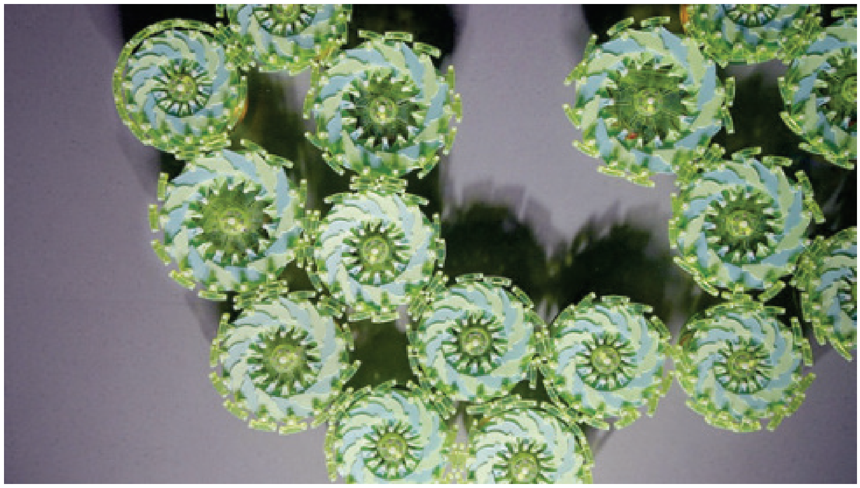
Increases in prevalence are not necessarily evidence of new HIV cases; people with the virus may simply be living longer or moving to different areas. But, Dwyer-Lindgren says, "it's also apparent that many people are not receiving treatment." Getting better estimates of new cases is an important next step, she adds: "There's a lot of work still to be done."

—*Tanya Lewis*

TECH

Robot Herd

Simple automatons expand and contract to move as one



RICHA BATRA, JANE NISSELSON AND KYLE PARSONS *Columbia Engineering*

Scientists have created a robot consisting of multiple units that can operate as a cluster, responding to stimuli and acting on their environment without the need for any centralized control—much like living cells.

Each of the circular units, or "particles," measures up to 23.5 centimeters in diameter. The particles are loosely joined together with magnets and can move only by expanding or contracting. But despite their individual simplicity, as a group they are capable of more sophisticated behavior, such as moving toward a light source. The weakly linked mass is more resilient than many other robotic systems because it has no single point of failure and can keep working even if some individuals become disabled, the researchers reported in March in *Nature*.

The scientists say miniaturized versions of the particles could be used in search and rescue operations—for example, spreading sensor-equipped units over the debris field of a collapsed house to find buried victims. Tiny units could also deliver drugs to hard-to-reach parts of the human body or boost research by modeling the cellular action involved in organ formation.

The prototype particles are equipped with light sensors and simple electronics that make them expand or contract in accordance with an algorithm. Each particle measures the intensity of nearby light and broadcasts that reading to its neighbors. By comparing how much light it detects relative to the others, each unit decides when to start a cycle of expansion and contraction—causing them all to move as a group.

The researchers created clusters of up to 24 particles and showed they could shuffle toward a light source—a kind of motion comparable to the way living cells aggregate and migrate for wound healing and other functions. "In our system, each particle is very simple, and there is no central control over the cluster," says Daniela Rus, director of the Computer Science & Artificial Intelligence Laboratory at the Massachusetts Institute of Technology and one of the team leaders. The units "work together without relying on any particular individuals." (Rus serves on *Scientific American's* board of advisers.)

The robot can also skirt obstacles and push objects around. And in simulations with up to 100,000 units, even if 20 percent stopped functioning the cluster could still travel at about half of its top speed.

"This kind of technology is expected to be applied to tasks such as searching, collecting and transmitting information and transporting [objects] as a swarm," says Hajime Asama, a professor of engineering at the University of Tokyo, who was not involved in the study. "But there are still many problems to be solved before reaching actual applications, including the ability to adapt to changes in tasks, the environment and the robot's own state." *—Tim Hornyak*

ANIMAL BEHAVIOR

Fast-Flapping Friends

Pigeons fly together even though it expends more energy

A group of birds flitting in unison is awe-inspiring to humans, and the birds themselves get predator protection and navigational help from their companions. A new study finds pigeons pay an enormous cost to fly together, even in pairs—yet they still choose to do it.

Certain birds, such as geese, travel in V formations to save energy by using the airflows their neighbors create. But smaller species such as pigeons flock in disorganized groups where this benefit would not apply; a 2011 study found pigeons actually flap faster, thus working harder, when in tight clusters.

To examine this phenomenon more closely, scientists at the University of Oxford and Royal Holloway, University of London, tracked pigeons' flap frequency and flight paths when flying alone and in pairs. They found that the birds beat their wings once more per second when in a pair—an 18 percent increase in frequency from flying alone and a much bigger leap than going from spread-out groups to dense ones in the 2011 study. Nevertheless, most pairs remained together. The new work was published in June in *PLOS Biology.*

Study authors propose that when trying to stick together, the birds flap faster to improve their control and visual stability. "They fly really quite fast," says lead author Lucy Taylor of Oxford. "You're having to fly at speed and not hit anything, and that's kind of an amazing feat." Tracking devices on the pigeons suggest higher wingbeat frequencies did keep them more stable, although University of Montana researcher Bret Tobalske says a more direct measurement—such as from cameras affixed to the birds' heads—would be needed to know definitively. "I think that it's novel and important work that's building on the previous work," says Tobalske, who studies bird flight and was not involved in either study.

Taylor thinks the increase in energy use between pairs and larger flocks would be much smaller than the jump from single to pair because flocking in groups simply builds on the new challenges created by flying with a partner. "You're then having to coordinate with another bird," she says. "When you have more birds, it may require more coordination." But Taylor adds that the experiment should next be scaled up to see how things change as the flock gets bigger.

Yet even pairing up provides benefits. The researchers found the pigeons' routes were more direct when they had partners. Each bird would also have a partner helping to look out for approaching predators—and a chance the predator might eat its companion instead.

Pigeons accept the energy cost for these benefits because, as Tobalske puts it, "nothing in life is free." —*Leila Sloman*

HUGH MACKINTOSH *Getty Images*

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic*. She was science editor at *Time* and managing editor of *Scientific American Mind*.

Too Much of a Good Thing

Gulping vitamins can have surprising risks

By Claudia Wallis

More than half of American adults take vitamin pills. I've watched in wonder as some of my more health-conscious friends kick off their morning with an impressive array of multicolored supplements: A, C, D, calcium, magnesium, you name it. And it's not just my friends: data from the National Health and Nutrition Examination Survey (NHANES) indicate a trend away from all-in-one multivitamins and toward specific supplements—especially fish oil and vitamin D. Most of this is self-prescribed. According to a 2016 analysis of the NHANES data, less than a quarter of supplements are taken at the recommendation of a health professional.

Most of this nutritional enthusiasm does no harm—apart from the budgetary kind—and for those with inadequate diets or special health concerns, supplements can do a world of good. But it is wise to keep in mind that doses that far exceed the recommended dietary allowances (RDAs) set by the Institute of Medicine can be hazardous. A reminder comes from a recent study linking excessive B vitamins to a heightened risk of hip fracture.

The study, published in May, combed through the vitamin habits of nearly 76,000 postmenopausal women participating in the decades-long Nurses' Health Study. Lo and behold, those who took high doses of vitamin B_6 (35 milligrams or more daily), together with B_{12} (20 micrograms or more), had a nearly 50 percent greater risk of fracturing their hip than those taking low doses or none. High doses of B_6 alone also raised the risk. The study confirms similar findings in a large Norwegian trial, published in 2017, that looked at whether these vitamins and folic acid could reduce heart attacks and strokes in patients with narrowed blood vessels. Alas, they did not, and to the great surprise of researchers, high doses were linked to hip fractures. Taken together, "the results are quite convincing," says Haakon Meyer, a professor of epidemiology and preventive medicine at the University of Oslo and an author of both studies.

Why these vitamins would have such an effect is not clear. Meyer suggests two possible pathways. Too much B_6 can be toxic to the nervous system, raising the chances of falling and cracking a hip. The nurses on high doses took 20 to 30 times the RDA, he notes. "Traditionally, we thought the doses needed to get these adverse effects would be much higher, but we don't know for sure." Another possibility is that B_6 competes with estrogen in binding to steroid receptors, compromising the hormone's role in bone health. Both ideas, he says, would require more evidence.

The B vitamin findings are reminiscent of a discovery made some 20 years ago that linked excessive vitamin A (retinol) with hip fractures. This research, published in 2002, also relied on the trove of data from the Nurses' Health Study. Walter Willett, a professor of nutrition and epidemiology at the Harvard T. H. Chan School of Public Health, cites the response from the vitamin industry as "a situation where things worked right." Manufacturers quickly reduced the amount of vitamin A in their multivitamins, he says, "and without most people being aware of it, a huge number of hip fractures were prevented." Willett, who is a coauthor with Meyer of the new study, suggests that something similar may be in order for B_6 and possibly B_{12} and that an expert panel review would be a sensible next step. "We might deal with most of the problem just by bringing down the level of B_6 [in supplements] to the RDA level," he explains. B_{12} is a more complex matter, however. Ten to 30 percent of adults older than age 50 need extra B_{12} because of poor absorption. Meyer points out that excess B_{12} alone does not seem to raise the risk of fracture.

The bottom line is that although vitamins and minerals are essential for health, more is not necessarily better. Research shows, for example, that taking large amounts of beta carotene (a vitamin A precursor) seems to accelerate lung cancer in smokers, even though the nutrient may have anticancer properties in other contexts. Like everything in nutrition, vitamins are complicated. Just consider the fact that B_6 plays a role in more than 100 different enzyme reactions. Perhaps because of that complexity, many seemingly logical uses of vitamins yield disappointing results. For instance, even though low blood levels of vitamin D correlate with greater risk of heart attacks and strokes, taking D supplements generally does not help, according to a 2019 analysis.

Vitamins are vital when your diet is deficient. Willett thinks a daily multivitamin is a sensible insurance policy. The irony, he observes, is that the people most apt to take lots of supplements are educated folks with a healthy diet—in other words, those who need them the least. SA

Illustration by Celia Krampien

Wade Roush is the host and producer of Soonish, a podcast about technology, culture, curiosity and the future. He is a co-founder of the podcast collective Hub & Spoke and a freelance reporter for print, online and radio outlets, such as *MIT Technology Review,* Xconomy, WBUR and WHYY.

Apple's Amazing New Screen

It will revamp our ideas of what a display can do

By Wade Roush

"The manner in which human sense perception is organized, the medium in which it is accomplished, is determined not only by nature but by historical circumstances," German cultural critic Walter Benjamin wrote in 1935. We see the world, he was saying, as if on a screen constructed by everyone who came before us.

Speaking of screens: Tucked into the product announcements at the Apple Worldwide Developers Conference in June was a new piece of gear that set hearts aflame among photographers, film editors and designers. It's a new Apple-built LCD screen, the Pro Display XDR, intended as the companion to Apple's new high-end Mac Pro. (They're both expected to be available this fall.)

I got a close-up look, and everything about it is eye-popping: its resolution (6,016 by 3,384 pixels, or "6K"); brightness (peaking at about 30 times brighter than a movie screen and two to three times brighter than an average television); and contrast ratio (1,000,000:1—like a piece of white paper in sunlight as compared with the same paper in moonlight). And of course, its $4,999 price tag, which puts it squarely in the professional market.

But here's why you should care, even if your job doesn't depend on being able to see every last detail of the documentary you're shooting in 4K digital video. *In a world of mass-produced images, technology sets our visual expectations,* as Benjamin would have understood. Photography forced painters away from literal representations and toward impressionism and abstraction. Movies made photography look static. Color film made the black-and-white past look antique. High-definition TV made standard definition look grainy. And recent innovations, such as high dynamic range (HDR) photography and videography, can make older pictures seem flat and lifeless. Now along comes Apple, touting a screen so contrasty that the company decided the term "HDR" was insufficient—XDR stands for "extreme dynamic range."

Despite the name, though, providing greater dynamic range isn't just about showing deep blacks or vivid whites. It's about revealing more of the subtle detail often lost in light and shadows. In short, HDR imaging tries to depict the world the way the human eye can see it. Up to now, professionals needed reference monitors priced in the tens of thousands of dollars to experience graphics and video in their full HDR glory. Apple, as it has done before with high-pixel-count "retina" screens, is nudging this technology into the realm where it might be affordable to independent filmmakers, small design studios, radiology practices or science laboratories—anyone for whom details and fidelity count.

Apple reached deep into its bag of tricks to make the Pro Display work. For one thing, the screen is illuminated by an array of 576 blue LEDs rather than the strips of white LEDs around the borders of traditional displays. Because blue light can be emitted by a single chip, it can be controlled more precisely than white light, according to Vincent Gu, the Apple display engineer who leads one of the teams behind the project. The blue light hits a color-correction sheet and "goes through a quantum physics transformation" that converts it into wide-spectrum light, he says.

And the display itself is a computer. A new timing controller modulates not just the LCD pixels but the light sources behind them—analyzing content and turning the LEDs all the way off in places where the image should be black, for example. "The algorithm inside of that timing controller is harmoniously orchestrating all this," Gu says. "We're doing a lot of heavy computation. But we do not manipulate what the user intended."

Colleen Novielli, part of the Mac marketing team, says Apple's goal is to help video editors, photographers, 3-D animators, and others understand precisely how their work will look once it reaches end users on a movie screen or a printed page. "Everyone will be able to truly do their best work because they can see what they're supposed to be seeing," Novielli told me.

But given the pace of change in the electronics industry, it seems likely that similar technology will inevitably filter down to the consumer level, perhaps changing what we all expect. As Benjamin marveled, "The enlargement of a snapshot does not simply render more precise what in any case was visible, though unclear: it reveals entirely new structural formations of the subject." In the screen is our new reality. SA

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Illustration by Jay Bendt

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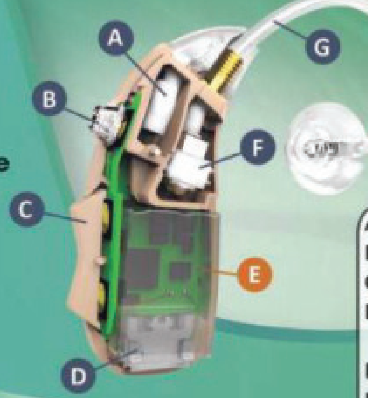

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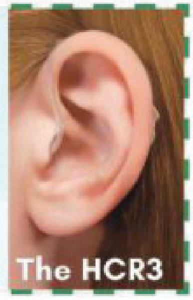

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TRUTH LIES & UNCERTAINTY

On July 8 President Donald Trump stood in the East Room of the White House and delivered a speech celebrating his administration's environmental leadership. Flanked by his Secretary of the Interior David Bernhardt, a former oil and gas lobbyist, and EPA head Andrew Wheeler, a former coal lobbyist, Trump extolled his team's stewardship of public lands, its efforts to ensure "the cleanest air and cleanest water," and its success in reducing carbon emissions. In reality, Trump has opened up millions of acres to drilling and mining and sought to reverse multiple air- and water-pollution regulations. As for carbon emissions, they spiked an estimated 3.4 percent last year, and this administration is withdrawing the U.S. from the Paris climate change agreement that nearly every other nation on the planet is participating in.

The speech was surreal but apparently strategic: It came on the heels of polls showing that Americans are growing increasingly worried about the environment. It remains to be seen whether Trump will sway environmentally concerned voters by using false claims, but clearly his team thinks that's a possibility. Truly we live in interesting times. How did we get here, and how do we get out?

In this special issue of *Scientific American,* we set out to explore how it is that we can all live in the same universe yet see reality so differently. Basic science illuminates the deep roots of this phenomenon. Even in physics and mathematics, truth is not entirely clear-cut. And mounting evidence from neuroscience indicates that our perceptions are not direct representations of the external world. Rather our brains—each one unique—make guesses about reality based on the sensory signals they receive.

Still, there can be no doubt that factors specific to our modern era are exacerbating our collective unmooring—technological developments that abet the warping of truth and the normalization of lies. Social media amplifies toxic misinformation on an unprecedented scale. Cyberattacks on election machinery and voter-registration systems threaten not only election outcomes but democracy itself.

Uncertainty in the world makes us all the more susceptible to such campaigns. But it's not all doom and gloom. By understanding how we instinctively deal with unknowns and how bad actors exploit the information ecosystem, we can mount defenses against weaponized narratives—and build mutual understanding to solve society's most pressing challenges.

—Seth Fletcher, Jen Schwartz and Kate Wong, Issue Editors

INSIDE

Illustration by Red Nose Studio

PART I:

TRUTH

Illustration by Red Nose Studio

PHYSICS

VIRTUALLY REALITY

HOW CLOSE CAN PHYSICS BRING US TO A TRULY FUNDAMENTAL UNDERSTANDING OF THE WORLD?

By George Musser

George Musser is a contributing editor to *Scientific American* and author of *Spooky Action at a Distance* (Farrar, Straus and Giroux, 2015) and *The Complete Idiot's Guide to String Theory* (Alpha, 2008).

Physics seems to be one of the only domains of human life where truth is clear-cut. The laws of physics describe hard reality. They are grounded in mathematical rigor and experimental proof. They give answers, not endless muddle. There is not one physics for you and one physics for me but a single physics for everyone and everywhere. Physics often seems weird, but that's a good sign—it is not beholden to preconceptions. In a world that can seem claustrophobic, where the same debates go round in circles, physics injects some genuine novelty into life and jolts us out of the ruts we fall into.

Physics is also the bedrock of the broader search for truth. If you follow the chains of explanation in other sciences, you eventually wind up in physics. The success of physics and its role in grounding other sciences support a broadly naturalistic, or physicalist, worldview: that all phenomena have physical explanations and that notions such as élan vital or incorporeal souls have no place in serious thought anymore. Physics does not dictate how we run our lives or resolve pressing moral dilemmas, but it sets the backdrop against which we decide these questions.

Yet if physics strikes most people as truth seeking at its purest, it doesn't always seem that way to physicists themselves. They sometimes seem to be struck by a collective imposter syndrome. Although they may presume that the truth is out there and they are capable of finding it—they have to, or what would be the point?—they have their doubts, which surface in informal discussions, at conferences devoted to the broad direction of their subject, in renewed efforts to reach out to philosophers for help, and in books and blogs for the general public. These worries are most acute in fundamental physics, which is not the entire subject but does play an outsized role in it. Many fret that the Large Hadron Collider has yet to turn up any new phenomena, giving them nothing to work with to derive the next level of laws. They worry whether proposed unified theories, such as string theory, can ever be tested. Some deem their subject overly mathematical; others think it mathematically sloppy. Truth can be elusive even in the best-established theories. Quantum mechanics is as well tested a theory as can be, yet its interpretation remains inscrutable.

Illustration by Brook VanDevelder

A bench scientist faces more concrete problems. Is a wire broken? Is the code buggy? Is the measurement a statistical fluke? Still, even these prosaic worries can be surprisingly subtle, and they are not entirely divorced from the overarching questions of physics. Everything must be judged within a broader framework of knowledge.

Many physicists take these troubles to mean that their field has gone astray and that their colleagues are too blinkered to notice. But another reading is that the elusiveness of truth is an important clue. Unlike other domains of human life, the difficulties with truth that physicists face come not from dissembling but from brutal honesty: from being completely frank about our limitations when we come face to face with reality. Only by confronting those limitations can we overcome them.

MISGIVINGS ABOUT THE PROGRESS of physics are hardly new. As long as there have been physicists, there have been physicists who worry their field has come up against an insuperable barrier. Research is always a muddle when you're in the thick of it. It seems remarkable that we humans could understand reality at all, so any roadblock could well be a sign our luck has finally run out.

Over the generations, physicists have oscillated between self-assurance and skepticism, periodically giving up on ever finding the deep structure of nature and downgrading physics to the search for scraps of useful knowledge. Pressed by his contemporaries to explain how gravity works, Isaac Newton responded: "I frame no hypotheses." Niels Bohr, commenting on quantum mechanics, wrote: "Our task is not to penetrate into the essence of things, the meaning of which we don't know anyway, but rather to develop concepts which allow us to talk in a productive way about phenomena in nature." Both men's views were complicated: Newton did, in fact, frame several hypotheses for gravity, and Bohr at other times said that quantum theory captured reality. On the whole, though, they made progress by setting aside grand questions of why the world is as it is.

Historically, physicists eventually do return to those questions. Newton failed to explain gravity, but later generations took up the challenge, culminating with Einstein's general theory of relativity. The interpretation of quantum mechanics came back onto the physics agenda in the 1960s and, though unsettled, has spun off practical ideas such as quantum cryptography. What reawakens physicists' curiosity is the sense that, as the late philosopher Hilary Putnam put it, the success of physics theories would be miraculous if they were not attuned to reality. Even more basically, how can we be doing experiments if there isn't something real to do them on? This position is known as realism. It holds that entities we do not directly observe but infer theoretically—such as atoms, particles, and space and time—really do exist. Theories are true because they reflect reality, albeit imperfectly. The cycling between realism and the opposing position, antirealism, will undoubtedly continue, as each evolves under pressure from the other.

This competition has been good for physics. Antirealist physicist-philosopher Ernst Mach inspired Einstein to rethink how we know what we know—or think we know. That set the course for all that followed in physics. When we accept we see the world through colored lenses, we can compensate. Some features of reality are relative to an observer, whereas others are common to all observers. Two people moving at different speeds may disagree on the distance between places, the duration of an event or, in some cases, which of two events came first. The dispute between them is unresolvable. But the arithmetic combination of distance and duration—the spatiotemporal distance—is a fact common to both, an "invariant." Invariants define objective truth.

IN ADDITION TO THE GENERIC CONCERNS that physicists of the past shared, physicists today have come up against many specific and unexpected limits to knowledge. Almost no matter which interpretation of quantum mechanics you choose, some things about the quantum world are beyond us. For instance, if you shoot a photon at a half-silvered mirror, it might pass through, or it might reflect off, and there's no way you can tell what it will do. The outcome is decided randomly. Some think the photon does what it does for no reason at all; the randomness is intrinsic. Others think there is some hidden reason. Still others think the photon both passes through and reflects, but we are able to see only one of these outcomes. Whichever it is, the underlying causes are cloaked.

Particles are easy to manipulate, which is why quantum physics is commonly described in terms of particles. But most physicists think the same rules apply to all things, even living things. Thus, it is not clear when the photon makes its choice to pass through or reflect, if indeed it ever chooses. When it hits the mirror, the combined system of the two enters a state of indecision. When a measuring device registers the path, it, too, is caught between the possibilities. If you send your friend to see what has happened, to you that person sees both eventualities. Physicists have yet to find any threshold of size or complexity of a system that forces the outcome. (Size and complexity are important in defining what the options are, but not in the final selection.) For now they know of only one place where the ambiguity is resolved: in our own conscious perception. We never experience photons doing two mutually contradictory things at once. Therefore, physicists are left with an unwanted element of subjectivity in their theory.

To Christopher A. Fuchs of the University of Massachusetts Boston, the lesson is that observers are active participants in nature, helping to construct what they observe, and a fully third-person perspective is impos-

IN BRIEF

Physics may seem focused on the objective determination of facts. Yet the field has just as many—perhaps more—struggles with the notion of truth as any other discipline.

Quantum mechanics, for instance, suggests that particles have no definite reality—by most interpretations, their properties are undecided until measured.

Lately scientists are interested in how the uncertainties of physics affect one of the largest uncertainties of science—the question of how consciousness operates.

sible. The mathematics of quantum theory jumbles together subjective and objective elements. His "QBist" interpretation tries to strip away the subjective elements and reveal the real structure that lies within, much as Einstein did with relativity theory.

Philosopher Richard Healey of the University of Arizona has a related "pragmatist" view that quantum theory is a representation not of the world but of the interface between the world and a human or another agent. We can use it to judge the probabilities of things that might happen, just as a technical stock trader buys and sells based on market trends rather than economic fundamentals. Such a trader can become rich without a clue what the companies are doing. Unlike Fuchs, Healey doesn't think that a description of physical reality is tucked inside quantum theory. That, he thinks, will require an entirely new theory.

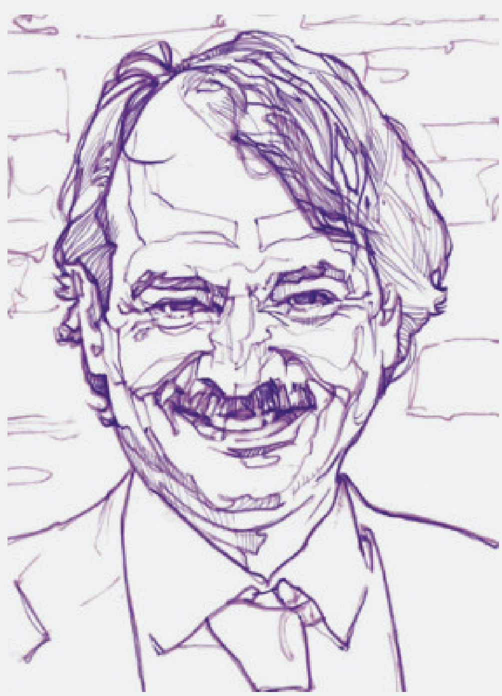
At the opposite pole, if you do take quantum theory to be a representation of the world, you are led to think of it as a theory of co-existing alternative realities. Such multiple worlds or parallel universes also seem to be a consequence of cosmological theories: the same processes that gave rise to our universe should beget others as well. Additional parallel universes could exist in higher dimensions of space beyond our view. Those universes are populated with variations on our own universe. There is not a single definite reality.

Although theories that predict a multiverse are entirely objective—no observers or observer-dependent quantities appear in the basic equations—they do not eliminate the observer's role but merely relocate it. They say that our view of reality is heavily filtered, and we have to take that into account when applying the theory. If we do not see a photon do two contradictory things at once, it does not mean the photon is not doing both. It might just mean we get to see only one of them. Likewise, in cosmology, our mere existence creates a bias in our observations. We necessarily live in a universe that can support human life, so our measurements of the cosmos might not be fully representative.

Parallel universes do not alter the truth that we experience. If you suffer in this universe, it is little comfort that near duplicates of you thrive elsewhere. But these other worlds are corrosive to the pursuit of broader truth. Because the other universes are generally not observable, they represent an insuperable limit to our direct knowledge. If those universes are utterly unlike our own, our empirical knowledge is not merely limited but deceived. The laws of physics risk descending into anarchy: they do not say that one thing happens rather than another, because both happen, and which we see is blind luck. The distinction between fact and fiction is just a matter of location.

EVEN SOME ASPECTS of fundamental physics that seem firmly established are surprisingly subtle. Physicists routinely speak of particles and fields: localized motes of matter and continuous, fluidlike entities such as the

HOW A PHYSICIAN SEARCHES FOR ANSWERS



The answer to questions about human life isn't a certain thing, like measuring how a stone drops to the ground in exactly so many seconds. If it were, it probably would not be life. It would be a stone. Within biomedicine, it's tricky finding out if an effect is real—there are different standards across different fields. Not all tools will work for every question, and there are different levels of complexity for what we know before we even start a study.

Still, the one core dimension across biomedicine is the ability to replicate, in a new study, what was seen in the first investigation. For many years in the field, we have been discouraged from doing this. Why waste money to do the exact thing you had done before, let alone something someone else had done before? But many researchers are realizing it is not possible to leave out replication studies.

To make replication work, though, it is essential to have a detailed explanation of how the original study was done. You need the instructions, the raw data and maybe even some custom-built computer software. For a long time, scientists didn't want to share that information, but that is changing. Science is a communal effort, and we should default to being open and sharing.

John P. A. Ioannidis, a professor of medicine at Stanford University, as told to Brooke Borel

Illustration by Bud Cook

electric or magnetic field. Yet their theories indicate that no such things can exist. The combination of quantum mechanics with relativity theory rules out particles: according to several mathematical theorems, nothing can be localized in the way that the traditional concept of a particle implies. The number of particles that observers will see depends on their own state of motion; it is not invariant and therefore does not qualify as an objective fact. Groups of particles can have collective properties above and beyond the properties of the individuals.

Fields, too, are not what they appear to be. Modern quantum theories long ago did away with electric and magnetic fields as concrete structures and replaced them with a hard-to-interpret mathematical abstraction. Among its many odd features, the abstraction is highly redundant; it is more complex than the real phenomena it is meant to represent. Physicists have sought alternative structures that align with reality, but those structures are no longer really fields. For now they continue to describe the world in terms of particles and fields, aware that the full story still eludes them.

Truth can be elusive even in the best-established theories. Quantum mechanics is as well tested a theory as can be, yet its interpretation remains inscrutable.

Proposed unified theories of physics introduce new complications. String theory, in particular, has been controversial. It goes all in on parallel universes, with all their strange consequences for truth. It also relies heavily on so-called dualities: different mathematical expressions that make the same predictions for observations, indicating they are alternative ways to describe the same situation. These dualities are powerful because they allow for lateral thinking. If an equation is too hard to solve, you can use a duality to translate it into a simpler one. But if multiple mathematical formulations are equivalent, how do we know which, if any, corresponds to reality?

Many critics of string theory complain that no known instrument can test it because it involves such minuscule effects. But that criticism applies equally to its competitors. This is the curse of success. There are not a lot of cracks in existing theories that could let us see through to a deeper level. Lacking experimental guidance, physicists have had to develop these theories mathematically. Quantum mechanics and relativity theory are so tightly constraining that they are almost enough on their own to dictate the form of the unified theory. Nevertheless, all the proposed theories rely heavily on judgment calls about beauty and elegance that might turn out to be wrong.

A strange tendency is built into the entire project of unification. The deeper physicists dive into reality, the more reality seems to evaporate. If distinct things are manifestations of the same underlying stuff, their distinctness must be a product of how they behave rather than their intrinsic nature. Physical explanation replaces nouns with verbs: what things are is a product of what their components do. String theory may not be right, but it illustrates the trend. According to it, the vast zoo of particle species are different vibration patterns of a single type of primitive and featureless thing called a string. Taken to its logical end, this reasoning suggests that no nouns will be left at all.

Some philosophers conclude that the entire category of "thing" is misguided. According to a view known as structural realism, relations are the primary ingredient of nature, and what we perceive as things are hubs of relations. This view has its oddities, however. What differentiates physical from mathematical objects or a simulation from the original system? Both involve the same sets of relations, so there seems to be nothing to tell them apart. And if there are no nouns, then what is acting out the verbs? Is physics built on quicksand?

IT IS NOT JUST THE PHYSICS problems that make physicists wonder whether they are on the right track. Many have gotten interested in consciousness, drawn by the so-called hard problem of consciousness. The methods of science seem inherently incapable of describing subjective experience. Our inner mental life is hidden from external observation and does not seem reducible to mathematical description. It strikes many researchers as an unnecessary add-on with no place in the physical scheme of things. By this argument, some researchers say understanding the mind could demand some new principle of science or new way of thinking. Physicists are intrigued that their basic picture of the world could be missing something so important.

That is not the only reason that physicists have been giving thought to the mind. The multiverse is one example of how we may perceive a filtered version of reality, and once you start down this path of wondering how truth might be skewed, you might entertain possibilities that make the multiverse sound tame. Immanuel Kant argued that the structure of our minds conditions what we perceive. In that tradition, physicist Markus Müller of the Institute for Quantum Optics and Quantum Information in Vienna and cognitive scientist Donald Hoffman of the University of California, Irvine, among others, have argued that we

perceive the world as divided into objects situated within space and time, not necessarily because it has this structure but because that is the only way we *could* perceive it.

Just because our brains navigate the world successfully does not mean they capture its structure faithfully. In machine learning, researchers have found that computer systems are often better at making predictions or controlling equipment when they eschew direct representations of the world. Similarly, reality might be completely unlike what our minds or our theories present to us. Scholars such as philosopher Colin McGinn and Harvard University psychologist Steven Pinker have suggested that our particular style of reasoning is why we find consciousness so hard. Perhaps one day we will construct artificial minds that see right through the problems that stump us, although they might get hung up on those we think are easy.

If anything restores confidence that truth is within our grasp, it is that we can divide and conquer. Although "real" is sometimes equated with "fundamental," each of the multiple levels of description in science has an equal claim to be considered real. Therefore, even if things vanish at the roots of nature, we are perfectly entitled to think of things in daily life. Even if quantum mechanics is mystifying, we can build a solid understanding of the world on it. And even if we worry that we aren't experiencing the fundamental reality, we are still experiencing *our* reality, and there's plenty to study there.

If we find that our theories are clutching at vapors, that's not a bad thing. It's reminding us to be humble. Physicists can be full of themselves, but the most experienced and accomplished among them are usually circumspect. They tend to be the first people to point out the problems with their own ideas, if only to avoid the embarrassment of someone else doing it for them. No one ever said that finding the truth would be easy. ■

MORE TO EXPLORE

A Fight for the Soul of Science. Natalie Wolchover in *Quanta Magazine.* Published online December 16, 2015. **www.quantamagazine.org/physicists-and-philosophers-debate-the-boundaries-of-science-20151216**

Lost in Math: How Beauty Leads Physics Astray. Sabine Hossenfelder. Basic Books, 2018.

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FROM OUR ARCHIVES

Parallel Universes. Max Tegmark; May 2003.

Quantum Weirdness? It's All in Your Mind. Hans Christian von Baeyer; June 2013.

What Is Real? Meinard Kuhlmann; August 2013.

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MATHEMATICS

NUMBERS GAME

PHILOSOPHERS CANNOT AGREE ON WHETHER MATHEMATICAL OBJECTS EXIST OR ARE PURE FICTIONS

By Kelsey Houston-Edwards

When I tell someone I am a mathematician, one of the most curious common reactions is: "I really liked math class because everything was either right or wrong. There is no ambiguity or doubt." I always stutter in response. Math does not have a reputation for being everyone's favorite subject, and I hesitate to temper anyone's enthusiasm. But math is full of uncertainties—it just hides them well.

Of course, I understand the point. If your teacher asks whether 7 is a prime number, the answer is definitively "yes." By definition, a prime number is a whole number greater than 1 that is only divisible by itself and 1, such as 2, 3, 5, 7, 11, 13, and so on. Any math teacher, anywhere in the world, anytime in the past several thousand years, will mark you correct for stating that 7 is prime and incorrect for stating that 7 is not prime. Few other disciplines can achieve such incredible consensus. But if you ask 100 mathematicians what explains the truth of a mathematical statement, you will get 100 different answers. The number 7 might really exist as an abstract object, with primality being a feature of that object. Or it could be part of an elaborate game that mathematicians devised. In other words, mathematicians agree to a remarkable degree on whether a statement is true or false, but they cannot agree on what exactly the statement is about.

One aspect of the controversy is the simple philosophical question: Was mathematics discovered by humans, or did we invent it? Perhaps 7 is an actual object, existing independently of us, and mathematicians are discovering facts about it. Or it might be a figment of our imaginations

whose definition and properties are flexible. The act of doing mathematics actually encourages a kind of dual philosophical perspective, where math is treated as both invented and discovered.

This all seems to me a bit like improv theater. Mathematicians invent a setting with a handful of characters, or objects, as well as a few rules of interaction, and watch how the plot unfolds. The actors rapidly develop surprising personalities and relationships, entirely independent of the ones mathematicians intended. Regardless of who directs the play, however, the denouement is always the same. Even in a chaotic system, where the endings can vary wildly, the same initial conditions will always lead to the same end point. It is this inevitability that gives the discipline of math such notable cohesion. Hidden in the wings are difficult questions about the fundamental nature of mathematical objects and the acquisition of mathematical knowledge.

INVENTION

HOW DO WE KNOW whether a mathematical statement is correct or not? In contrast to scientists, who usually try to infer the basic principles of nature from observations, mathematicians start with a collection of objects and rules and then rigorously demonstrate their consequences. The result of this deductive process is called a proof, which often builds from simpler facts to a more complex fact. At first glance, proofs seem to be key to the incredible consensus among mathematicians.

But proofs confer only conditional truth, with the truth of the conclusion depending on the truth of the assumptions. This is the problem with the common idea that consensus among mathematicians results from the proof-based structure of arguments. Proofs have core assumptions on which everything else hinges—and many of the philosophically fraught questions about mathematical truth and reality are actually about this starting point. Which raises the question: Where do these foundational objects and ideas come from?

Often the imperative is usefulness. We need numbers, for example, so that we can count (heads of cattle, say) and geometric objects such as rectangles to measure, for example, the areas of fields. Sometimes the reason is aesthetic—how interesting or appealing is the story that results? Altering the initial assumptions will sometimes unlock expansive structures and theories, while precluding others. For example, we could invent a new system of arithmetic where, by fiat, a negative number times a negative number is negative (easing the frustrated explanations of math teachers), but then many of the other, intuitive and desirable properties of the number line would disappear. Mathematicians judge foundational objects (such as negative numbers) and their properties (such as the result of multiplying them together) within the context of a larger, consistent mathematical landscape. Before proving a new theorem, therefore, a mathematician needs to watch the play unfold. Only then can the theorist know what to prove: the inevitable, unvarying conclusion. This gives the process of doing mathematics three stages: invention, discovery and proof.

The characters in the play are almost always constructed out of simpler objects. For example, a circle is defined as all points equidistant from a central point. So its definition relies on the definition of a point, which is a simpler type of object, and the distance between two points, which is a property of those simpler objects. Similarly, multiplication is repeated addition, and exponentiation is repeated multiplication of a number by itself. In consequence, the properties of exponentiation are inherited from the properties of multiplication. Conversely, we can learn about complicated mathematical objects by studying the simpler objects they are defined in terms of. This has led some mathematicians and philosophers to envision math as an inverted pyramid, with many complicated objects and ideas deduced from a narrow base of simple concepts.

In the late 19th and early 20th centuries a group of mathematicians and philosophers began to wonder what holds up this heavy pyramid of mathematics. They worried feverishly that math has no foundations—that nothing was grounding the truth of facts like $1 + 1 = 2$. (An obsessive set of characters, several of them struggled with mental illness.) After 50 years of turmoil, the expansive project failed to produce a single, unifying answer that satisfied all the original goals, but it spawned various new branches of mathematics and philosophy.

Some mathematicians hoped to solve the foundational crisis by producing a relatively simple collection of axioms from which all mathematical truths can be derived. The 1930s work of mathematician Kurt Gödel, however, is often interpreted as demonstrating that such a reduction to axioms is impossible. First, Gödel showed that any reasonable candidate system of axioms will be incomplete: mathematical statements exist that the system can neither prove nor disprove. But the most devastating blow came in Gödel's second theorem about the incompleteness of mathematics. Any foundational system of axioms should be consistent—meaning, free of statements that can be both proved and disproved. (Math would be much less satisfying if we could prove that 7 is prime and 7 is not prime.) Moreover, the system should be able to prove—to mathematically guarantee—its own consistency. Gödel's second theorem states that this is impossible.

The quest to find the foundations of mathematics did lead to the incredible discovery of a system of basic axioms, known as Zermelo-Fraenkel set theory, from which one can derive most of the interesting and relevant mathematics. Based on sets, or collections of objects, these axioms are not the idealized foundation that some historical mathematicians and philosophers had hoped for, but they are remarkably simple and do undergird the bulk of mathematics.

Kelsey Houston-Edwards is an assistant professor of mathematics at the Olin College of Engineering. She wrote and hosted the online *PBS Infinite Series* and was a AAAS Mass Media Fellow at *NOVA Next*.

IN BRIEF

Mathematicians tend to hold two simultaneous and incompatible views of the objects they study.

Prime numbers, for example, have surprising relations with one another that mathematicians are still discovering.

Such explorations, of what appears to be an alien landscape, encourage the idea that mathematical objects exist independently of humans.

If mathematical objects are real, however, why can one not touch, see or otherwise interact with them? Such questions often lead mathematicians to postulate that, in fact, the world of mathematical objects is fictitious.

Illustration by Brook VanDevelder

HOW A HISTORICAL LINGUIST SEARCHES FOR ANSWERS

Like any scientist, linguists rely on the scientific method. One of the principal goals of linguistics is to describe and analyze languages to discover the full range of what is possible and not possible in human languages. From this, linguists aim to reach their goal of understanding human cognition through the capacity for human language.

So there is an urgency to efforts to describe endangered languages, to document them while they are still in use, to determine the full range of what is linguistically possible. There are around 6,500 known human languages; around 45 percent of them are endangered.

Linguists use a specific set of criteria to identify endangered languages and to determine just how endangered a language is: Are children still learning the language? How many individual people speak it? Is the percentage of speakers declining with respect to the broader population? And are the contexts in which the language is used decreasing?

The question of scientific objectivity and "truth" is connected to endangered language research. Truth, in a way, is contextual. That is, what we hold to be true can change as we get more data and evidence or as our methods improve. The investigation of endangered languages often discovers things that we did not know were possible in languages, forcing us to reexamine previous claims about the limits of human language, so that sometimes what we thought was true can shift.

Lyle Campbell, an emeritus professor of linguistics at the University of Hawaii at Mānoa, as told to Brooke Borel

Throughout the 20th century mathematicians debated whether Zermelo-Fraenkel set theory should be augmented with an additional rule, known as the axiom of choice: If you have infinitely many sets of objects, then you can form a new set by choosing one object from each set. Think of a row of buckets, each containing a collection of balls, and one empty bucket. From each bucket in the row, you can choose one ball and place it in the empty bucket. The axiom of choice would allow you to do this with an infinite row of buckets. Not only does it have intuitive appeal, it is necessary to prove several useful and desirable mathematical statements. But it also implies some strange things, such as the Banach-Tarski paradox, which states that you can break a solid ball into five pieces and reassemble those pieces into two new solid balls, each equal in size to the first. In other words, you can double the ball. Foundational assumptions are judged by the structures they produce, and the axiom of choice implies many important statements but also brings extra baggage. Without the axiom of choice, math seems to be missing crucial facts, though with it, math includes some strange and potentially undesirable statements.

The bulk of modern mathematics uses a standard set of definitions and conventions that have taken shape over time. For example, mathematicians used to regard 1 as a prime number but no longer do. They still argue, however, whether 0 should be considered a natural number (sometimes called the counting numbers, natural numbers are defined as 0,1,2,3… or 1,2,3…, depending on who you ask). Which characters, or inventions, become part of the mathematical canon usually depends on how intriguing the resulting play is—observing which can take years. In this sense, mathematical knowledge is cumulative. Old theories can be neglected, but they are rarely invalidated, as they often are in the natural sciences. Instead mathematicians simply choose to turn their attention to a new set of starting assumptions and explore the theory that unfolds.

DISCOVERY

AS NOTED EARLIER, mathematicians often define objects and axioms with a particular application in mind. Over and over again, however, these objects surprise them during the second stage of the mathematical process: discovery. Prime numbers, for example, are the building blocks of multiplication, the smallest multiplicative units. A number is prime if it cannot be written as the product of two smaller numbers, and all the nonprime (composite) numbers can be constructed by multiplying a unique set of primes together.

In 1742 mathematician Christian Goldbach hypothesized that every even number greater than 2 is the sum of two primes. If you pick any even number, the so-called Goldbach conjecture predicts that you can find two prime numbers that add up to that even number. If you pick 8, those two primes are 3 and 5; pick 42, and that is 13 + 29. The Goldbach conjecture is surpris-

Illustration by Bud Cook

ing because although primes were designed to be multiplied together, it suggests amazing, accidental relations between even numbers and the *sums* of primes.

An abundance of evidence supports Goldbach's conjecture. In the 300 years since his original observation, computers have confirmed that it holds for all even numbers smaller than 4×10^{18}. But this evidence is not enough for mathematicians to declare Goldbach's conjecture correct. No matter how many even numbers a computer checks, there could be a counterexample—an even number that is not the sum of two primes—lurking around the corner.

Imagine that the computer is printing its results. Each time it finds two primes that add up to a specific even number, the computer prints that even number. By now it is a very long list of numbers, which you can present to a friend as a compelling reason to believe the Goldbach conjecture. But your clever friend is always able to think of an even number that is not on the list and asks how you know that the Goldbach conjecture is true for that number. It is impossible for all (infinitely many) even numbers to show up on the list. Only a mathematical proof—a logical argument from basic principles demonstrating that Goldbach's conjecture is true for every even number—is enough to elevate the conjecture to a theorem or fact. To this day, no one has been able to provide such a proof.

The Goldbach conjecture illustrates a crucial distinction between the discovery stage of mathematics and the proof stage. During the discovery phase, one seeks overwhelming evidence of a mathematical fact—and in empirical science, that is often the end goal. But mathematical facts require a proof.

Patterns and evidence help mathematicians sort through mathematical findings and decide what to prove, but they can also be deceptive. For example, let us build a sequence of numbers: 121, 1211, 12111, 121111, 1211111, and so on. And let us make a conjecture: all the numbers in the sequence are not prime. It is easy to gather evidence for this conjecture. You can see that 121 is not prime, because $121 = 11 \times 11$. Similarly, 1211, 12111 and 121111 are all not prime. The pattern holds for a while—long enough that you would likely get bored checking—but then it suddenly fails. The 136th element in this sequence (that is, the number 12111…111, where 136 "1"s follow the "2") is prime.

It is tempting to think that modern computers can help with this problem by allowing you to test the conjecture on more numbers in the sequence. But there are examples of mathematical patterns that hold true for the first 10^{42} elements of a sequence and then fail. Even with all the computational power in the world, you would never be able to test that many numbers.

Even so, the discovery stage of the mathematical process is extremely important. It reveals hidden connections such as the Goldbach conjecture. Often two entirely distinct branches of math are intensively studied in isolation before a profound relation between them is uncovered. A relatively simple example is Euler's identity, $e^{i\pi} + 1 = 0$, which connects the geometric constant π with the number i, defined algebraically as the square root of -1, via the number e, the base of natural logarithms. These surprising discoveries are part of the beauty and curiosity of math. They seem to point at a deep underlying structure that mathematicians are only beginning to understand.

In this sense, math feels both invented and discovered. The objects of study are precisely defined, but they take on a life of their own, revealing unexpected complexity. The process of mathematics therefore seems to require that mathematical objects be simultaneously viewed as real and invented—as objects with concrete, discoverable properties and as easily manipulable inventions of mind. As philosopher Penelope Maddy writes, however, the duality makes no difference to how mathematicians work, "as long as double-think is acceptable."

REAL OR UNREAL?

MATHEMATICAL REALISM is the philosophical position that seems to hold during the discovery stage: the objects of mathematical study—from circles and prime numbers to matrices and manifolds—are real and exist independently of human minds. Like an astronomer exploring a far-off planet or a paleontologist studying dinosaurs, mathematicians are gathering insights into real entities. To prove that Goldbach's conjecture is true, for example, is to show that the even numbers and the prime numbers are related in a particular way through addition, just like a paleontologist might show that one type of dinosaur descended from another by showing that their anatomical structures are related.

Realism in its various manifestations, such as Platonism (inspired by the Greek philosopher's theory of Platonic forms), makes easy sense of mathematics' universalism and usefulness. A mathematical object has a property, such as 7 being a prime number, in the same way that a dinosaur might have had the property of being able to fly. And a mathematical theorem, such as the fact that the sum of two even numbers is even, is true because even numbers really exist and stand in a particular relation to each other. This explains why people across temporal, geographical and cultural differences generally agree about mathematical facts—they are all referencing the same fixed objects.

But there are some important objections to realism. If mathematical objects really exist, their properties are certainly very peculiar. For one, they are causally inert, meaning they cannot be the cause of anything, so you cannot literally interact with them. This is a problem because we seem to gain knowledge of an object through its impact. Dinosaurs decomposed into bones that paleontologists can see and touch, and a planet can pass in front of a star, blocking its light from our view. But a circle is an abstract object, independent of space and time. The fact that π is the ratio of the circumference to the diameter of a circle is not

about a soda can or a doughnut; it refers to an abstract mathematical circle, where distances are exact and the points on the circle are infinitesimally small. Such a perfect circle is causally inert and seemingly inaccessible. So how can we learn facts about it without some type of special sixth sense?

That is the difficulty with realism—it fails to explain how we know facts about abstract mathematical objects. All of which might cause a mathematician to recoil from his or her typically realist stance and latch onto the first step of the mathematical process: invention. By framing mathematics as a purely formal mental exercise or a complete fiction, antirealism easily skirts problems of epistemology.

Formalism, a type of antirealism, is a philosophical position that asserts that mathematics is like a game, and mathematicians are just playing out the rules of the game. Stating that 7 is a prime number is like stating that a knight is the only chess piece that can move in an L shape. Another philosophical position, fictionalism, claims that mathematical objects are fictions. Stating that 7 is a prime number is then like stating that unicorns are white. Mathematics makes sense within its fictional universe but has no real meaning outside of it.

There is an inevitable trade-off. If math is simply made up, how can it be such a necessary part of science? From quantum mechanics to models of ecology, mathematics is an expansive and precise scientific tool. Scientists do not expect particles to move according to chess rules or the crack in a dinner plate to mimic Hansel and Gretel's path—the burden of scientific description is placed exclusively on mathematics, which distinguishes it from other games or fictions.

In the end, these questions do not affect the practice of mathematics. Mathematicians are free to choose their own interpretations of their profession. In *The Mathematical Experience,* Philip Davis and Reuben Hersh famously wrote that "the typical working mathematician is a Platonist on weekdays and a formalist on Sundays." By funneling all disagreements through a precise process—which embraces both invention and discovery—mathematicians are incredibly effective at producing disciplinary consensus. SA

MORE TO EXPLORE

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Where Proof, Evidence and Imagination Intersect. Patrick Honner in *Quanta Magazine.* Published online March 14, 2019.

FROM OUR ARCHIVES

Why Isn't 1 a Prime Number? Evelyn Lamb; ScientificAmerican.com, published online April 2, 2019.

scientificamerican.com/magazine/sa

NEUROSCIENCE

OUR INNER UNIVERSES

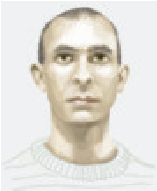
REALITY IS CONSTRUCTED BY THE BRAIN, AND NO TWO BRAINS ARE EXACTLY ALIKE

By Anil K. Seth

> **"We do not see things as they are, we see them as we are."**
>
> —from *Seduction of the Minotaur,* by Anaïs Nin (1961)

On the 10th of April this year Pope Francis, President Salva Kiir of South Sudan and former rebel leader Riek Machar sat down together for dinner at the Vatican. They ate in silence, the start of a two-day retreat aimed at reconciliation from a civil war that has killed some 400,000 people since 2013. At about the same time in my laboratory at the University of Sussex in England, Ph.D. student Alberto Mariola was putting the finishing touches to a new experiment in which volunteers experience being in a room that they believe is there but that is not. In psychiatry clinics across the globe, people arrive complaining that things no longer seem "real" to them, whether it is the world around them or their own selves. In the fractured societies in which we live, what is real—and what is not—seems to be increasingly up for grabs. Warring sides may experience and believe in different realities. Perhaps eating together in silence can help because it offers a small slice of reality that can be agreed on, a stable platform on which to build further understanding.

Illustration by Brook VanDevelder



Anil K. Seth is a professor of cognitive and computational neuroscience at the University of Sussex in England and co-director of the university's Sackler Center for Consciousness Science. His research focuses on the biological basis of consciousness.

IN BRIEF

The reality we perceive is not a direct reflection of the external objective world. **Instead it is the product** of the brain's predictions about the causes of incoming sensory signals.

The property of realness that accompanies our perceptions may serve to guide our behavior so that we respond appropriately to the sources of sensory signals.

We need not look to war and psychosis to find radically different inner universes. In 2015 a badly exposed photograph of a dress tore across the Internet, dividing the world into those who saw it as blue and black (me included) and those who saw it as white and gold (half my lab). Those who saw it one way were so convinced they were right—that the dress truly was blue and black or white and gold—that they found it almost impossible to believe that others might perceive it differently.

We all know that our perceptual systems are easy to fool. The popularity of visual illusions is testament to this phenomenon. Things seem to be one way, and they are revealed to be another: two lines appear to be different lengths, but when measured they are exactly the same; we see movement in an image we know to be still. The story usually told about illusions is that they exploit quirks in the circuitry of perception, so that what we perceive deviates from what is there. Implicit in this story, however, is the assumption that a properly functioning perceptual system will render to our consciousness things precisely as they are.

The deeper truth is that perception is never a direct window onto an objective reality. All our perceptions are active constructions, brain-based best guesses at the nature of a world that is forever obscured behind a sensory veil. Visual illusions are fractures in the Matrix, fleeting glimpses into this deeper truth.

Take, for example, the experience of color—say, the bright red of the coffee mug on my desk. The mug really does seem to be red: its redness seems as real as its roundness and its solidity. These features of my experience seem to be truly existent properties of the world, detected by our senses and revealed to our mind through the complex mechanisms of perception.

Yet we have known since Isaac Newton that colors do not exist out there in the world. Instead they are cooked up by the brain from mixtures of different wavelengths of colorless electromagnetic radiation. Colors are a clever trick that evolution has hit on to help the brain keep track of surfaces under changing lighting conditions. And we humans can sense only a tiny slice of the full electromagnetic spectrum, nestled between the lows of infrared and the highs of ultraviolet. Every color we perceive, every part of the totality of each of our visual worlds, comes from this thin slice of reality.

Just knowing this is enough to tell us that perceptual experience cannot be a comprehensive representation of an external objective world. It is both less than that and more than that. The reality we experience—the way things *seem*—is not a direct reflection of what is actually out there. It is a clever construction by the brain, for the brain. And if my brain is different from your brain, my reality may be different from yours, too.

THE PREDICTIVE BRAIN

IN PLATO'S Allegory of the Cave prisoners are chained to a blank wall all their lives, so that they see only the play of shadows cast by objects passing by a fire behind them, and they give the shadows names because for them the shadows are what is real. A thousand years later, but still a thousand years ago, Arabian scholar Ibn al-Haytham wrote that perception, in the here and now, depends on processes of "judgment and inference" rather than involving direct access to an objective reality. Hundreds of years later again Immanuel Kant realized that the chaos of unrestricted sensory data would always remain meaningless without being given structure by preexisting conceptions or "beliefs," which for him included a priori frameworks such as space and time. Kant's term "noumenon" refers to a "thing in itself"—*Ding an sich*—an objective reality that will always be inaccessible to human perception.

Today these ideas have gained a new momentum through an influential collection of theories that turn on the idea that the brain is a kind of prediction machine and that perception of the world—and of the self within it—is a process of brain-based prediction about the causes of sensory signals.

Our perceptions come from the inside out just as much as, if not more than, from the outside in.

These new theories are usually traced to German physicist and physiologist Hermann von Helmholtz, who in the late 19th century proposed that perception is a process of unconscious inference. Toward the end of the 20th century Helmholtz's notion was taken up by cognitive scientists and artificial-intelligence researchers, who reformulated it in terms of what is now generally known as predictive coding or predictive processing.

The central idea of predictive perception is that the brain is attempting to figure out what is out there in the world (or in here, in the body) by continually making and updating best guesses about the causes of its sensory inputs. It forms these best guesses by combining prior expectations or "beliefs" about the world, together with incoming sensory data, in a way that takes into account how reliable the sensory signals are. Scientists usually conceive of this process as a form of Bayesian inference, a framework that specifies how to update beliefs or best guesses with new data when both are laden with uncertainty.

In theories of predictive perception, the brain approximates this kind of Bayesian inference by continu-

ally generating predictions about sensory signals and comparing these predictions with the sensory signals that arrive at the eyes and the ears (and the nose and the fingertips, and all the other sensory surfaces on the outside and inside of the body). The differences between predicted and actual sensory signals give rise to so-called prediction errors, which are used by the brain to update its predictions, readying it for the next round of sensory inputs. By striving to minimize sensory-prediction errors everywhere and all the time, the brain implements approximate Bayesian inference, and the resulting Bayesian best guess is what we perceive.

To understand how dramatically this perspective shifts our intuitions about the neurological basis of perception, it is helpful to think in terms of bottom-up and top-down directions of signal flow in the brain. If we assume that perception is a direct window onto an external reality, then it is natural to think that the content of perception is carried by bottom-up signals—those that flow from the sensory surfaces inward. Top-down signals might contextualize or finesse what is perceived, but nothing more. Call this the "how things seem" view because it seems as if the world is revealing itself to us directly through our senses.

The prediction machine scenario is very different. Here the heavy lifting of perception is performed by the top-down signals that convey perceptual predictions, with the bottom-up sensory flow serving only to calibrate these predictions, keeping them yoked, in some appropriate way, to their causes in the world. In this view, our perceptions come from the inside out just as much as, if not more than, from the outside in. Rather than being a passive registration of an external objective reality, perception emerges as a process of active construction—a controlled hallucination, as it has come to be known.

Why controlled hallucination? People tend to think of hallucination as a kind of false perception, in clear contrast to veridical, true-to-reality, normal perception. The prediction machine view suggests instead a continuity between hallucination and normal perception. Both depend on an interaction between top-down, brain-based predictions and bottom-up sensory data, but during hallucinations, sensory signals no longer keep these top-down predictions appropriately tied to their causes in the world. What we call hallucination, then, is just a form of uncontrolled perception, just as normal perception is a controlled form of hallucination.

This view of perception does not mean that nothing is real. Writing in the 17th century, English philosopher John Locke made an influential distinction between "primary" and "secondary" qualities. Primary qualities of an object, such as solidity and occupancy of space, exist independently of a perceiver. Secondary qualities, in contrast, exist only in relation to a perceiver—color is a good example. This distinction explains why conceiving of perception as controlled hallucination does not mean it is okay to jump in front of a bus. This bus has primary qualities of solidity and space occupancy that exist independently of our perceptual machinery and that can do us injury. It is the way in which the bus appears to us that is a controlled hallucination, not the bus itself.

POORLY EXPOSED photograph of a dress appears blue and black to some people, white and gold to others.

SWIKED.TUMBLR.COM

TRIPPING IN THE LAB

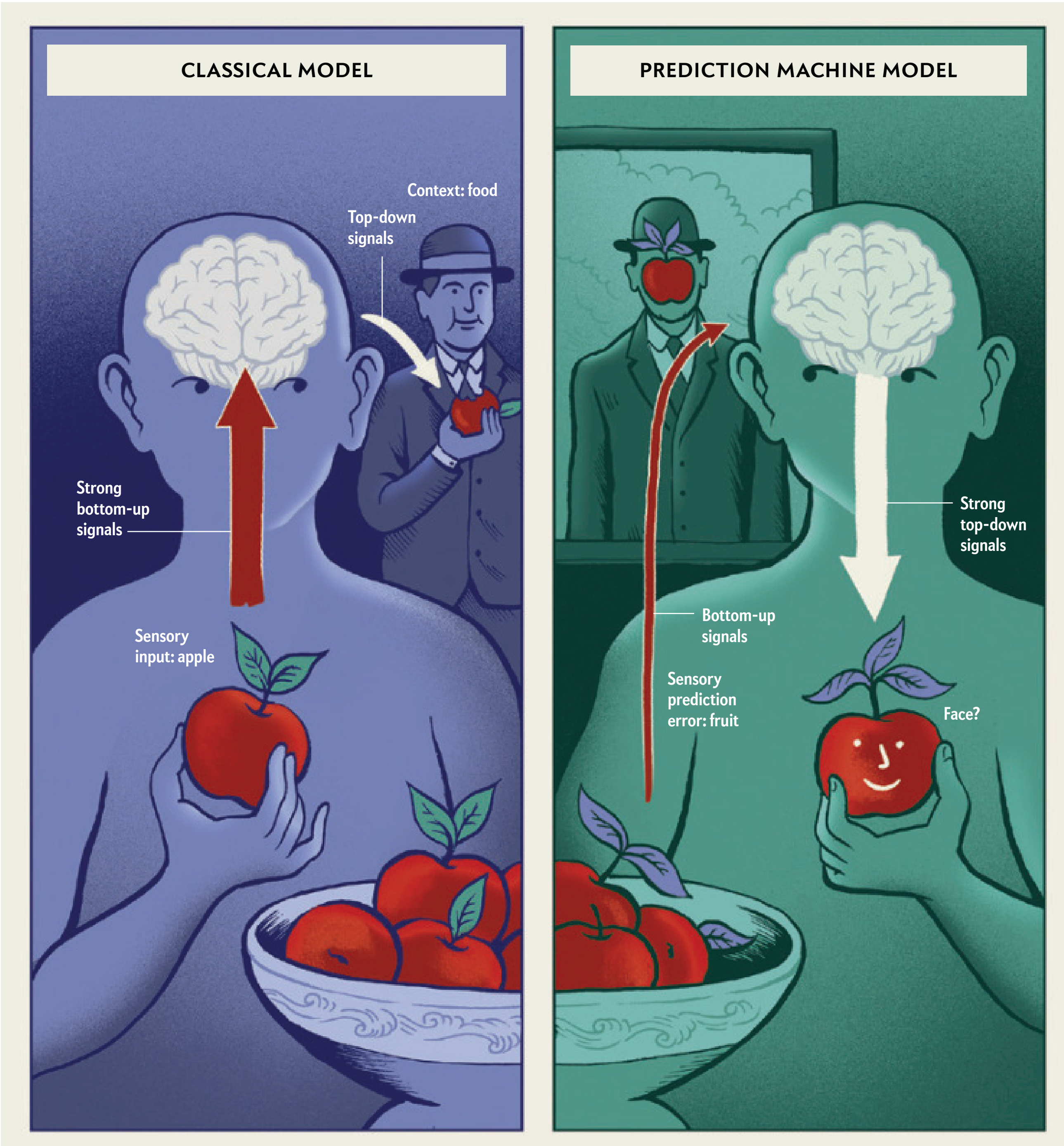
A GROWING BODY of evidence supports the idea that perception is controlled hallucination, at least in its broad outlines. A 2015 study by Christoph Teufel of Cardiff University in Wales and his colleagues offers a striking example. In this study, patients with early-stage psychosis who were prone to hallucinations were compared with healthy individuals on their ability to recognize so-called two-tone images.

Take a look at the photograph on page 45—a sample of a two-tone image. Probably all you will see is a bunch of black-and-white splotches. Now, after you have read the rest of this sentence, look at the image on page 47. Then have another look at the first photo; it ought to look rather different. Where previously there was a splotchy mess, there are now distinct objects, and something is happening.

What I find remarkable about this exercise is that in your second examination of the photo on page 45,

Origins of Perception

The classical view of perception (*blue panel*) holds that it is a direct window onto an external reality. Sensory signals flow from the bottom up, entering the brain through receptors in our eyes, ears, nose, tongue and skin to reveal the outside world to us as it is. Top-down signals within the brain serve only to finesse what is perceived. In the prediction machine view of perception (*green panel*), in contrast, perceptual content is carried by top-down predictions made by the brain based on prior experience. Bottom-up signals function mainly to convey prediction errors, which rein in the brain's hypotheses. Perception is thus a controlled hallucination in this model.



[redacted]

Illustration by Matteo Farinella

the sensory signals arriving at your eyes have not changed at all from the first time you saw it. All that has changed are your brain's predictions about the causes of these sensory signals. You have acquired a new high-level perceptual expectation, and this is what changes what you consciously see.

If you show people many of these two-tone images, each followed by the full picture, they might subsequently be able to identify a good proportion of two-tone images, though not all of them. In Teufel's study, people with early-stage psychosis were better at recognizing two-tone images after having seen the full image than were healthy control subjects. In other words, being hallucination-prone went along with perceptual priors having a stronger effect on perception. This is exactly what would be expected if hallucinations in psychosis depended on an overweighting of perceptual priors so that they overwhelmed sensory prediction errors, unmooring perceptual best guesses from their causes in the world.

TWO-TONE IMAGE looks like a mess of black-and-white splotches, until you see the full image on page 47.

RICHARD ARMSTRONG *Getty Images*

Recent research has revealed more of this story. Phil Corlett of Yale University and his colleagues paired lights and sounds in a simple design to engender expectations among their study subjects of whether or not a light would appear on a given experimental trial. They combined this design with brain imaging to uncover some of the brain regions implicated in predictive perception. When they looked at the data, Corlett and his team were able to identify regions such as the superior temporal sulcus, deep in the temporal lobe of the cortex, that were specifically associated with top-down predictions about auditory sensations. This is an exciting new development in mapping the brain basis of controlled hallucinations.

In my lab we have taken a different approach to exploring the nature of perception and hallucination. Rather than looking into the brain directly, we decided to simulate the influence of overactive perceptual priors using a unique virtual-reality setup masterminded by our resident VR guru, Keisuke Suzuki. We call it, with tongue firmly in cheek, the "hallucination machine."

Using a 360-degree camera, we first recorded panoramic video footage of a busy square in the University of Sussex campus on a Tuesday at lunchtime. We then processed the footage through an algorithm based on Google's AI program DeepDream to generate a simulated hallucination. What happens is that the algorithm takes a so-called neural network—one of the workhorses of AI—and runs it backward. The network we used had been trained to recognize objects in images, so if you run it backward, updating the network's input instead of its output, the network effectively projects what it "thinks" is there onto and into the image. Its predictions overwhelm the sensory inputs, tipping the balance of perceptual best guessing toward these predictions. Our particular network was good at classifying different breeds of dogs, so the video became unusually suffused by dog presences.

Many people who have viewed the processed footage through the VR headset have commented that the experience is rather reminiscent not of the hallucinations of psychosis but of the exuberant phenomenology of psychedelic trips.

By implementing the hallucination machine in slightly different ways, we could generate different kinds of conscious experience. For example, running the neural network backward from one of its middle layers, rather than from the output layer, leads to hallucinations of object parts, rather than whole objects. As we look ahead, this method will help us match specific features of the computational architecture of predictive perception to specific aspects of what experiences of hallucinations are like. And by understanding hallucinations better, we will be able to understand normal experience better, too, because predictive perception is at the root of all our perceptual experience.

THE PERCEPTION OF REALITY

ALTHOUGH THE HALLUCINATION MACHINE is undoubtedly trippy, people who experience it are fully aware that what they are experiencing is not real. Indeed, despite rapid advances in VR technology and computer graphics, no current VR setup delivers an experience that is sufficiently convincing to be indistinguishable from reality.

This is the challenge we took up when designing a

HOW A PALEOBIOLOGIST SEARCHES FOR ANSWERS

Our basic unit of truth in paleobiology is the fossil—a clear record of life in the past—and we also use genetic evidence from living organisms to help us put fossils within the tree of life. Together they help us understand how these creatures changed and how they are related. Because we are looking at extinct animals as they existed in a broader ecosystem, we pull in information from other fields: chemical analysis of surrounding rocks to get a sense of the fossil's age, where the world's landmasses might have been at the time, what kind of environmental changes were happening, and so on.

To discover fossils, we scour the landscape to find them among rocks. You can tell the difference between a fossil and any old rock by its shape and its internal structure. For example, a fossil bone will have tiny cylinders called osteons where blood vessels once ran through the bone. Some fossils are obvious: a leg of a dinosaur, a giant, complete bone. Smaller bits can be telling, too. For mammals, which I study, you can tell a lot from the shape of a single tooth. And we can combine this information with genetics, by using DNA samples from living creatures that we think are related to the fossils, based on anatomy and other clues.

We just don't do these investigations to reconstruct past worlds but also to see what they can tell us about our current world. There was a huge spike in temperature 55 million years ago, for example. It was nothing like today, but still, we've found radical changes in the animals and plants from that era. We can compare those changes to see how related creatures may respond to current climate change.

Anjali Goswami, a professor and research leader at the Natural History Museum in London, as told to Brooke Borel

new "substitutional reality" setup at Sussex—the one we were working on when Pope Francis convened the retreat with Salva Kiir and Riek Machar. Our aim was to create a system in which volunteers would experience an environment as being real—and believe it to be real—when in fact it was not real.

The basic idea is simple. We again prerecorded some panoramic video footage, this time of the interior of our VR lab rather than of an outside campus scene. People coming to the lab are invited to sit on a stool in the middle of the room and to put on a VR headset that has a camera attached to the front. They are encouraged to look around the room and to see the room as it actually is, via the camera. But at some point, without telling them, we switch the feed so that the headset now displays not the live real-world scene but rather the prerecorded panoramic video. Most people in this situation continue to experience what they are seeing as real even though it is now a fake prerecording. (This is actually very tricky to pull off in practice—it requires careful color balancing and alignment to avoid people noticing any difference that would tip them off to the shift.)

I find this result fascinating because it shows that it is possible to have people experience an unreal environment as being fully real. This demonstration alone opens new frontiers for VR research: we can test the limits of what people will experience, and believe, to be real. It also allows us to investigate how experiencing things as being real can affect other aspects of perception. Right now we are running an experiment to find out whether people are worse at detecting unexpected changes in the room when they believe that what they are experiencing is real. If things do turn out this way (the study is ongoing), that finding would support the idea that the perception of things as being real itself acts as a high-level prior that can substantively shape our perceptual best guesses, affecting the contents of what we perceive.

THE REALITY OF REALITY

THE IDEA THAT THE WORLD of our experience might not be real is an enduring trope of philosophy and science fiction, as well as of late-night pub discussions. Neo in *The Matrix* takes the red pill, and Morpheus shows him how what he thought was real is an elaborate simulation, while the real Neo lies prone in a human body farm, a brain-in-a-vat power source for a dystopian AI. Philosopher Nick Bostrom of the University of Oxford has famously argued, based largely on statistics, that we are likely to be living inside a computer simulation created in a posthuman age. I disagree with this argument because it assumes that consciousness can be simulated—I do not think this is a safe assumption—but it is thought-provoking nonetheless.

Although these chunky metaphysical topics are fun to chew on, they are probably impossible to resolve. Instead what we have been exploring throughout this article is the relation between appearance and reality in

Illustration by Bud Cook

our conscious perceptions, where part of this appearance is the appearance of being real itself.

The central idea here is that perception is a process of active interpretation geared toward adaptive interaction with the world through the body rather than a recreation of the world within the mind. The contents of our perceptual worlds are controlled hallucinations, brain-based best guesses about the ultimately unknowable causes of sensory signals. And for most of us, most of the time, these controlled hallucinations are experienced as real. As Canadian rapper and science communicator Baba Brinkman suggested to me, when we agree about our hallucinations, maybe that is what we call reality.

But we do not always agree, and we do not always experience things as real. People with dissociative psychiatric conditions such as derealization or depersonalization syndrome report that their perceptual worlds, even their own selves, lack a sense of reality. Some varieties of hallucination, various psychedelic hallucinations among them, combine a sense of unreality with perceptual vividness, as does lucid dreaming. People with synesthesia consistently have additional sensory experiences, such as perceiving colors when viewing black letters, which they recognize as not real. Even with normal perception, if you look directly at the sun you will experience the subsequent retinal afterimage as not being real. There are many such ways in which we experience our perceptions as not fully real.

What this means to me is that the property of realness that attends most of our perceptions should not be taken for granted. It is another aspect of the way our brain settles on its Bayesian best guesses about its sensory causes. One might therefore ask what purpose it serves. Perhaps the answer is that a perceptual best guess that includes the property of being real is usually more fit for purpose—that is, better able to guide behavior—than one that does not. We will behave more appropriately with respect to a coffee cup, an approaching bus or our partner's mental state when we experience it as really existing.

But there is a trade-off. As illustrated by the dress illusion, when we experience things as being real, we are less able to appreciate that our perceptual worlds may differ from those of others. (The leading explanation for the differing perceptions of the garment holds that people who spend most of their waking hours in daylight see it as white and gold; night owls, who are mainly exposed to artificial light, see it as blue and black.) And even if these differences start out small, they can become entrenched and reinforced as we proceed to harvest information differently, selecting sensory data that are best aligned with our individual emerging models of the world, and then updating our perceptual models based on these biased data. We are all familiar with this process from the echo chambers of social media and the newspapers we choose to read. I am suggesting that the same principles apply also at a deeper level, underneath our sociopolitical beliefs, right down to the fabric of our perceptual realities. They may even apply to our perception of being a self—the experience of being me or of being you—because the experience of being a self is itself a perception.

This is why understanding the constructive, creative mechanisms of perception has an unexpected social relevance. Perhaps once we can better appreciate the diversity of experienced realities scattered among the billions of perceiving brains on this planet, we will find new platforms on which to build a shared understanding and a better future—whether between sides in a civil war, followers of different political parties, or two people sharing a house and faced with washing the dishes. ■

PERCEPTUAL SHIFT: Viewing this photograph changes what one consciously sees in the two-tone image on page 45.

RICHARD ARMSTRONG *Getty Images*

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

PART 2:

LIES

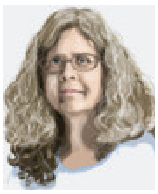
Illustration by Red Nose Studio

ANIMAL BEHAVIOR

DECEPTION IN THE WILD

HOMO SAPIENS IS NOT THE ONLY SPECIES THAT LIES. DISHONESTY ABOUNDS IN THE ANIMAL KINGDOM

By Barbara J. King



Barbara J. King is emerita professor of anthropology at the College of William and Mary. Her studies of monkeys and apes have led her to examine emotion and intelligence in a wide range of animal species.

The animal world seems to burst with sugar and spice these days. Evidence for cooperation and compassion among swimming, flying and walking creatures has captured public imagination. In the ocean, groupers, wrasse and eels form a multispecies team, working together to flush out and consume prey in bouts of collaborative hunting. In the sky, variegated fairy wrens and splendid fairy wrens recognize one another, form stable partnerships and jointly defend patches of eucalyptus scrubland. Among chickens, mother hens show empathetic distress when they see their chicks experience mild discomfort. Chimpanzees rush to console the loser of a fight, even when they themselves played no part in the altercation. And in an act of ultimate sacrifice, rats give up a chocolate reward to rescue companions made to tread water in a small pool.

IN BRIEF

Humans are not alone in their deceitful ways. A wide variety of animals have been found to carry out disinformation campaigns.

Animals may mislead members of their own species or other species via camouflage or mimicry.

When the false signaling is done with intent, it is called tactical deception—a strategy deployed by creatures ranging from cuttlefish to dogs.

For centuries scholars of animal behavior overemphasized the role of rivalry and violence among animals. The current focus on kindness and care is a necessary corrective to that long-standing view of nature as "red in tooth and claw," as poet Alfred, Lord Tennyson put it. Yet even as we swoon over animal sweetness, there is a risk of that pendulum swinging too far and eclipsing part of the story. Many animals carry out disinformation campaigns aimed at others, within and across species. They mislead, cheat and lie in rampant acts of deception.

INTENT TO DECEIVE

DECEPTION IN NONHUMAN ANIMALS is defined as the sending out of false signals in an attempt to modify the behavior of another animal in ways that benefit the sender. Cuttlefish are masters of such disinformation. Relatives of the octopus, they have the ability to quickly change color, thanks to pigment-containing cells in their skin called chromatophores. Their powers of disguise can make mating a turbulent affair. In 2017 marine biologists led by Justine Allen of Brown University reported that they had observed a male common European cuttlefish approach a female as they scuba-dived in the Aegean Sea off Turkey. The female moved away with apparent indifference. The male camouflaged himself against the background for six minutes, leaving the female seemingly unaware of his continued presence. Then, suddenly, he lunged and grabbed her, and the two mated head to head.

Illustration by Lisk Feng

HOW A SOCIAL TECHNOLOGIST SEARCHES FOR ANSWERS

The biggest epistemological question facing the field of machine learning is: What is our ability to test a hypothesis?

Algorithms learn to detect patterns and details from massive sets of examples—for instance, an algorithm could learn to identify a cat after seeing thousands of cat photographs. Until we have greater interpretability, we can test how a result was achieved by appealing conclusions from the algorithms. This raises the specter that we don't have real accountability for the results of deep-learning systems—let alone due process when it comes to their effects on social institutions. These issues are part of a live debate in the field.

Also, does machine learning represent a type of rejection of the scientific method, which aims to find not only correlation but also causation? In many machine-learning studies, correlation has become the new article of faith, at the cost of causation. That raises real questions about verifiability.

In some cases, we may be taking a step backward. We see this in the space of machine vision and affect recognition. These are systems that extrapolate from photographs of people to predict their race, gender, sexuality or likelihood of being a criminal. These sorts of approaches are both scientifically and ethically concerning—with echoes of phrenology and physiognomy. The focus on correlation should raise deep suspicions in terms of our ability to make claims about people's identity. That's a strong statement, by the way, but given the decades of research on these issues in the humanities and social sciences, it should not be controversial.

Kate Crawford, a distinguished research professor at New York University, co-founder of the AI Now Institute at N.Y.U. and member of Scientific American*'s board of advisers, as told to Brooke Borel*

In an Australian species called the mourning cuttlefish, deception goes beyond camouflage. When a male swims along between a female paramour on the left and a male competitor on the right, he displays two sets of signals containing polar-opposite information. From his left side he issues typical male courtship signals. On his right side, though, he emits the signals typical of a female. To his male competitor, then, this suitor appears to be just another female. Brilliant—and sneaky!

Biologist Culum Brown of Macquarie University in Sydney and his team call the mourning cuttlefish male's double signaling "tactical deception" because it is deployed with forethought. It occurs in a specific context (when a male courts a female in the presence of a single rival male). Camouflage, mimicry and tactical deception are three key types of animal deception, with blurred boundaries between categories, as the cuttlefish examples illustrate. When attempts to mislead are carried out intentionally, whether through camouflage, mimicry or some other behavior, that is tactical deception.

As visual primates, we humans may be biased toward recognizing deception based on misdirection of images. Yet other senses, too, may be tricked. A highly vocal bird called the fork-tailed drongo, a resident of the Kalahari Desert in Africa, emits alarm calls on sighting predators. Sometimes this is honest signaling that benefits not only other drongos but also the birds' neighbors: southern pied babblers and meerkats will dive for safety when they hear the drongo's calls. But other times drongos do something not as honest, even downright obnoxious. For instance, if a drongo spots a meerkat in possession of a particularly winsome food item such as a plump gecko, the bird may call falsely—in the absence of any predators at all. On hearing the call, the meerkat drops the food and flees to safety. The drongo then scoops up and consumes the gecko. Zoologist Tom P. Flower, now at Capilano University in British Columbia, and his colleagues have found that this type of food thievery results in nearly a quarter of the biomass intake of drongos. Any opportunity to up one's quota of stolen delicacies makes good evolutionary sense for these birds.

Drongos' penchant for pretending does not end there, though. Truthful signaling is the norm in the animal world. Too much disinformation offered to the same audience, and the jig will be up because a deceiver's social partners are likely to catch on. The "cry wolf" syndrome operates in other animals besides little boys, after all. Evolution has shaped the vocal repertoire of drongos accordingly: the birds have at least 51 different false alarms, which they vary during repeated food-theft attempts, according to Flower and his collaborators. In aiming to steal edibles from the same "targets" more than once, drongos change their alarm-call type nearly 75 percent of the time, and in a spectacular act of betrayal they often utter the alarm calls characteristic of their targets themselves. This strategic combination of vocal mimicry and tactical deception keeps the targets guessing, to the drongos' advantage. Like cuttlefish, drongos intend to deceive.

Illustration by Bud Cook

1

2

That is the hypothesis, at least. It is a reasonable notion because in both cases, false signals are broadcast not willy-nilly but only after thoughtful assessment of the animals' dynamic social world.

Given our own evolved tendencies toward intentional deception, it is no surprise that our closest living relatives, monkeys and apes, are among the prime animal con artists. Primatologist Frans de Waal of Emory University has recounted a time when Yeroen, a chimpanzee at the Arnhem Zoo in the Netherlands, limped only in the presence of his great rival Nikkie, a fake hobbling apparently meant to gain sympathy. Systematic research on chimpanzees and many kinds of monkeys shows that these primates think up innovative ways to distract and mislead social partners when there is a mating or food prize at stake that they want for themselves.

3

WILD LIARS: The common fruit fly (*1*), mourning cuttlefish (*2*) and fork-tailed drongo (*3*) are among the many animals that have been found to deceive.

ALONGKOT SUMRITJEARAPOL *Getty Images* (1); S. ROHRLACH *Getty Images* (2); TREVOR PLATT *Getty Images* (3)

UNCONSCIOUS HUSTLING

BUT THE INTRICACY, indeed the elegance, of animal deception does not depend on conscious intent. The magnificent spider of Australia hunts moths at night using a ball of sticky silk termed a bolas. This grandiosely named arachnid is white in color with varied markings across its body. Rather than spinning a web to catch prey, this spider produces a single strand of silk with a bolas at the end and flings the line at nearby moths. Here is the magnificently Machiavellian part: the bolas gives off a pheromone that mimics the scent of a female moth. Lured by the irresistible odor, male moths flutter close and become ensnared in the sticky silk. The spiders may gobble the moths right away or store them for a snack later on. Nothing about the spiders' deception suggests a thought-out strategy. Instead evolution has promoted the behavior because it benefits their reproductive success.

The same mechanism explains deception in fruit flies. These insects are not shy about their cannibalistic tendencies—young larvae readily consume older or injured individuals. Yet they rarely slurp up fruit-fly eggs. Ecologist Sunitha Narasimha of the University of Lausanne in Switzerland and her team discovered why. It turns out a pheromone exuded by the fruit-fly mother seals the eggs, preventing telltale odors from leaking out, which in turn masks their identity from the tiny cannibals. It is a nifty way to disguise eggs in plain sight in a species not known for straight-up parental protection.

Sex and reproduction offer a ripe context for the sharing of false signals. Among birds, cuckoo females are famous for depositing their eggs into the nests of other females, then fleeing the scene. The nesting mothers are fooled into expending labor to care for offspring not their own. This behavior is widespread far beyond cuckoos. Called conspecific brood parasitism, meaning within-species cheating that deploys an egg as a freeloader in a nest, it is practiced by 200 bird species.

In some animals, the deception starts before any offspring are produced. Female brown trout sometimes quiver violently as though they are ready to lay eggs even when they are not. In a 2001 study of this startling behavior, Erik Petersson and Torbjörn Järvi, both then at the National Board of Fisheries in Sweden, called it "false orgasm." In response, tricked males spew their sperm yet fertilize nothing at all. Why do the females spend this extra energy? They may just be discouraging unwanted males. Intriguingly, though, Petersson and Järvi found that the frequency of false orgasm went up as females neared the time of genuine spawning. So it could also be that females seek—and achieve—release of sperm from multiple males because doing so boosts the vigor of their offspring.

DOMESTICATED LIARS

EVEN AT OUR very own home and hearth, animals may deceive. Dogs are lauded for their supreme loyalty, yet the real picture is more complicated. Working with domestic dogs, ethologist Marianne Heberlein of the University of Zurich arranged for the dogs to interact with one of two women who either shared food with them (call her Ms. Cooperator) or failed to share and took the food herself (Ms. Competitor). The dogs could then lead these partners to a favored food, a nonfavored food or a location with no food. On day one, the dogs led Ms. Cooperator more often to the location with the preferred food. By day two, the dogs had acquired more knowledge about their situation. Now they led Ms. Competitor less often to the preferred-food location and inhibited their searching behavior toward the preferred food in her presence.

As anyone who has lived with dogs knows, they are not great at forgoing beloved foods. Apparently the dogs in this experiment wanted to increase their chances of getting the desirable food later—and knew that deceiving the selfish Ms. Competitor might just increase their odds. Maybe, too, Heberlein says, they just did not fancy the notion of a disliked human getting a treat. Whatever their motivation, the dogs' deception was tactical.

What is the take-home lesson here? Be nice to dogs, and naturally, they will be nice to you. More broadly, animal duplicity may be carried out with awareness and sometimes even with emotional gusto. For this reason, we may see something of ourselves in the dogs or in cuttlefish who give off false signals in mating and birds who mislead to steal food. And yet across species—including those animals who deceive in the absence of premeditated intent—the same individuals may act honestly in some circumstances and connivingly in others. That Janus-headed nature may sound familiar to us, too. SA

MORE TO EXPLORE

"False Orgasm" in Female Brown Trout: Trick or Treat? Erik Petersson and Torbjörn Järvi in *Animal Behaviour,* Vol. 61, No. 2, pages 497–501; February 2001.

It Pays to Cheat: Tactical Deception in a Cephalopod Social Signalling System. Culum Brown et al. in *Biology Letters,* Vol. 8, No. 5, pages 729–732; October 23, 2012.

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Chimpanzees Strategically Manipulate What Others Can See. Katja Karg et al. in *Animal Cognition,* Vol. 18, No. 5, pages 1069–1076; September 2015.

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***Drosophila melanogaster* Cloak Their Eggs with Pheromones, Which Prevents Cannibalism.** Sunitha Narasimha et al. in *PLOS Biology,* Vol. 17, No. 1, Article No. e2006012; January 10, 2019.

FROM OUR ARCHIVES

The Orca's Sorrow. Barbara J. King; March 2019.

scientificamerican.com/magazine/sa

NETWORK SCIENCE

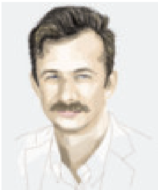
WHY WE TRUST LIES

THE MOST EFFECTIVE MISINFORMATION STARTS WITH SEEDS OF TRUTH

By Cailin O'Connor and James Owen Weatherall

[redacted]

In the mid-1800s a caterpillar the size of a human finger began spreading across the northeastern U.S. This appearance of the tomato hornworm was followed by terrifying reports of fatal poisonings and aggressive behavior toward people. In July 1869 newspapers across the region posted warnings about the insect, reporting that a girl in Red Creek, N.Y., had been "thrown into spasms, which ended in death" after a run-in with the creature. That fall the *Syracuse Standard* printed an account from one Dr. Fuller, who had collected a particularly enormous specimen. The physician warned that the caterpillar was "as poisonous as a rattlesnake" and said he knew of three deaths linked to its venom.



Cailin O'Connor is an associate professor of logic and philosophy of science and **James Owen Weatherall** is a professor of logic and philosophy of science at the University of California, Irvine.

They are co-authors of *The Misinformation Age: How False Beliefs Spread* (Yale University Press, 2019). Both are members of the Institute for Mathematical Behavioral Sciences.

IN BRIEF

Social media has facilitated the proliferation of false belief at an unprecedented scale.

By modeling the ways misinformation spreads via networks of people, researchers learn how social trust and conformity affect how communities reach consensus.

Adding propagandists to the models shows how easily belief can be manipulated, even when scientists collect ample evidence.

Although the hornworm is a voracious eater that can strip a tomato plant in a matter of days, it is, in fact, harmless to humans. Entomologists had known the insect to be innocuous for decades when Fuller published his dramatic account, and his claims were widely mocked by experts. So why did the rumors persist even though the truth was readily available? People are social learners. We develop most of our beliefs from the testimony of trusted others such as our teachers, parents and friends. This social transmission of knowledge is at the heart of culture and science. But as the tomato hornworm story shows us, our ability has a gaping vulnerability: sometimes the ideas we spread are wrong.

Over the past five years the ways in which the social transmission of knowledge can fail us have come into sharp focus. Misinformation shared on social media Web sites has fueled an epidemic of false belief, with widespread misconceptions concerning topics ranging from the prevalence of voter fraud, to whether the Sandy Hook school shooting was staged, to whether vaccines are safe. The same basic mechanisms that spread fear about the tomato hornworm have now intensified—and, in some cases, led to—a profound public mistrust of basic societal institutions. One consequence is the largest measles outbreak in a generation.

"Misinformation" may seem like a misnomer here. After all, many of today's most damaging false beliefs are initially driven by acts of propaganda and disinformation, which are deliberately deceptive and intended to cause harm. But part of what makes propaganda and disinformation so effective in an age of social media is the fact that people who are exposed to it share it widely among friends and peers who trust them, with no intention of misleading anyone. Social media transforms disinformation into misinformation.

Many communication theorists and social scientists have tried to understand how false beliefs persist by modeling the spread of ideas as a contagion. Employing mathematical models involves simulating a simplified representation of human social interactions using a computer algorithm and then studying these simulations to learn something about the real world. In a contagion model, ideas are like viruses that go from mind to mind. You start with a network, which consists of nodes, representing individuals, and edges, which represent social connections. You seed an idea in one "mind" and see how it spreads under various assumptions about when transmission will occur.

Contagion models are extremely simple but have been used to explain surprising patterns of behavior, such as the epidemic of suicide that reportedly swept through Europe after publication of Goethe's *The Sorrows of Young Werther* in 1774 or when dozens of U.S. textile workers in 1962 reported suffering from nausea and numbness after being bitten by an imaginary insect. They can also explain how some false beliefs propagate on the Internet. Before the last U.S. presidential election, an image of a young Donald Trump appeared on Facebook. It included a quote, attributed to a 1998 interview in *People* magazine, saying that if Trump ever ran for president, it would be as a Republican because the party is made up of "the dumbest group of voters." Although it is unclear who "patient zero" was, we know that this meme passed rapidly from profile to profile.

The meme's veracity was quickly evaluated and debunked. The fact-checking Web site Snopes reported that the quote was fabricated as early as October 2015. But as with the tomato hornworm, these efforts to disseminate truth did not change how the rumors spread. One copy of the meme alone was shared more than half a million times. As new individuals shared it over the next several years, their false beliefs infected friends who observed the meme, and they, in turn, passed the false belief on to new areas of the network.

This is why many widely shared memes seem to be immune to fact-checking and debunking. Each person who shared the Trump meme simply trusted the friend who had shared it rather than checking for themselves. Putting the facts out there does not help if no one bothers to look them up. It might seem like the problem here is laziness or gullibility—and thus that the solution is merely more education or better critical thinking skills. But that is not entirely right. Sometimes false beliefs persist and spread even in communities where everyone works very hard to learn the truth by gathering and sharing evidence. In these cases, the problem is not unthinking trust. It goes far deeper than that.

The urge to conform is a profound part of the human psyche and one that can lead us to take actions we know to be harmful.

TRUST THE EVIDENCE

THE FACEBOOK PAGE "Stop Mandatory Vaccination" has more than 140,000 followers. Its moderators regularly post material that is framed to serve as evidence for this community that vaccines are harmful or ineffective, including news stories, scientific papers and interviews with prominent vaccine skeptics. On other Facebook group pages, thousands of concerned parents ask and answer questions about vaccine safety, often sharing scientific papers and legal advice supporting antivaccination efforts. Participants in these online communities care very much about whether vaccines are harm-

ful and actively try to learn the truth. Yet they come to dangerously wrong conclusions. How does this happen?

The contagion model is inadequate for answering this question. Instead we need a model that can capture cases where people form beliefs on the basis of evidence that they gather and share. It must also capture why these individuals are motivated to seek the truth in the first place. When it comes to health topics, there might be serious costs to acting on false beliefs. If vaccines are safe and effective (which they are) and parents do not vaccinate, they put their kids and immunosuppressed people at unnecessary risk. If vaccines are not safe, as the participants in these Facebook groups have concluded, then the risks go the other way. This means that figuring out what is true, and acting accordingly, matters deeply.

PROTESTERS use the language of "choice" to spread misinformation about vaccine safety.

RICH PEDRONCELLI AP Photo

To better understand this behavior in our research, we drew on what is called the network epistemology framework. It was first developed by economists 20 years ago to study the social spread of beliefs in a community. Models of this kind have two parts: a problem and a network of individuals (or "agents"). The problem involves picking one of two choices: These could be "vaccinate" and "don't vaccinate" your children. In the model, the agents have beliefs about which choice is better. Some believe vaccination is safe and effective, and others believe it causes autism. Agent beliefs shape their behavior—those who think vaccination is safe choose to perform vaccinations. Their behavior, in turn, shapes their beliefs. When agents vaccinate and see that nothing bad happens, they become more convinced vaccination is indeed safe.

The second part of the model is a network that represents social connections. Agents can learn not only from their own experiences of vaccinating but also from the experiences of their neighbors. Thus, an individual's community is highly important in determining what beliefs they ultimately develop.

The network epistemology framework captures some essential features missing from contagion models: individuals intentionally gather data, share data and then experience consequences for bad beliefs. The findings teach us some important lessons about the social spread of knowledge. The first thing we learn is that working together is better than working alone, because an individual facing a problem like this is likely to prematurely settle on the worse theory. For instance, he or she might observe one child who turns out to have autism after vaccination and conclude that vaccines are not safe. In a community there tends to be some diversity in what people believe. Some test one action; some test the other. This diversity means that usually enough evidence is gathered to form good beliefs.

But even this group benefit does not *guarantee* that agents learn the truth. Real scientific evidence is probabilistic, of course. For example, some nonsmokers get lung cancer, and some smokers do not get lung cancer. This means that some studies of smokers will find no connection to cancer. Relatedly, although there is no actual statistical link between vaccines and autism, some vaccinated children will be autistic. Thus, some parents observe their children developing symptoms of autism after receiving vaccinations. Strings of misleading evidence of this kind can be enough to steer an entire community wrong.

In the most basic version of this model, social influence means that communities end up at consensus. They decide either that vaccinating is safe or that it is dangerous. But this does not fit what we see in the real world. In actual communities, we see polarization—entrenched disagreement about whether or not to vaccinate. We argue that the basic model is missing two crucial ingredients: social trust and conformism.

Social trust matters to belief when individuals treat some sources of evidence as more reliable than others. This is what we see when anti-vaxxers trust evidence shared by others in their community more than evidence produced by the Centers for Disease Control and Prevention or other medical research groups. This mistrust can stem from all sorts of things, including previous negative experiences with doctors or concerns that health care or governmental institutions do not care about their best interests. In some cases, this distrust may be justified, given that there is a long history of medical researchers and clinicians ignoring legitimate issues from patients, particularly women.

Yet the net result is that anti-vaxxers do not learn from the very people who are collecting the best evidence on the subject. In versions of the model where individuals do not trust evidence from those who hold very different beliefs, we find communities polarize,

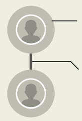
How Network Science Maps the Spread of Misinformation

We use network science to better understand how social connections influence the beliefs and behaviors of individuals in a social network—and especially how false beliefs can spread from person to person. Here we look at two kinds of network models that capture different ways in which ideas or beliefs spread. Each node in these models represents an individual. Each edge, or connection between the nodes, represents a social tie.

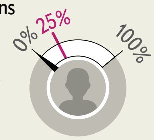
THE CONTAGION MODEL

Contagion models treat ideas or beliefs like viruses that spread between individuals in a social network. There are different ways that this "infection" can work. In some models, everyone will be infected by an infected neighbor. In others, ideas spread whenever some percentage of an individual's neighbors become infected. Here we illustrate these "complex contagions" with examples where individuals take on a new belief if at least 25 percent of their neighbors hold it. In these models, the structure of the network affects how ideas spread.

How to Read the Contagion Plots


Each circular node is a person who is influenced by ideas presented by others. Each line represents a connection between individuals.

The gauge at the top of the nodes indicates the percent of that person's connections who hold a particular belief. In the scenarios below, the threshold for an individual to take on the belief of their neighbors is 25% (at least 1 out of 4).

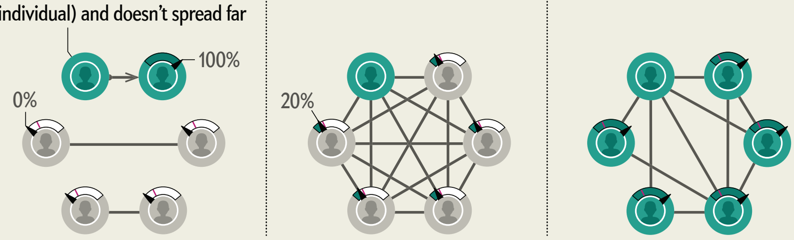


BONDING AND BRIDGING: In less connected groups, ideas cannot reach all members. Sometimes too many connections can also stop the spread of an idea. Some networks have tight-knit cliques, where even if an idea spreads within one clique, it can be difficult for it to spread to other cliques.

Too few connections: Complex idea (*green*) starts with a node (individual) and doesn't spread far

Too many connections: Idea doesn't spread

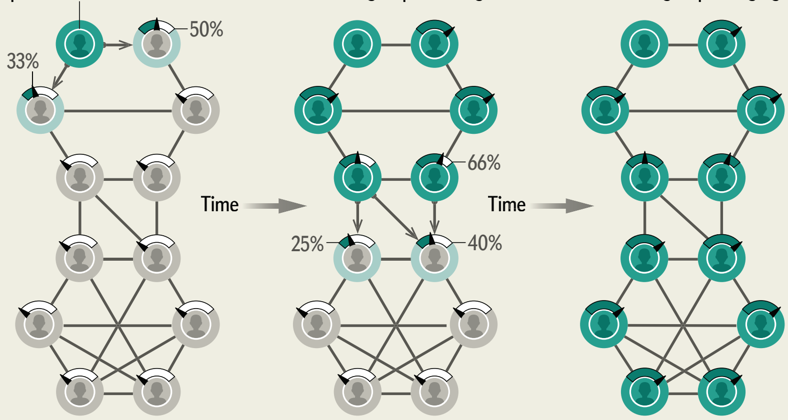
Just right: Idea spreads



Starting point: Complex idea starts with an individual

Idea spreads within group (bonding)

Idea spreads to another group (bridging)



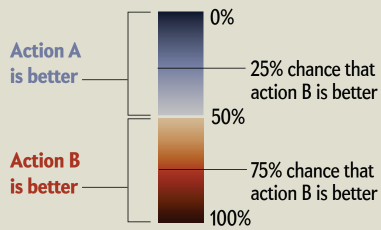
NETWORK EPISTEMOLOGY FRAMEWORK

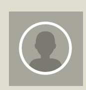
Network epistemology models represent situations in which people form beliefs by gathering and sharing evidence. This sort of model applies to many cases in science. Beliefs do not simply spread from individual to individual. Instead, each individual has some degree of certainty about an idea. This prompts them to gather evidence in support of it, and that evidence changes their beliefs. Each individual shares their evidence with network neighbors, which also influences their beliefs.

How to Read the Network Epistemology Framework Plots

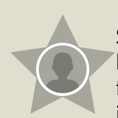
Each circular or square node is a person who is influenced by evidence presented by others. Each has a belief about whether **action A** (*blue*) or **action B** (*orange*) is better. Their belief can strengthen, weaken and/or flip over time, as shown here by changing colors.

The strength of the color represents the individual's level of certainty in a particular action. For example, an assignment of 75% means that the individual thinks that there is a 75% chance that **action B** is better than **action A**. If the value is greater than 50%, then the individual performs **action B**. Then, we use Bayes's rule—which probability theory tells us is the rational way to change beliefs in light of evidence—to update the individual's credence in light of this result and then update all connections in their network.




Square nodes are individuals who test actions and update their beliefs accordingly (evidence seekers)

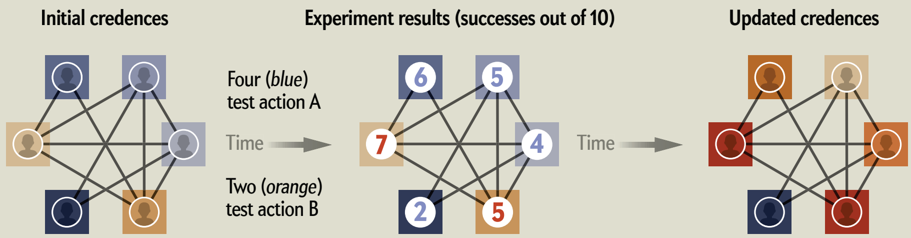

Circular nodes represent individuals who observe results from others but do not test the actions directly (observers)


Stars represent individuals who do not hold beliefs of their own but instead focus on introducing selective results into the system (propagandists)

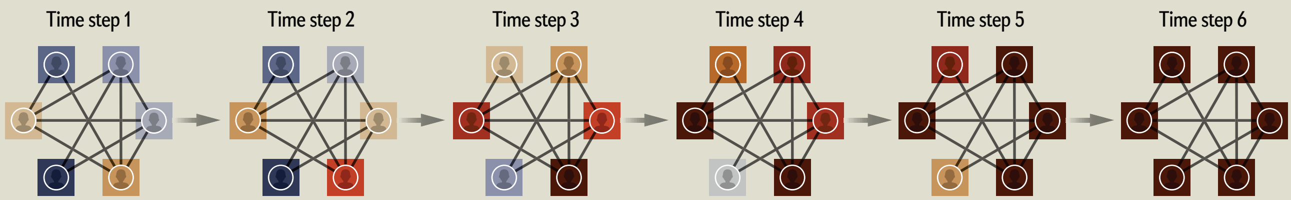
SOURCES: THE WISDOM AND/OR MADNESS OF CROWDS, BY NICKY CASE *https://ncase.me/crowds;* *THE MISINFORMATION AGE: HOW FALSE BELIEFS SPREAD*, BY CAILIN O'CONNOR AND JAMES OWEN WEATHERALL. YALE UNIVERSITY PRESS, 2019

Graphic by Jen Christiansen

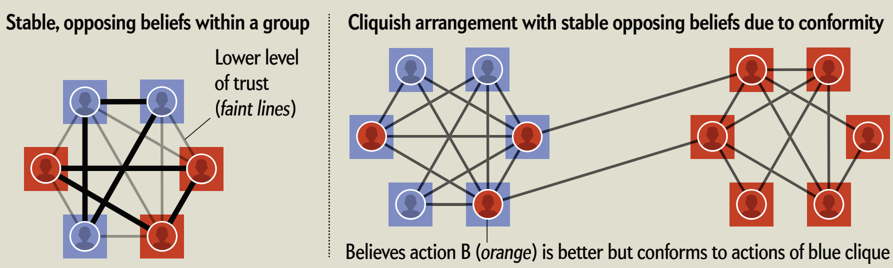
UPDATING AND EXPERIMENTING: Individuals in these models start with some random level of certainty, or credence, about whether action A or B is better. They then take the action they prefer—that is, "experiment." Their outcomes provide evidence about the success of these actions, which they share with neighbors. All individuals update their credences based on what they observe.



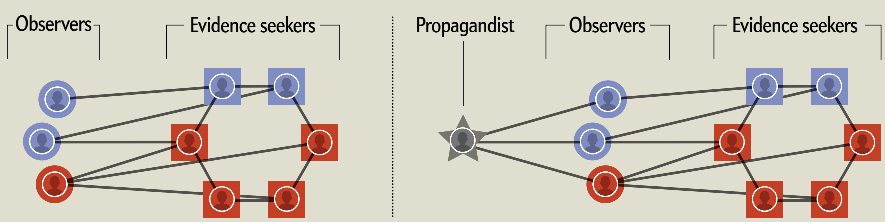
CONVERGENCE ON TRUE BELIEFS: Over time, the social connections in these models mean that groups of people come to a consensus about whether A or B is better. As they gather and share evidence, they usually learn that the better action is, indeed, better. Someone trying the worse action, for instance, will see how much better their neighbor is doing and switch. Sometimes, though, strings of misleading evidence will convince the entire group that the worse action is better.



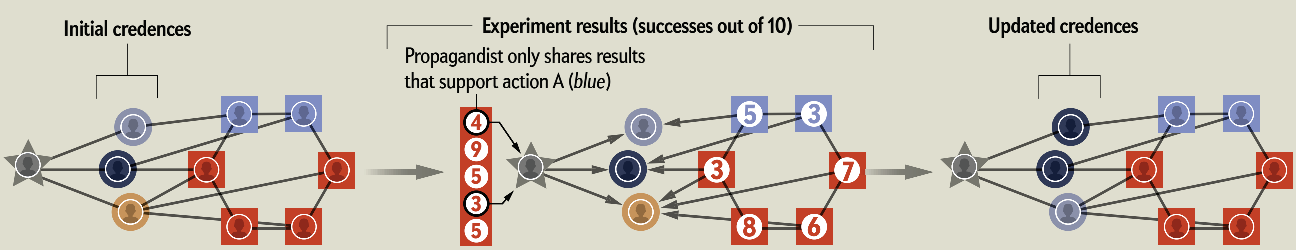
POLARIZATION: If we add social trust or conformity to these models, they may no longer reach consensus. If each individual trusts the evidence that comes from those who share their beliefs, polarized camps that only listen to those in their group form. If each individual seeks to conform their actions with group members, good ideas fail to spread between cliques.



EVIDENCE SEEKERS, OBSERVERS AND PROPAGANDISTS: In some cases, propagandists try to mislead a group of people about scientific results. We can use these models to represent a set of evidence seekers who gather evidence, a group of observers who update beliefs based on this evidence, and a propagandist who misleads the observers.



BELIEF UPDATING WHEN SELECTIVE RESULTS ARE IN PLAY: Industrial propagandists shape public belief by selectively sharing only those results that happen to spuriously support the worse action. This can mislead the public, even in cases when groups of evidence seekers converge to a consensus about the true belief. This strategy for public disinformation takes advantage of the inherent randomness of scientific results to mislead.



and those with poor beliefs fail to learn better ones.

Conformism, meanwhile, is a preference to act in the same way as others in one's community. The urge to conform is a profound part of the human psyche and one that can lead us to take actions we know to be harmful. When we add conformism to the model, what we see is the emergence of cliques of agents who hold false beliefs. The reason is that agents connected to the outside world do not pass along information that conflicts with their group's beliefs, meaning that many members of the group never learn the truth.

Conformity can help explain why vaccine skeptics tend to cluster in certain communities. Some private and charter schools in southern California have vaccination rates in the low double digits. And rates are startlingly low among Somali immigrants in Minneapolis and Orthodox Jews in Brooklyn—two communities that have recently suffered from measles outbreaks.

Interventions into vaccine skepticism need to be sensitive to both social trust and conformity. Simply sharing new evidence with skeptics will likely not help, because of trust issues. And convincing trusted community members to speak out for vaccination might be difficult because of conformism. The best approach is to find individuals who share enough in common with members of the relevant communities to establish trust. A rabbi, for instance, might be an effective vaccine ambassador in Brooklyn, whereas in southern California, you might need to get Gwyneth Paltrow involved.

Social trust and conformity can help explain why polarized beliefs can emerge in social networks. But at least in some cases, including the Somali community in Minnesota and Orthodox Jewish communities in New York, they are only part of the story. Both groups were the targets of sophisticated misinformation campaigns designed by anti-vaxxers.

INFLUENCE OPERATIONS

HOW WE VOTE, what we buy and who we acclaim all depend on what we believe about the world. As a result, there are many wealthy, powerful groups and individuals who are interested in shaping public beliefs—including those about scientific matters of fact. There is a naive idea that when industry attempts to influence scientific belief, they do it by buying off corrupt scientists. Perhaps this happens sometimes. But a careful study of historical cases shows there are much more subtle—and arguably more effective—strategies that industry, nation states and other groups utilize. The first step in protecting ourselves from this kind of manipulation is to understand how these campaigns work.

A classic example comes from the tobacco industry, which developed new techniques in the 1950s to fight

HOW A STATISTICIAN SEARCHES FOR ANSWERS

In statistics, we aren't generally seeing the whole universe but only a slice of it. A small slice usually, which could tell a completely different story than another small slice. We are trying to make a leap from these small slices to a bigger truth. A lot of people take that basic unit of truth to be the *p*-value, a statistical measure of how surprising what we see in our small slice is, if our assumptions about the larger universe hold. But I don't think that's correct.

In reality, the notion of statistical significance is based on an arbitrary threshold applied to the *p*-value, and it may have very little to do with substantive or scientific significance. It's too easy to slip into a thought pattern that provides that arbitrary threshold with meaning—it gives us a false sense of certainty. And it's also too easy to hide a multitude of scientific sins behind that *p*-value.

One way to strengthen the *p*-value would be to shift the culture toward transparency. If we not only report the *p*-value but also show the work on how we got there—the standard error, the standard deviation or other measures of uncertainty, for example—we can give a better sense of what that number means. The more information we publish, the harder it is to hide behind that *p*-value. Whether we can get there, I don't know. But I think we should try.

***Nicole Lazar,** a professor of statistics at the University of Georgia, as told to Brooke Borel*

Illustration by Bud Cook

the growing consensus that smoking kills. During the 1950s and 1960s the Tobacco Institute published a bimonthly newsletter called "Tobacco and Health" that reported only scientific research suggesting tobacco was not harmful or research that emphasized uncertainty regarding the health effects of tobacco.

The pamphlets employ what we have called selective sharing. This approach involves taking real, independent scientific research and curating it, by presenting only the evidence that favors a preferred position. Using variants on the models described earlier, we have argued that selective sharing can be shockingly effective at shaping what an audience of nonscientists comes to believe about scientific matters of fact. In other words, motivated actors can use seeds of truth to create an impression of uncertainty or even convince people of false claims.

Selective sharing has been a key part of the antivaxxer playbook. Before the recent measles outbreak in New York, an organization calling itself Parents Educating and Advocating for Children's Health (PEACH) produced and distributed a 40-page pamphlet entitled "The Vaccine Safety Handbook." The information shared—when accurate—was highly selective, focusing on a handful of scientific studies suggesting risks associated with vaccines, with minimal consideration of the many studies that find vaccines to be safe.

The PEACH handbook was especially effective because it combined selective sharing with rhetorical strategies. It built trust with Orthodox Jews by projecting membership in their community (though published pseudonymously, at least some authors *were* members) and emphasizing concerns likely to resonate with them. It cherry-picked facts about vaccines intended to repulse its particular audience; for instance, it noted that some vaccines contain gelatin derived from pigs. Wittingly or not, the pamphlet was designed in a way that exploited social trust and conformism—the very mechanisms crucial to the creation of human knowledge.

Worse, propagandists are constantly developing ever more sophisticated methods for manipulating public belief. Over the past several years we have seen purveyors of disinformation roll out new ways of creating the impression—especially through social media conduits such as Twitter bots and paid trolls and, most recently, by hacking or copying your friends' accounts that certain false beliefs are widely held, including by your friends and others with whom you identify. Even the PEACH creators may have encountered this kind of synthetic discourse about vaccines. According to a 2018 article in the *American Journal of Public Health*, such disinformation was distributed by accounts linked to Russian influence operations seeking to amplify American discord and weaponize a public health issue. This strategy works to change minds not through rational arguments or evidence but simply by manipulating the social spread of knowledge and belief.

The sophistication of misinformation efforts (and the highly targeted disinformation campaigns that amplify them) raises a troubling problem for democracy. Returning to the measles example, children in many states can be exempted from mandatory vaccinations on the grounds of "personal belief." This became a flash point in California in 2015 following a measles outbreak traced to unvaccinated children visiting Disneyland. Then governor Jerry Brown signed a new law, SB277, removing the exemption.

Immediately vaccine skeptics filed paperwork to put a referendum on the next state ballot to overturn the law. Had they succeeded in getting 365,880 signatures (they made it to only 233,758), the question of whether parents should be able to opt out of mandatory vaccination on the grounds of personal belief would have gone to a direct vote—the results of which would have been susceptible to precisely the kinds of disinformation campaigns that have caused vaccination rates in many communities to plummet.

Luckily, the effort failed. But the fact that hundreds of thousands of Californians supported a direct vote about a question with serious bearing on public health, where the facts are clear but widely misconstrued by certain activist groups, should give serious pause. There is a reason that we care about having policies that best reflect available evidence and are responsive to reliable new information. How do we protect public well-being when so many citizens are misled about matters of fact? Just as individuals acting on misinformation are unlikely to bring about the outcomes they desire, societies that adopt policies based on false belief are unlikely to get the results they want and expect.

The way to decide a question of scientific fact—are vaccines safe and effective?—is not to ask a community of nonexperts to vote on it, especially when they are subject to misinformation campaigns. What we need is a system that not only respects the processes and institutions of sound science as the best way we have of learning the truth about the world but also respects core democratic values that would preclude a single group, such as scientists, dictating policy.

We do not have a proposal for a system of government that can perfectly balance these competing concerns. But we think the key is to better separate two essentially different issues: What are the facts, and what should we do in light of them? Democratic ideals dictate that both require public oversight, transparency and accountability. But it is only the second—how we should make decisions given the facts—that should be up for a vote. SA

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BEHAVIORAL ECONOMICS

CONTAGIOUS DISHONESTY

DISHONESTY BEGETS DISHONESTY, RAPIDLY SPREADING UNETHICAL BEHAVIOR THROUGH A SOCIETY

By Dan Ariely and Ximena Garcia-Rada

Imagine that you go to City Hall for a construction permit to renovate your house. The employee who receives your form says that, because of the great number of applications the office has received, the staff will take up to nine months to issue the permit. But if you give her $100, your form will make it to the top of the pile. You realize she has just asked for a bribe: an illicit payment to obtain preferential treatment. A number of questions are likely to go through your head. Will I pay to speed things up? Would any of my friends or relatives do the same? You would probably not wonder, however, whether being exposed to the request would, in and of itself, affect a subsequent ethical decision. That is the kind of question behavioral researchers ask to investigate how corruption spreads.

The extent of bribery is hard to measure, but estimates from the World Bank suggest that corrupt exchanges involve $1 trillion annually. In 2018 Transparency International reported that more than two thirds of 180 countries it surveyed got a score of less than 50 on a scale from 0 ("highly corrupt") to 100 ("very clean"). Major scandals regularly make global headlines, such as when Brazilian construction company Odebrecht admitted in 2016 to having paid upward of $700 million in bribes to politicians and bureaucrats in 12 countries. But petty corruption, involving small favors between a few people, is also very common. Transparency International's Global Corruption Barometer for 2017 shows that one in every four of those surveyed said they had paid a bribe when accessing public services in the previous year, with almost one in three reporting such payments in the Middle East and North Africa.

Dan Ariely is James B. Duke Professor of Psychology & Behavioral Economics at Duke University and founder of the Center for Advanced Hindsight. He is co-creator of a documentary on corruption and a bestselling author.

Ximena Garcia-Rada is a doctoral candidate of marketing at Harvard Business School. She studies how social factors influence consumer decision-making.

Illustration by Lisk Feng

Corruption, big or small, impedes the socioeconomic development of nations. It affects economic activities, weakens institutions, interferes with democracy and erodes the public's trust in government officials, politicians and their neighbors. Understanding the underlying psychology of bribery could be crucial to tackling the problem. Troublingly, our studies suggest that mere exposure to corruption is corrupting. Unless preventive measures are taken, dishonesty can spread stealthily and uninvited from person to person like a disease, eroding social norms and ethics—and once a culture of cheating and lying becomes entrenched, it can be difficult to dislodge.

CONTAGION

SUPPOSE YOU REFUSED the City Hall employee's request for a bribe. How would the experience influence your response to a subsequent ethical dilemma? In laboratory studies we conducted with behavioral researchers Vladimir Chituc, Aaron Nichols, Heather Mann, Troy Campbell and Panagiotis Mitkidis, which are currently under review at an academic journal, we sought an answer to that question.

We invited individuals to the behavioral lab in the university to play a game that involved throwing a virtual die for a reward. Everyone was told that they would be compensated based on the outcome of multiple rolls. In practice, however, they could misreport their rolls to earn more money. So all participants faced a conflict between playing the game by the rules and behaving dishonestly to earn more. We created this setup to assess how individuals balance external and internal—or psychological—rewards when making ethical decisions. Research that Nina Mazar, On Amir and one of us (Ariely) published in 2008 indicates that most people act unethically to the extent that they can benefit while also preserving their moral self-image—an observation they described as the theory of self-concept maintenance.

Our game involved rolling a virtual die 30 times on iPads. Many behavioral economists have used similar paradigms involving physical dice and coins to assess dishonesty in so-called decontextualized games—that is, games that are not affected by social or cultural norms. Prior to each roll, participants were instructed to choose a side of the die in their mind—top or bottom—and report their choice *after* seeing the outcome of the roll. They would earn a fixed amount of money per dot on the side they reported each time. So everyone had a financial incentive to cheat by reporting the high-paying side. For example, if the outcome of the roll was two on the top of the die and five on the bottom of the die, people might be tempted to say they had chosen "bottom" before the roll even if they had not.

This paradigm does not allow us to know whether someone cheated in a specific roll. Nevertheless, when results are aggregated across all rolls and participants in a group, the proportion of favorable rolls chosen can be compared against chance (50 percent) to assess the magnitude of dishonesty.

After participants received instructions about the game and how they would make money in the session, which they would get to take home, they were randomly assigned to a low- or a high-payment version. Those in the high-payment game would do exactly the same thing as those in the low-payment game but earn 10 times more. Everyone was told about the existence of the other game. Then, half the participants in the low-payment condition were offered the possibility of paying a bribe to be switched to the high-payment game.

The research assistant administering the session framed that opportunity as illegal to engender a moral dilemma similar to one that might arise in real life. The person mentioned that the boss was not around and that the participant could easily be switched to the high-paying game without anyone finding out. Thus, we ended up with three groups of people: low-payment no bribe, high-payment no bribe, and bribe exposed; the last group could be further split into bribe payers and bribe refusers. This arrangement allowed us to assess how ethically those exposed to the bribe would behave after having encountered the offer.

We administered three versions of the test to a total of 349 individuals in our behavioral lab. In the first two studies, some participants were offered the possibility of paying a $2 bribe to be placed in the high-payment version of the game, and 85 percent of them paid. Crucially, we observed that in the games they went on to play, bribe-exposed participants cheated more than participants who did not receive such a request. In the second study, for example, bribe-exposed participants cheated 9 percent more than those who played the high-payment version of the game and 14 percent more than participants who played the low-payment version of the game but had not been asked for a bribe.

In a third study, we tested whether people act more immorally when they pay a bribe or when they are merely exposed to one. We made the bribe costlier at $12, and 82 percent turned down the request, giving us a large sample size of bribe refusers. Disturbingly, even when we limited our analysis to this group of apparently ethical individuals, we found that bribe-exposed individuals cheated more than those who did not receive the illegal request. Taken together, results from these three experiments suggest that receiving a bribe request erodes individuals' moral character, prompting them to behave more dishonestly in subsequent ethical decisions.

ERODING NORMS

OUR WORK SUGGESTS that bribery is like a contagious disease: it spreads quickly among individuals, often by mere exposure, and as time passes it becomes harder and harder to control. This is because social norms—the patterns of behavior that are accepted as normal—impact how people will behave in many situations, in-

IN BRIEF

Corruption damages economies, institutions and democratic structures.

Exposure to bribery can, in and of itself, be corrupting—suggesting a mechanism by which unethical behavior may spread through society.

Social norms influence ethical behavior. Surprisingly, however, the innate tendency to cheat (or not) is the same across countries, despite vast differences in actual corruption levels.

Further research is required into what drives bribery and corruption, how it spreads and how it can be controlled.

cluding those involving ethical dilemmas. In 1991 psychologists Robert B. Cialdini, Carl A. Kallgren and Raymond R. Reno drew the important distinction between descriptive norms—the perception of what most people do—and injunctive norms—the perception of what most people approve or disapprove of. We argue that both types of norms influence bribery. Simply put, knowing that others are paying bribes to obtain preferential treatment (a descriptive norm) makes people feel that it is more acceptable to pay a bribe themselves. Similarly, thinking that others believe that paying a bribe is acceptable (an injunctive norm) will make people feel more comfortable when accepting a bribe request. Bribery becomes normative, affecting people's moral character.

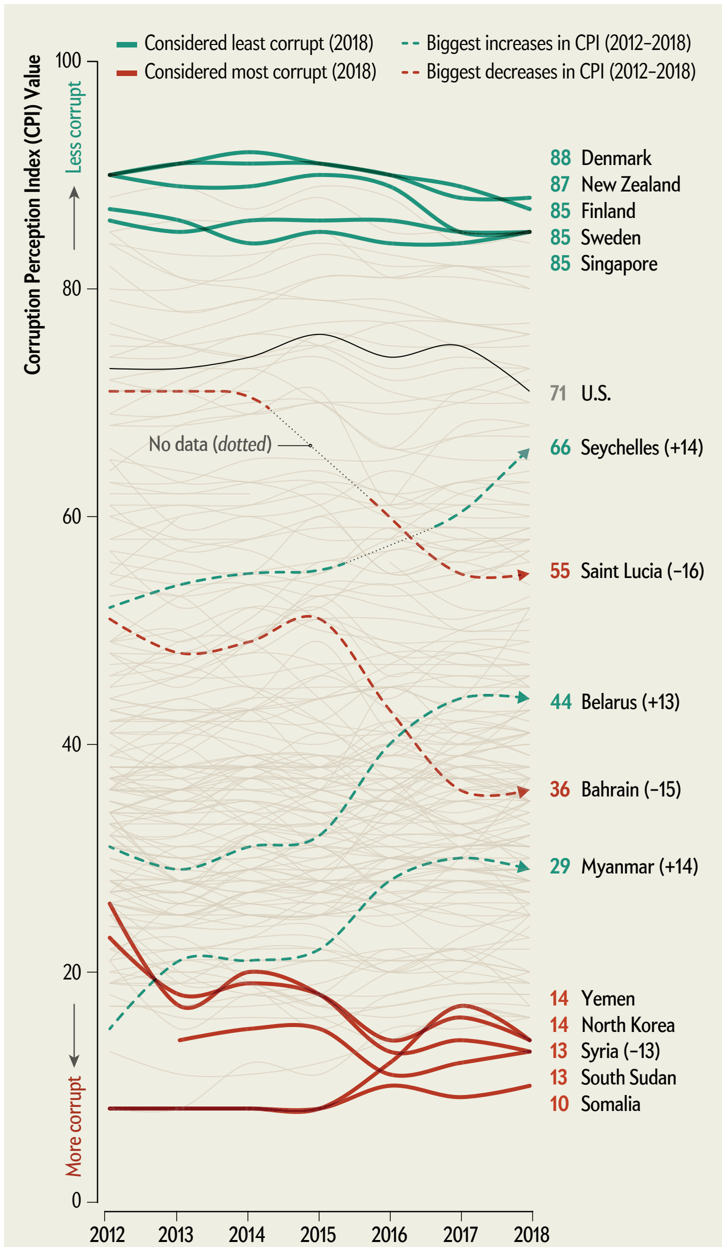
In 2009 Ariely, with behavioral researchers Francesca Gino and Shahar Ayal, published a study showing how powerful social norms can be in shaping dishonest behavior. In two lab studies, they assessed the circumstances in which exposure to others' unethical behavior would change someone's ethical decision-making. Group membership turned out to have a significant effect: When individuals observed an in-group member behaving dishonestly (a student with a T-shirt suggesting he or she was from the same school cheating in a test), they, too, behaved dishonestly. In contrast, when the person behaving dishonestly was an out-group member (a student with a T-shirt from the rival school), observers acted more honestly.

But social norms also vary from culture to culture: What is acceptable in one culture might not be acceptable in another. For example, in some societies giving gifts to clients or public officials demonstrates respect for a business relationship, whereas in other cultures it is considered bribery. Similarly, gifts for individuals in business relationships can be regarded either as lubricants of business negotiations, in the words of behavioral economists Michel André Maréchal and Christian Thöni, or as questionable business practices. And these expectations and rules about what is accepted are learned and reinforced by observation of others in the same group. Thus, in countries where individuals regularly learn that others are paying bribes to obtain preferential treatment, they determine that paying bribes is socially acceptable. Over time the line between ethical and unethical behavior becomes blurry, and dishonesty becomes the "way of doing business."

Interestingly, in cross-cultural research we published in 2016 with behavioral researchers Heather Mann, Lars Hornuf and Juan Tafurt, we found that people's underlying tendency to behave dishonestly is similar across countries. We studied 2,179 native residents in the U.S., Colombia, Portugal, Germany and China. Using a game similar to the one in our bribing studies, we observed that cheating levels in these countries were about the same. Regardless of the country, people were cheating to an extent that balanced the motive of earning money with that of maintaining a positive moral image of themselves. And contrary to

Corruption Perception Index

Levels of corruption in the public sector vary greatly around the world, according to Transparency International. Every year the nongovernmental agency uses opinion surveys and expert assessments to rank countries on a corruption scale ranging from 0 to 100. The chart displays the evolution of these rankings from 2012 to 2018, highlighting the most and least corrupt countries, as well as a few that evinced the greatest change in corruption. Levels of dishonest behavior can worsen or decline with surprising rapidity but are relatively stable in the least corrupt countries. Curiously, behavioral studies show that the innate inclination of individuals to behave dishonestly is roughly the same in different countries, regardless of their actual levels of corruption.



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SOURCE: TRANSPARENCY INTERNATIONAL (*CPI data*)

Graphic by Tiffany Farrant-Gonzalez

FAKE DOLLAR BILLS thrown by a protester swirl around FIFA's then president following a 2015 corruption scandal.

FABRICE COFFRINI *Getty Images*

commonly held beliefs (which we assessed among a different set of participants) about how these countries vary, we did not find more cheaters in countries with high corruption levels (such as Colombia) than in countries with low corruption levels (Germany).

So why do we observe huge international differences in levels of corruption and bribery? It turns out that although individuals' innate tendencies to behave honestly or otherwise are similar across countries, social norms and legal enforcement powerfully influence perceptions and behaviors. In 2007 economists Raymond Fisman and Edward Miguel published a study of parking violations among United Nations diplomats living in Manhattan. They found that diplomats from high-corruption countries accumulated more unpaid parking violations. But when enforcement authorities could confiscate diplomatic license plates of offenders, the number of unpaid violations decreased significantly. Their work suggests that cultural norms and legal enforcement are key factors in shaping ethical behavior.

PROBING DEEPER

BUT WHAT ARE the psychological mechanisms involved in the exchange of a bribe? Behavioral researchers have examined these in the lab and the field. For example, in recent research behavioral economists Uri Gneezy, Silvia Saccardo and Roel van Veldhuizen studied the psychology behind the acceptance of bribes. They conducted a lab study with 573 participants, divided into groups of three. Two participants competed for a prize by writing jokes, and the third chose the winner. The writers could bribe the referees by including $5 in an envelope when submitting their entry. Gneezy and his colleagues studied how referees reacted and how receiving a bribe distorted their judgment. They found when the referees could keep only the winner's bribe, bribes distorted their judgment, but when the referees could keep the bribe regardless of the winner, bribes no longer influenced their decision. This study suggests that people are influenced by bribes out of self-interest and not because they want to return the favor to whoever paid the bribe.

In related studies, published in 2017, Nils Köbis, now at the University of Amsterdam, and his colleagues tested the idea that severe corruption emerges gradually through a series of increasingly dishonest acts. They found that, in fact, participants in their four experiments were more likely to behave unethically when given the opportunity to do so in an abrupt manner—that is, when tempted with a single opportunity to behave unethically for a large gain rather than when faced with a series of choices for small benefits. As the researchers concluded, "sometimes the route to corruption leads over a steep cliff rather than a slippery slope."

Given how damaging corruption is to societies, we believe it is crucial to further probe its psychological roots. Three areas beg for future research. First, we need a fuller accounting of what drives a culture toward less ethical behavior. What, for example, prompts someone to ask for a bribe? What impacts the likelihood of accepting a bribe? Second, what are the consequences of bribery? Clearly, bribery and, more broadly, dishonesty are contagious. But future research could investigate the lasting effects of bribery over time and across domains: What happens when people are consistently exposed to bribes? Does recurring exposure to bribery strengthen or weaken the effect of bribes on individual dishonesty? Last, what kinds of interventions would be most effective in reducing bribe solicitations and acceptance?

Going back to our initial example, we see that the corrupt exchange that the City Hall employee offered might have seemed trivial or at least be considered an isolated event. Sadly, a single bribe request will affect the requester and the recipient. And notably, its dominolike effect can impact many individuals over time, spreading quickly across a society and, if left unchecked, entrenching a culture of dishonesty. SA

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HOW TO DEFRAUD DEMOCRACY

A WORST-CASE CYBERWARFARE SCENARIO FOR THE 2020 AMERICAN PRESIDENTIAL ELECTION

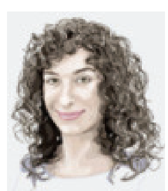
By J. Alex Halderman, as told to Jen Schwartz

[redacted]

J. Alex Halderman is a computer scientist who has shown just how easy it is to hack an election. His research group at the University of Michigan examines how attackers can target weaknesses in voting machinery, infrastructure, polling places and registration rolls, among other features. These days he spends much of his time educating lawmakers, cybersecurity experts and the public on how to better secure their elections. In the U.S., there are still serious vulnerabilities heading into the 2020 presidential contest.

Given the cracks in the system, existing technological capabilities and the motivations of adversaries, Halderman has speculated here on potential cybersecurity disasters that could throw the 2020 election—and democracy itself—into question. Halderman, however, is adamant about one thing: "The only way you can reach certainty that your vote won't be counted is by not casting it. I do not want to scare people off from the polls." What follows is based on two conversations that took place in October 2018 and June 2019; it has been edited and condensed.

J. Alex Halderman is a professor of computer science and engineering at the University of Michigan, where he is also director of the Center for Computer Security and Society. He is a 2019 Andrew Carnegie Fellow for his work in educating lawmakers and the public in how to strengthen election cybersecurity.



Jen Schwartz is a senior editor at *Scientific American* who covers the ways technology affects society.

THE 2016 U.S. PRESIDENTIAL election really did change everything. It caught much of the intelligence and cybersecurity communities off guard and taught us that our threat models for cyberwarfare were wrong. Thanks to the Mueller report, we now know that the Russians made a serious and coordinated effort to undermine the legitimacy of the 2016 election outcome. Their efforts were, I think, far more organized and multipronged than anyone initially realized. And to my knowledge, no state has since done any kind of rigorous forensics on their voting machines to see if they had been compromised. I am quite confident that the Russians will be back in 2020.

I think the intelligence community will continue to try to gain visibility into what malicious actors are planning and what they're doing. It's incredible, really, how much detail has come out of the indictments about specific actions by specific people in the Russian military and leadership. But it's hard to know what we're not seeing. And do we have a parallel level of visibility into North Korea or Iran or China? There are potentially a lot of sophisticated nation state actors that would want to do us harm in 2020 and beyond.

Since the 2016 elections many states have made improvements to their election machinery, but it's not enough, nor is it happening quickly enough. There are still 40 states that are using voting machines that are at least a decade old, and many of these machines are

not receiving software patches for vulnerabilities. Nearly 25 percent of states do not have complete paper trails, so they cannot do postelection auditing of physical ballots. Election security is not a partisan issue. Yet there are roadblocks, especially coming from Republican leadership in the Senate, that make it unlikely that an election security bill is going to advance. I think that is a terrible abdication of Congress's duty to provide for the common defense. So, many of the worst-case scenarios for election interference are still going to be possible in 2020.

LEADING UP TO ELECTION DAY

CYBERWARFARE often involves exploiting known vulnerabilities in systems and the basic limits of people's psychology and gullibility. During the primaries and in the months leading up to the election, influence operations on social media are going to get much more precise and data-driven than ever before—and therefore more effective and harder to detect.

Already presidential candidates are finely crafting political advertisements to specific demographics of voters to maximally influence them. So, you might receive one message from a candidate based on what's known about you in consumer databases. And people with slightly different views on certain issues might receive a different message from the same candidate. Of course, the bad guys who are trying to spread outright fictions will begin to harness the same strategy.

As we saw in 2016, one of the goals of attackers is to increase the amount of divisiveness in society—to reduce social cohesion. Suppose the Russians purchase access to the same consumer-profile data that advertisers in political campaigns use to target you. They can combine that with data from political polls and purchased (or stolen) voter-registration lists to figure out exactly how much your individual vote matters and use those tools to push customized disinformation at narrow groups of people. Attackers may even impersonate political candidates. In a crowded Democratic primary season, there will be sweeping opportunity to deploy microtargeted messaging to turn people against one another, even when they agree about most things.

We all assume that more transparency is a good thing. But people have always taken facts out of context when it is helpful to them and harmful to their opponents. Candidates increasingly live with the threat of targeted theft of true information. When information is selectively stolen from particular groups that an attacker wants to disadvantage, the truth can be used as a powerful and one-sided political weapon—and as we saw with the 2016 Hillary Clinton campaign, it was incredibly effective. It is such a fundamental threat to our notions of how the truth in journalism should play out in a democratic process that I'm sure it's going to happen again. And it can get a lot worse than the theft of e-mails. Imagine someone hacking into candidates' smartphones and secretly recording them during private moments or while talking to their aides. My research group is polling political campaigns to assess how well they are protecting themselves from this, and so far I don't think they are ready.

We're also going to see information that is doctored or entirely synthetic and made to appear real. In some ways, this creates a worse threat. Attackers don't have to actually catch the candidate saying something or e-mailing something if they can produce a record that's indistinguishable from the truth. We've seen recent advances in using machine learning to synthesize video of people saying things that they never actually said on camera. Overall, these tactics help to undermine our basic notions of what's true and what's not. It makes it easier for candidates to deny real things that they said by suggesting that the content of e-mails and recordings were forged and that people shouldn't be believing their own eyes and ears. It's a net loss for our ability to form political consensus based on reality.

Meanwhile each state runs its own independent voter-registration system. Since 2016 many states have taken great strides to protect those systems by installing better network-intrusion detection systems or by upgrading antiquated hardware and software. But many have not.

During the last election, Russians probed or attempted to get into voter-registration systems in at least 18 states. Some sources quote higher numbers. And according to the Senate Select Committee on Intelligence's findings, in some of those states the Russians were in a position to alter or destroy the registration data. If they follow through this time, across entire states people will go to the polls and be told that they aren't on the lists. Maybe they will be given provisional ballots. But if this happens to a large fraction of voters, then there will be such terrible delays that many will give up and go home. A sophisticated attacker could even cause the registration system to lie to voters who confirm their own registration status through online portals while corrupting information in the rolls that are used in polling places.

Attacks on preelection functions could be engineered to have a racial or partisan effect. Because of antidiscrimination laws, some voter-registration records include not only political affiliation but also race. With access to that database, someone could easily manipulate only the records belonging to people of a certain political party, racial group or geographical location.

In some states, online voter-registration systems also allow the voter to request an absentee ballot or to change the address to which the ballot is directed. An attacker could request vote-by-mail ballots for a large number of citizens and direct them to people working with the attacker who would fill them in and cast fake votes.

ON ELECTION DAY

ELECTION INTERFERENCE can be successful in many ways—it depends on an attacker's goals and level of

IN BRIEF

There are still major cybersecurity vulnerabilities facing the 2020 U.S. presidential election, in part because the election system is based on faith instead of evidence.

Foreign attackers could target voter-registration rolls and election machinery to either influence the outcome or sow chaos and doubt.

The worst-case scenarios could result in an unprecedented constitutional crisis.

Illustration by Lisk Feng

access. In a close election, if a coordinated group, say in Russia, thinks one candidate is much better than the other for their country, why not try to influence the outcome by undetectably manipulating votes? An attacker could infiltrate what are called election-management systems. There is a programming process by which the design of the ballot—the races and candidates and the rules for counting the votes—gets produced and then gets copied to every individual voting machine. Election officials usually copy it on memory cards or USB sticks for the election machines. That provides a route by which malicious code could spread from the centralized programming system to many voting machines in the field. Then the attack code runs on the individual voting machines, and it's just another piece of software. It has access to all the same data that the voting machine does, including all the electronic records of people's votes.

For 2020 I think ground zero for this kind of vote manipulation via cyberattack is an office building in the Midwest. Much of the country outsources its ballot design to just a few election vendors—the largest of which is a voting-machine manufacturer that, when I visited, told me it does the preelection programming for about 2,000 jurisdictions across 34 states. All of that's done from its headquarters, in a room I've been in that I'd describe as being part of a typical work building shared with other companies. If attackers can hack into that central facility and remotely infiltrate the company's computers, they can spread malicious code to voting machines and change election results across much of the country. The tactic might be as subtle as manipulating vote totals in close jurisdictions. It could easily go undetected.

The scientific consensus is that the best way to secure the vote is to use paper ballots and rigorously audit them, by having people inspect a random sample. Unfortunately, 12 states still don't have paper across the board. And some states, instead of adopting paper, are now having officials do auditing by looking at a scan of the original ballot on a computer screen. We have new research coming out that shows how you can use a computer algorithm to essentially do "deep fake" ballot scans. We used computer-vision techniques to automatically move the check marks around so that the scan of your ballot filled out in your distinctive handwriting reflects different votes than the ones you recorded on the piece of paper.

It might actually be scarier if attackers don't think one candidate is much better for their purposes than the other. Maybe their motivation is more general: to weaken American democracy. They could introduce malicious code that would make the election equipment essentially destroy itself when it is turned on in November 2020, which will cause massive chaos. Or they could have the equipment appear to work, but at the end of the day officials discover that no votes have been recorded. In the jurisdictions without paper backup, there is no other record of the vote. You would

HOW A DATA JOURNALIST SEARCHES FOR ANSWERS

People assume that because there are data, that the data must be true. But the truth is, all data are dirty. People create data, which means data have flaws just like people. One thing data journalists do is interrogate that assumption of truth, which serves an important accountability function—a power check to make sure we aren't collectively getting carried away with data and making bad social decisions.

To interrogate the data, you have to do a lot of janitorial work. You have to clean and organize them; you have to check the math. And you also have to acknowledge the uncertainty. If you are a scientist, and you don't have the data, you can't write the paper. But one of the fabulous things about being a data journalist is that sparse data don't deter us—sometimes the lack of data tells me something just as interesting. As a journalist, I can use words, which are a magnificent tool for communicating about uncertainty.

Meredith Broussard, *an associate professor at the Arthur L. Carter Journalism Institute at New York University, as told to Brooke Borel*

Illustration by Bud Cook

have to run a completely new election. The point of this kind of visible attack is that it undermines faith in the system and shakes people's confidence in the integrity of democracy.

ELECTION NIGHT AND BEYOND

YOU NEED TO GET PEOPLE to agree more or less about the truth and the conclusion of the election. But by the time November rolls around, we're all going to be primed to worry about the legitimacy of our process. So much is going to depend on how close the race seems on election night.

The way that results get transferred from your local precinct to the display on CNN or on the *New York Times* Web site is through a very centralized computer system operated by the Associated Press and others. What if an attacker were to hack those computer systems and cause the wrong call to be made on election night? We'd eventually find out about it because states go back and do their own totalization, but it might take days or even a couple of weeks until we discover a widespread error. People who want to believe the election was rigged would see this as confirmation it was rigged indeed.

Only 22 states have a requirement to complete any kind of postelection audit of their paper trail prior to legally certifying the results. And in 20 out of those 22 states, the requirement doesn't always result in a statistically significant level of auditing because they do not look at a large enough ballot sample to have high confidence in the result, especially when results are close. It's just based on the math and has nothing to do with politics. Only Rhode Island and Colorado require a statistically rigorous process called a risk-limiting audit, though other states are moving in that direction.

If, because of computer hacking, we don't arrive at election results in many states, we enter unknown territory. The closest precedent would be something like the Bush versus Gore election where the outcome was ultimately decided in the Supreme Court and wasn't known for a month after election day. It would be terrifying, and it might involve running the election again in states that were affected. You really can't replay an election and expect to get the same results because it's always going to be a different political environment.

Or let's say a candidate challenges a close election result. Under current rules and procedures, that is often the only way that people will ever go back and examine the physical evidence to check whether there was an attack. Right now we don't have the right forensic tools to be able to go back and see what happened where and who might have done what. It's not even clear who would have the jurisdiction to do those kinds of tests because election officials and law enforcement don't often go hand in hand. You don't want to turn it over to the police to decide who won.

In a real nightmare scenario, attackers could gain enough access to the voting system to tip the election result and cause one candidate to win by fraud. Then they could keep that a secret—but engineer it in such a way that at any time in the future, they could prove they had stolen the election.

Imagine a swing state like Pennsylvania, which is racing to replace its vulnerable paperless voting machines. Even if they can do so in time for November 2020, the state still doesn't require risk-limiting audits, which means outcome-changing fraud could go undetected. What if the whole election comes down to Pennsylvania, and an attacker was able to hack into its machines and change the reported results? They could set the manipulation so that if you sorted the names of the polling places alphabetically, the least significant digits of the votes for the winning candidate formed the digits of pi—or something like that. It would be a pattern that wouldn't be noticeable but that could later be pointed in a way that undeniably shows the results were fake.

Say this information comes out after the new administration has been in power for a certain amount of time, and no one can deny that the president is not the legitimate winner. Now we have an unprecedented constitutional crisis. Finally, imagine if the nation state that carries out this attack doesn't release its information publicly but instead uses it to blackmail the person who becomes president. This is pushing slightly into the realm of science fiction, though not by much.

The reality is that most cyberwarfare is more mundane. It's almost certain we're going to see attempts to sow doubt that are connected to the vulnerabilities in the election system just because it's so easy. You don't have to hack into a single piece of election equipment—all you have to do is suggest that someone might have.

It's hard to have an open conversation about the vulnerabilities in the system without risking contributing to attackers' goal of making people feel less confident in the results. But the fundamental problem is that the American election system is based on convincing the public to trust the integrity of the imperfect machinery and imperfect people that operate it. Ultimately our best defense is to make elections be based on evidence instead of on faith—and it is entirely doable. There are so many problems in cybersecurity and critical infrastructure where you could offer me billions of dollars and decades to do research, and I'd say, *Maybe we can make this a little bit better.* But election-security challenges can be solved without any major scientific breakthroughs and for only a few hundred million dollars. It's just a matter of political will. SA

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scientificamerican.com/magazine/sa

PART 3:

UNCERTAI

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Illustration by Red Nose Studio

TOUGH CALLS

HOW WE MAKE DECISIONS IN THE FACE OF INCOMPLETE KNOWLEDGE AND UNCERTAINTY

By Baruch Fischhoff

Psychologist **Baruch Fischhoff** is Howard Heinz University Professor in the department of engineering and public policy and the Institute for Politics and Strategy at Carnegie Mellon University. He is a member of the National Academy of Sciences and National Academy of Medicine and past president of the Society for Risk Analysis.

Psychologists study how humans make decisions by giving people "toy" problems. In one study, for example, my colleagues and I described to subjects a hypothetical disease with two strains. Then we asked, "Which would you rather have? A vaccine that completely protects you against one strain or a vaccine that gives you 50 percent protection against both strains?" Most people chose the first vaccine. We inferred that they were swayed by the phrase about complete protection, even though both shots gave the same overall chance of getting sick.

But we live in a world with real problems, not just toy ones—situations that sometimes require people to make life-and-death decisions in the face of incomplete or uncertain knowledge. Years ago, after I had begun to investigate decision-making with my colleagues Paul Slovic and the late Sarah Lichtenstein, both at the firm Decision Research in Eugene, Ore., we started getting calls about non-toy issues—calls from leaders in industries that produced nuclear power or genetically modified organisms (GMOs). The gist was: "We've got a wonderful technology, but people don't like it. Even worse, they don't like us. Some even think that we're evil. You're psychologists. Do something."

Illustration by Wesley Allsbrook

IN BRIEF

When people assess novel risks, they rely on mental models derived from previous experience, which may not be applicable.

Asking people how they form such assessments can reveal misleading preconceptions.

Experts can also test messages about risk to ensure the public understands them clearly.

We did, although it probably wasn't what these company officials wanted. Instead of trying to change people's minds, we set about learning how they *really* thought about these technologies. To that end, we asked them questions designed to reveal how they assessed risks. The answers helped us understand why people form beliefs about divisive issues such as nuclear energy—and today, climate change—when they do not have all the facts.

INTIMATIONS OF MORTALITY

TO START OFF, we wanted to figure out how well the general public understands the risks they face in everyday life. We asked groups of laypeople to estimate the annual death toll from causes such as drowning, emphysema and homicide and then compared their estimates with scientific ones. Based on previous research, we expected that people would make generally accurate predictions but that they would overestimate deaths from causes that get splashy or frequent headlines—murders, tornadoes—and underestimate deaths from "quiet killers," such as stroke and asthma, that do not make big news as often.

Overall, our predictions fared well. People overestimated highly reported causes of death and underestimated ones that received less attention. Images of terror attacks, for example, might explain why people who watch more television news worry more about terrorism than individuals who rarely watch. But one puzzling result emerged when we probed these beliefs. People who were strongly opposed to nuclear power believed that it had a very low annual death toll. Why, then, would they be against it? The apparent paradox made us wonder if by asking them to predict average annual death tolls, we had defined risk too narrowly. So, in a new set of questions we asked what risk really meant to people. When we did, we found that those opposed to nuclear power

HOW A BEHAVIORAL SCIENTIST SEARCHES FOR ANSWERS

The kind of control you have in bench science is much tighter than in behavioral science—the power to detect small effects in people is much lower than in, say, chemistry. Not only that, people's behaviors change across time and culture. When we think about truth in behavioral science, it's really important not only to reproduce a study directly but also to extend reproduction to a larger number of situations—field studies, correlational studies, longitudinal studies.

So how do we measure racism, something that's not a single behavior but a pattern of outcomes—a whole system by which people are oppressed? The best approach is to observe the pattern of behaviors and then see what happens when we alter or control for a variable. How does the pattern change? Take policing. If we remove prejudice from the equation, racially disparate patterns persist. The same is true of poverty, education and a host of things we think predict crime. None of them are sufficient to explain patterns of racially disparate policing outcomes. That means we still have work to do. Because it's not like we don't know how to produce nonviolent and equitable policing. Just look at the suburbs. We've been doing it there for generations.

Of course, there is uncertainty. In most of this world, we are nowhere near confidence about causality. Our responsibility as scientists is to characterize these uncertainties because a wrong calculation in what drives something like racism is the difference between getting policies right and getting them wrong.

Phillip Atiba Goff, *Franklin A. Thomas Professor in Policing Equity at the John Jay College of Criminal Justice at the City University of New York and president of the Center for Policing Equity, as told to Brooke Borel*

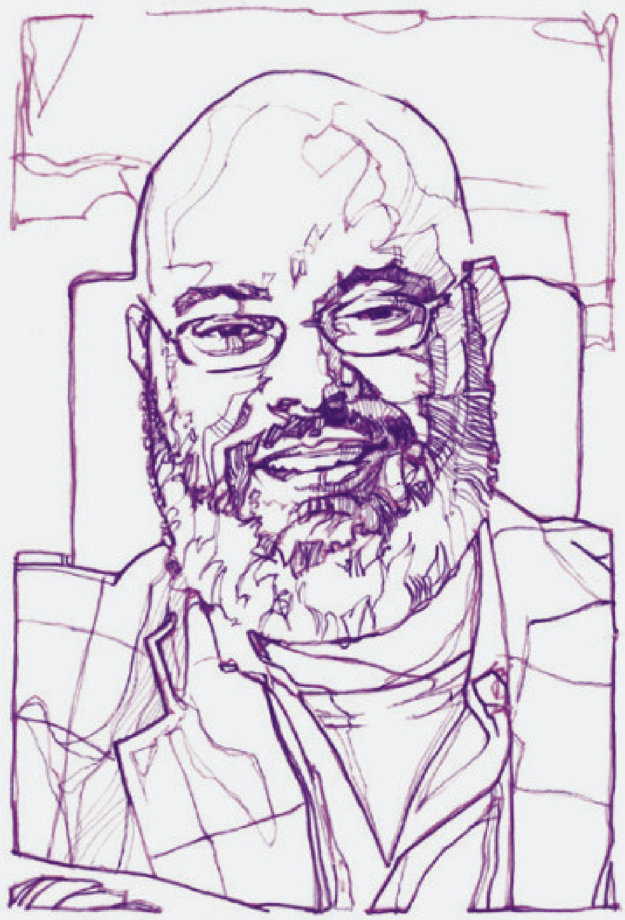


Illustration by Bud Cook

thought the technology had a greater potential to cause widespread catastrophes. That pattern held true for other technologies as well.

To find out whether knowing more about a technology changed this pattern, we asked technical experts the same questions. The experts generally agreed with laypeople about nuclear power's death toll for a typical year: low. But when they defined risk themselves, on a broader time frame, they saw less potential for problems. The general public, unlike the experts, emphasized what could happen in a very bad year. The public and the experts were talking past each other and focusing on different parts of reality.

UNDERSTANDING RISK

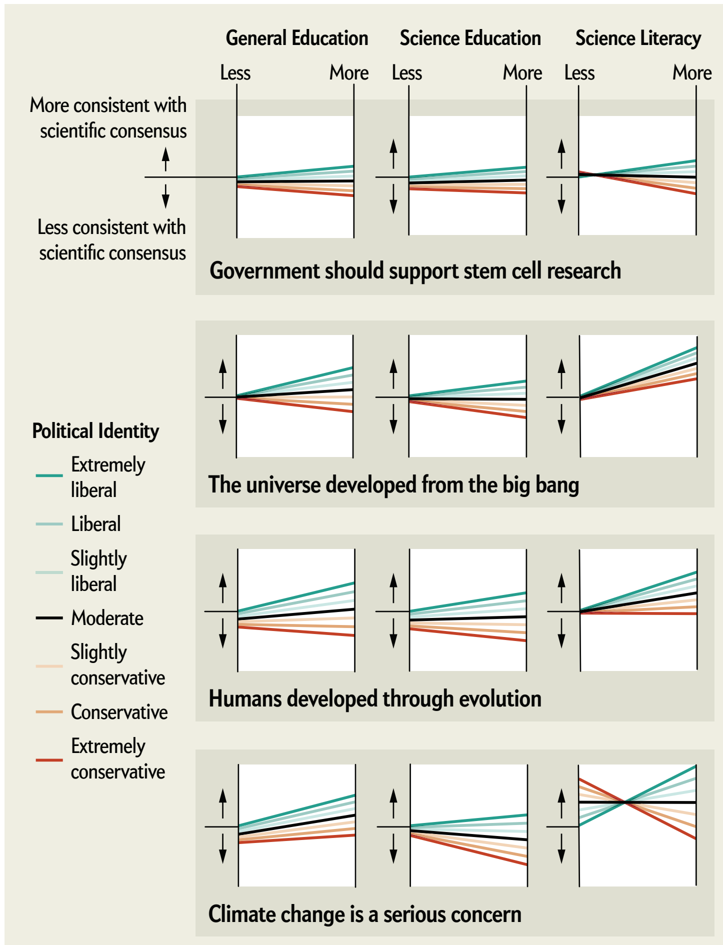
DID EXPERTS always have an accurate understanding of the probabilities for disaster? Experts analyze risks by breaking complex problems into more knowable parts. With nuclear power, the parts might include the performance of valves, control panels, evacuation schemes and cybersecurity defenses. With GMO crops, the parts might include effects on human health, soil chemistry and insect species.

The quality and accuracy of a risk analysis depend on the strength of the science used to assess each part. Science is fairly strong for nuclear power and GMOs. For new technologies such as self-driving vehicles, it is a different story. The components of risk could be the probability of the vehicle laser-light sensors "seeing" a pedestrian, the likelihood of a pedestrian acting predictably, and the chances of a driver taking control at the exact moment when a pedestrian is unseen or unpredictable. The physics of pulsed laser-light sensors is well understood, but how they perform in snow and gloom is not. Research on how pedestrians interact with autonomous vehicles barely exists. And studies of drivers predict that they cannot stay vigilant enough to handle infrequent emergencies.

When scientific understanding is incomplete, risk analysis shifts from reliance on established facts to expert judgment. Studies of those judgments find that they are often quite good—but only when experts get good feedback. For example, meteorologists routinely compare their probability-of-precipitation forecasts with the rain gauge at their station. Given that clear, prompt feedback, when forecasters say that there is a 70 percent chance of rain, it rains about 70 percent of the time. With new technologies such as the self-driving car or gene editing, however, feedback will be a long time coming. Until it does, we will be unsure—and the experts themselves will not know—how accurate their risk estimates really are.

When the Public Disagrees about Science

On politically controversial scientific issues, polarization is greater among better-informed people. Investigators saw this effect in two national surveys in the U.S. The surveys, conducted in 2006 and 2010, combined to cover just more than 6,500 people. Participants were asked what they believed on several hot topics and whether they agreed with scientific consensus. As education and science literacy increased among liberals and conservatives, so did their divergence. This may be because more well-versed people are better attuned to the position of their political group and more confident in defending it.



SOURCE: "INDIVIDUALS WITH GREATER SCIENCE LITERACY AND EDUCATION HAVE MORE POLARIZED BELIEFS ON CONTROVERSIAL SCIENCE TOPICS," BY CAITLIN DRUMMOND AND BARUCH FISCHHOFF, IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 114, NO. 36; SEPTEMBER 5, 2017

[redacted]

THE SCIENCE OF CLIMATE SCIENCE

EXPERT JUDGMENT, which is dependent on good feedback, comes into play when one is predicting the costs and benefits of attempts to slow climate change or to adapt to it. Climate analyses combine the judgments of experts from many research areas, including obvious ones, such as atmospheric chemistry and oceanography, and less obvious ones, such as botany, archaeology and glaciology. In complex climate analyses, these expert judgments reflect great knowedge driven by evidence-based feedback. But some aspects still remain uncertain.

My first encounter with these analyses was in 1979, as part of a project planning the next 20 years of cli-

Graphic by Jen Christiansen

mate research. Sponsored by the Department of Energy, the project had five working groups. One dealt with the oceans and polar regions, a second with the managed biosphere, a third with the less managed biosphere, and a fourth with economics and geopolitics. The fifth group, which I joined, dealt with social and institutional responses to the threat.

Even then, 40 years ago, the evidence was strong enough to reveal the enormous gamble being taken with our planet. Our overall report, summarizing all five groups, concluded that "the probable outcome is beyond human experience."

THINKING OF THE UNTHINKABLE

HOW, THEN, CAN RESEARCHERS in this area fulfill their duty to inform people about accurate ways to think about events and choices that are beyond their experience?

Risky Business

The way people view the risks of technologies and activities depends on factors such as familiarity, whether exposure is voluntary or involuntary, and the likelihood of fatalities. Novelty, involuntary exposure and lethal potential lead people to rate things as riskier, assessments that sometimes differ from scientific counts and estimates. The results come from surveys given to laypeople and first published in 1978; they have been repeated often with similar findings.

[redacted]

SOURCE: *RISK: A VERY SHORT INTRODUCTION*, BY BARUCH FISCHHOFF AND JOHN KADVANY. OXFORD UNIVERSITY PRESS, 2011; REDRAFTED FROM "HOW SAFE IS SAFE ENOUGH? A PSYCHOMETRIC STUDY OF ATTITUDES TOWARDS TECHNOLOGICAL RISKS AND BENEFITS," BY BARUCH FISCHHOFF ET AL., IN *POLICY SCIENCES*, VOL. 9, NO. 2; APRIL 1978

Scientists can, in fact, accomplish this if they follow two basic lessons from studies of decision-making.

LESSON 1: The facts of climate science will not speak for themselves. The science needs to be translated into terms that are relevant to people's decisions about their lives, their communities and their society. While most scientists are experienced communicators in a classroom, out in the world they may not get feedback on how clear or relevant their messages are.

Addressing this feedback problem is straightforward: test messages before sending them. One can learn a lot simply by asking people to read and paraphrase a message. When communication researchers have asked for such rephrasing about weather forecasts, for example, they have found that some are confused by the statement that there is a "70 percent chance of rain." The problem is with the words, not the number. Does the forecast mean it will rain 70 percent of the time? Over 70 percent of the area? Or there is a 70 percent chance of at least 0.01 inch of rain at the weather station? The last interpretation is the correct answer.

Many studies have found that numbers, such as 70 percent, generally communicate much better than "verbal quantifiers," such as "likely," "some" or "often." One classic case from the 1950s involves a U.S. National Intelligence Estimate that said that "an attack on Yugoslavia in 1951 should be considered a serious possibility." When asked what probability they had in mind, the analysts who signed the document gave a wide range of numbers, from 20 to 80 percent. (The Soviets did not invade.)

Sometimes people want to know more than the probability of rain or war when they make decisions. They want to understand the processes that lead to those probabilities: how things work. Studies have found that some critical aspects of climate change research are not intuitive for many people, such as how scientists can bicker yet still agree about the threat of climate change or how carbon dioxide is different from other pollutants. (It stays in the atmosphere longer.) People may reject the research results unless scientists tell them more about how they were derived.

LESSON 2: People who agree on the facts can still disagree on what to do about them. A solution that seems sound to some can seem too costly or unfair to others.

For example, people who like plans for carbon capture and sequestration, because it keeps carbon dioxide out of the air, might oppose using it on coal-fired power plants. They fear an indirect consequence: cleaner coal may make mountaintop-removal mining more acceptable. Those who know what cap-and-trade schemes are meant to do—create incentives for reducing emissions—might still believe that they will benefit banks more than the environment.

These examples show why two-way communication

Graphic by Jen Christiansen

is so important in these situations. We need to learn what is on others' minds and make them feel like partners in decision-making. Sometimes that communication will reveal misunderstandings that research can reduce. Or it may reveal solutions that make more people happy. One example is British Columbia's revenue-neutral carbon tax, whose revenues make other taxes lower; it has also produced broad enough political support to weather several changes of government since 2008. Sometimes, of course, better two-way communication will reveal fundamental disagreements, and in those cases action is a matter for the courts, streets and ballot boxes.

YOUNG activists gathered in New York City in May to demand immediate action on climate change.

ERIK McGREGOR *Getty Images*

MORE THAN SCIENCE

THESE LESSONS about how facts are communicated and interpreted are important because climate-related decisions are not always based on what research says or shows. For some individuals, scientific evidence or economic impacts are less important than what certain decisions reveal about their beliefs. These people ask how their choice will affect the way others think about them, as well as how they think about themselves.

For instance, there are people who forgo energy conservation measures but not because they are against conservation. They just do not want to be perceived as eco-freaks. Others who conserve do it more as a symbolic gesture and not based on a belief that it makes a real difference. Using surveys, researchers at Yale Climate Connections have identified what they call Six Americas in terms of attitudes, ranging from alarmed to dismissive. People at those two extremes are the ones who are most likely to adopt measures to conserve energy. The alarmed group's motives are what you might expect. Those in the dismissive group, though, may see no threat from climate change but also have noted they can save money by reducing their energy consumption.

Knowing the science does not necessarily mean agreeing with the science. The Yale study is one of several that found greater polarization among different political groups as people in the groups gained knowledge of some science-related issues. In ongoing research, Caitlin Drummond, currently a postdoctoral fellow at the University of Michigan's Erb Institute, and I have uncovered a few hints that might account for this phenomenon. One possible explanation is that more knowledgeable people are more likely to know the position of their affiliated political group on an issue and align themselves with it. A second possibility is that they feel more confident about arguing the issues. A third, related explanation is that they are more likely to see, and seize, the chance to express themselves than those who do not know as much.

WHEN DECISIONS MATTER MOST

ALTHOUGH DECISION SCIENCE researchers still have much to learn, their overall message about ways to deal with uncertain, high-stakes situations is optimistic. When scientists communicate poorly, it often indicates that they have fallen prey to a natural human tendency to exaggerate how well others understand them. When laypeople make mistakes, it often reflects their reliance on mental models that have served them well in other situations but that are not accurate in current circumstances. When people disagree about what decisions to make, it is often because they have different goals rather than different facts.

In each case, the research points to ways to help people better understand one another and themselves. Communication studies can help scientists create clearer messages. And decision science can help the public to refine their mental models to interpret new phenomena. By reducing miscommunication and focusing on legitimate disagreements, decision researchers can help society have fewer conflicts and make dealing with the ones that remain easier for us all. SA

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DATA SCIENCE

CONFRONTING UNKNOWNS

HOW TO INTERPRET UNCERTAINTY IN COMMON FORMS OF DATA VISUALIZATION

By Jessica Hullman

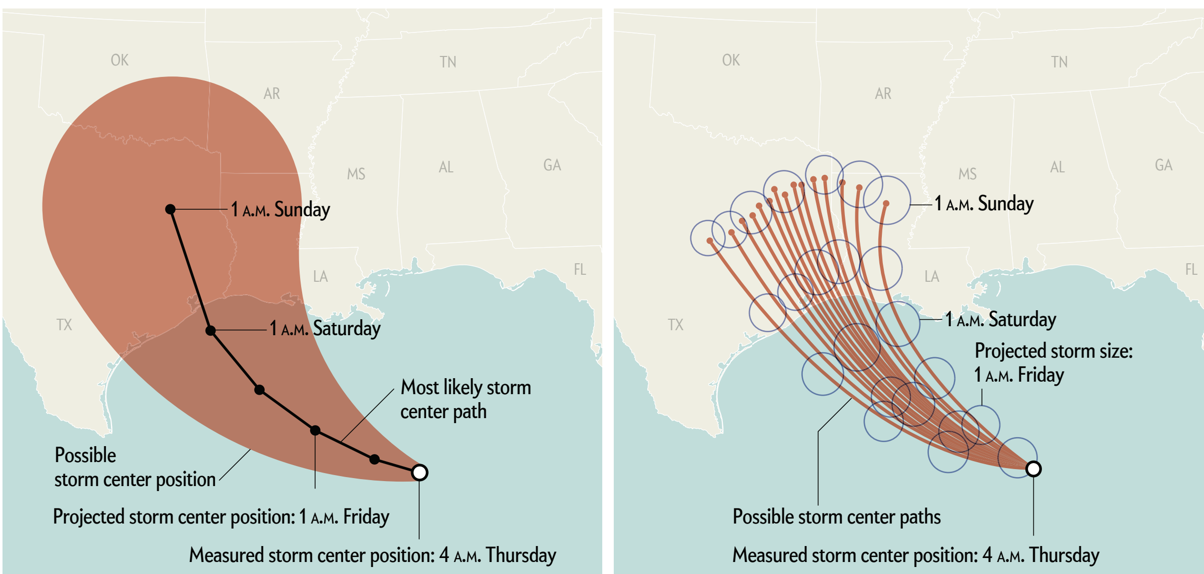
Jessica Hullman is a professor of computer science and journalism at Northwestern University. She and her research group develop and evaluate data-visualization and data-interaction techniques to enhance reasoning about uncertainty.

When tracking a hurricane, forecasters often show a map depicting a "cone of uncertainty." It starts as a point—the hurricane's current position—and widens into a swath of territory the storm might cross in the upcoming days. The most likely path is along the centerline of the cone, with the probability falling off toward the edges. The problem: many people misinterpret the cone as the size of the future storm.

Researchers have found that the misunderstanding can be prevented if forecasters instead show a number of possible paths. Yet this approach can also introduce misunderstanding: lots of people think the probability of damage is greater where each path intersects land and less likely between the lines (*maps*).

Uncertainty pervades the data that scientists and all kinds of organizations use to inform decisions. Visual depictions of information can help clarify the uncertainty—or compound confusion. Ideally, visualizations help us make judgments, analytically and emotionally, about the probability of different outcomes. Abundant evidence on human reasoning suggests, however, that when people are asked to make judgments involving probability, they often discount uncertainty. As society increasingly relies on data, graphics designers are grappling with how best to show uncertainty clearly.

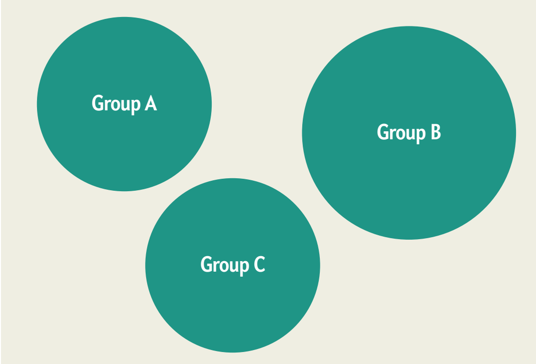
What follows is a gallery of visualization techniques for displaying uncertainty, organized roughly from less effective to more effective. Seeing how different approaches are chosen and implemented can help us become more savvy consumers of data and the uncertainty involved. ■

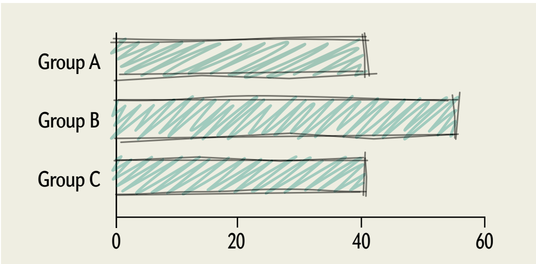


"CONE OF UNCERTAINTY" (*left*) shows where a hurricane may head, according to a group of forecasts. An alternative is to show the specific path predicted by each forecast (*right*). Both approaches have pros and cons in helping people judge the risk they may face, but the one on the right makes it clearer that the path is difficult to predict.

SOURCES: NATIONAL HURRICANE CENTER (*cone of uncertainty*); "VISUALIZING UNCERTAIN TROPICAL CYCLONE PREDICTIONS USING REPRESENTATIVE SAMPLES FROM ENSEMBLES OF FORECAST TRACKS," BY LE LIU ET AL., IN *IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS*, VOL. 25; AUGUST 20, 2018 (*multiple storm paths*)

Maps by Tiffany Farrant-Gonzalez





NO QUANTIFICATION

The least effective way to present uncertainty is to not show it at all. Sometimes data designers try to compensate for a lack of specified uncertainty by choosing a technique that implies a level of imprecision but does not quantify it. For example, a designer might map data to a visual variable that is hard for people to define, such as a circle floating in space (*top*) rather than a dot on a graph that has *x* and *y* axes. This approach makes the reader's interpretation more error-prone. Alternatively a designer might use a program that creates a hand-drawn or "sketchy" feel (*bottom*). Both approaches are risky.

PROS

- If readers sense that a visualization is difficult to quantify or is simply impressionistic, they may be more cautious in making inferences or decisions based on it.

CONS

- Readers may not realize that the visualization is intended to convey imprecision and may reach conclusions that have large errors.
- Even if readers recognize that the visualization was chosen to imply imprecision, they have no way of inferring how much uncertainty is involved.

INTERVALS

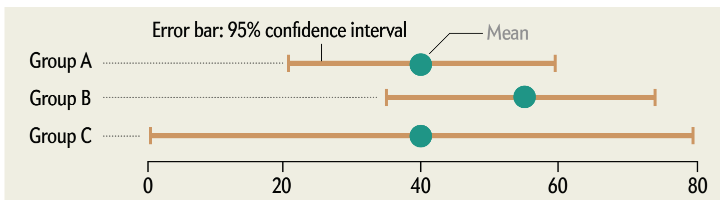
Intervals may be the most common representations of quantified uncertainty. Error bars (*top*) and confidence envelopes (*bottom*) are widely recognized, but even though they seem exact and straightforward, they are notoriously hard to interpret properly. Research shows they are often misunderstood, even by scientists.

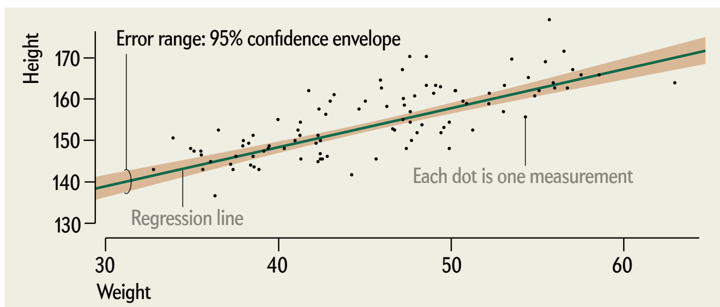
PROS

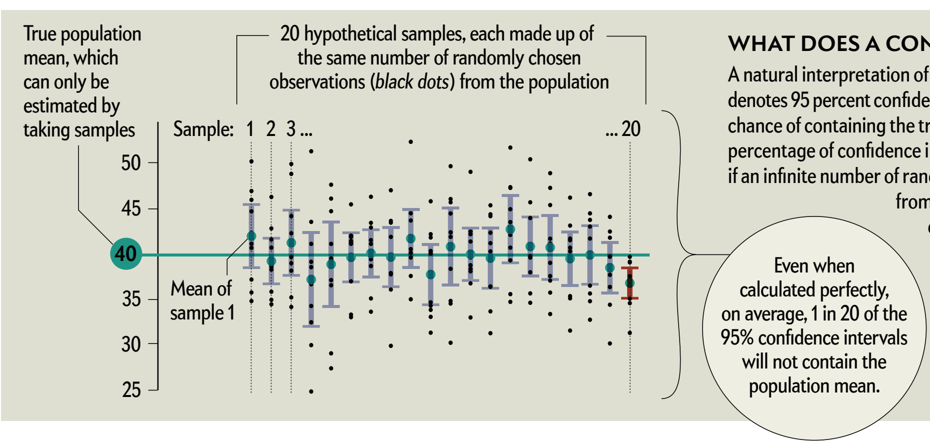
- Widely recognized as a representation of uncertainty.
- Offers a simple format for expressing the possibility of different values.
- The choice of interval can be customized for different types of questions about the same data set. For example, when one is making inferences about the range of values in a population, intervals based on standard deviation are helpful; for inferences about the range of values of a statistic like a mean, intervals based on standard error are appropriate.

CONS

- Ambiguity in what is shown: intervals may represent standard deviation, standard error or something else. Each has a unique interpretation.
- Readers can make "deterministic construal errors"—interpreting the ends of the error bar as the high and low values in observed measurements rather than estimates denoting uncertainty.
- Error bars can lead to "within-the-bar bias," common in bar charts. Below, readers may see the bar values to the right of the dots as more probable than the bar values to the left.
- Easy to ignore the uncertainty regions in favor of the central tendency, which may lead to incorrect decisions.







WHAT DOES A CONFIDENCE INTERVAL MEAN?

A natural interpretation of an error bar or confidence envelope that denotes 95 percent confidence is that the interval has a 95 percent chance of containing the true value. Yet it actually refers to the percentage of confidence intervals that would include the true value if an infinite number of random samples of the same size were pulled from the data and each time a 95 percent confidence interval was constructed. Although in practice this pervasive misinterpretation may not drastically change decisions, the fact that even scientists make such mistakes shows how challenging it can be to interpret uncertainty depictions correctly.

Graphics by Jessica Hullman and Jen Christiansen

PROBABILITY DENSITY MAPS

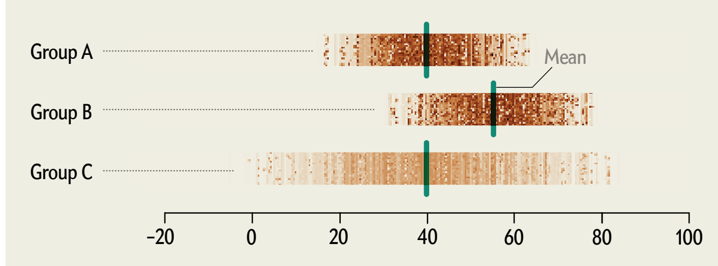
Designers can map uncertainty directly to a visual property of the visualization. For example, a gradient plot (*top*) can shift from dark color (high probability) at the center to lighter color (low probability) at the edges. In a violin plot (*bottom*), wider points mean greater probability. Mapping probability density to a visual variable displays uncertainty in greater detail than interval methods (error bars and confidence envelopes), but its effectiveness depends on how well readers can perceive differences in shading, height or other visual properties.

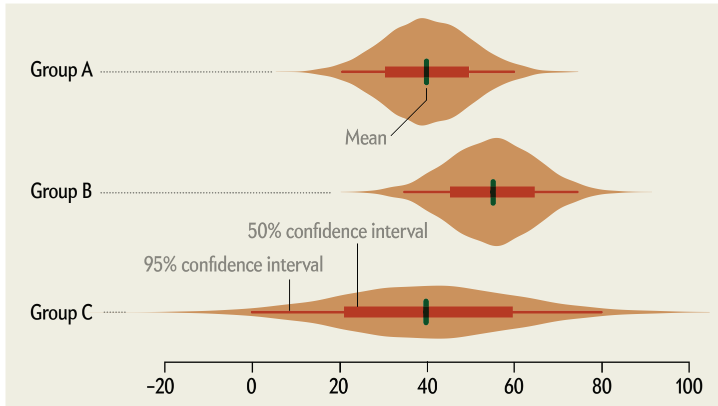
PROS

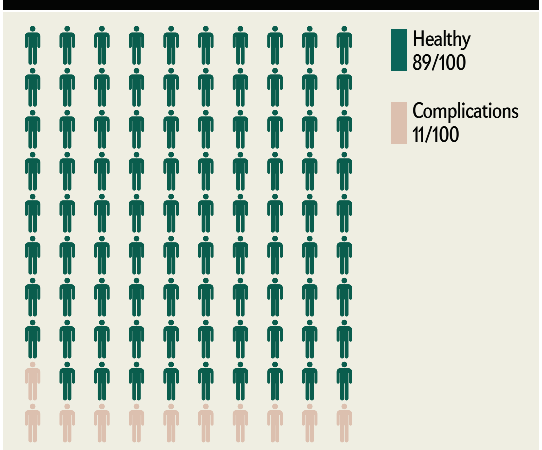
- Often well aligned with intuition: dark shading or hard boundaries are certain; light shading or fuzzy boundaries are uncertain.
- Avoids common biases such as those raised by intervals.

CONS

- Readers may not recognize that density reflects probability.
- Readers often equate the part of the visualization that is easiest to read (darkest, widest) with the data values themselves and misinterpret the parts that are harder to read (lightest, most narrow) as the uncertainty.
- Estimates can be biased to the darkest or highest points.
- Can be difficult to infer specific probability values.







ARRAYS OF ICONS

Reframing a probability such as 30 percent as a frequency—three out of 10—can make it easier for people to understand uncertainty and consequently use such information appropriately. People may better understand discrete probabilities because they run into them in everyday experiences.

PROS

- More self-explanatory than some other techniques because readers can readily see that probability is analogous to the number of times a symbol appears.
- Readers can make quick estimates if a small number of symbols is used because our visual system recognizes small quantities immediately without counting.

CONS

- Designed to present only a single probability.

MULTIPLE SAMPLES IN SPACE

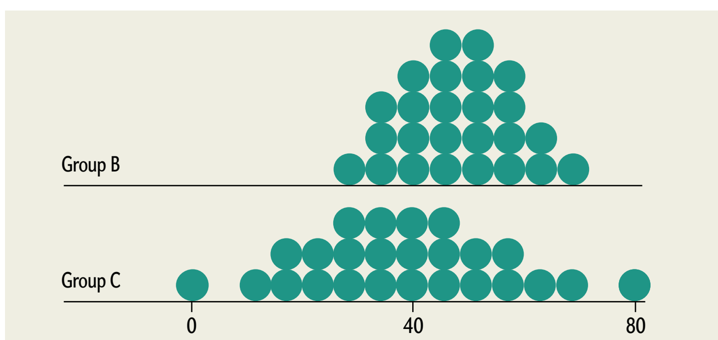
Plotting of multiple samples in space can be used to show probability in a discrete format for one or more variable quantities. One example of this approach is a quantile dot plot. It shows a number of distinct cases from the quantiles of the data distribution, so that the number of dots (such as two dots high or five dots high, in the example below) conveys probability. When there is uncertainty about parameter values from which estimates are drawn, such as initial conditions, samples can be generated that vary these parameters. and can be shown in a single visualization.

PROS

- A designer can choose how many data samples to present, aiming to show enough to convey the distribution but not so many that it becomes difficult for a reader to make out the individual samples.

CONS

- Plotting many data samples can result in occlusion, making probability estimates more error-prone.
- Sampling introduces imprecision, especially if the underlying distribution is heavily skewed by outliers.

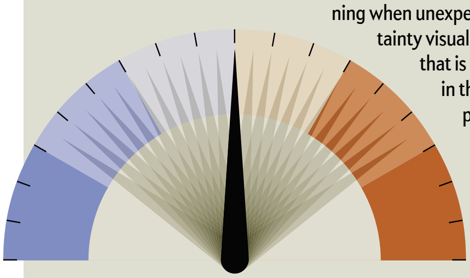


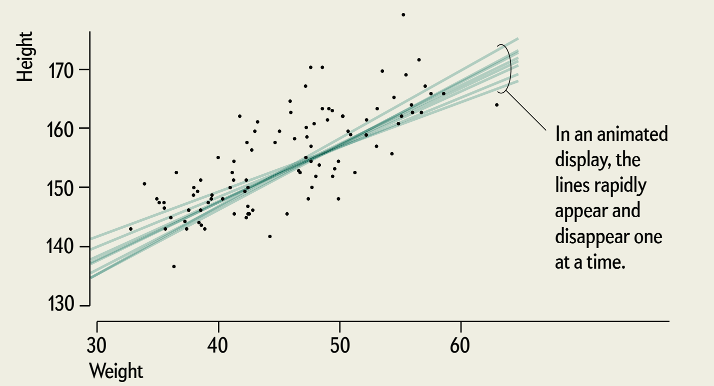
Graphics by Jessica Hullman and Jen Christiansen

A JITTERY ELECTION NIGHT NEEDLE

Sometimes an uncertainty visualization is controversial. On the night of the 2016 presidential election in the U.S., the o m introduced an animated gauge on its Web site to display predictions about the outcome. A continuum of colored areas made up the background, from a landslide Clinton win (t) to a landslide Trump win (t). The data model behind the gauge updated several times a minute as new local results came in. An animated needle jiggled back and forth rapidly, even more frequently than the model was updated.

Seeing a constantly moving visualization made many viewers anxious on an evening when unexpected events transpired. Uncertainty visualizations o provoke anxiety that is proportional to the uncertainty in the data. But after decades of people seeing only static projections for election outcomes that allowed viewers to overlook uncertainty, suddenly shifting to a visualization that provoked a visceral reaction to uncertainty was unsettling.


Chance of winning election



MULTIPLE SAMPLES IN TIME

Plotting multiple possible outcomes as frames in an animation makes uncertainty visceral and much harder to ignore. This technique, called hypothetical outcome plots, can be used for simple and complex visualizations. Perceptual studies indicate that people are surprisingly adept at inferring the distribution of data from the frequency of occurrences: we do not necessarily need to count the number of times an event occurs to estimate its probability. One important factor is the speed of events, which must be fast enough so that people can see a sufficient number of samples yet slow enough for them to consciously register what they saw.

PROS

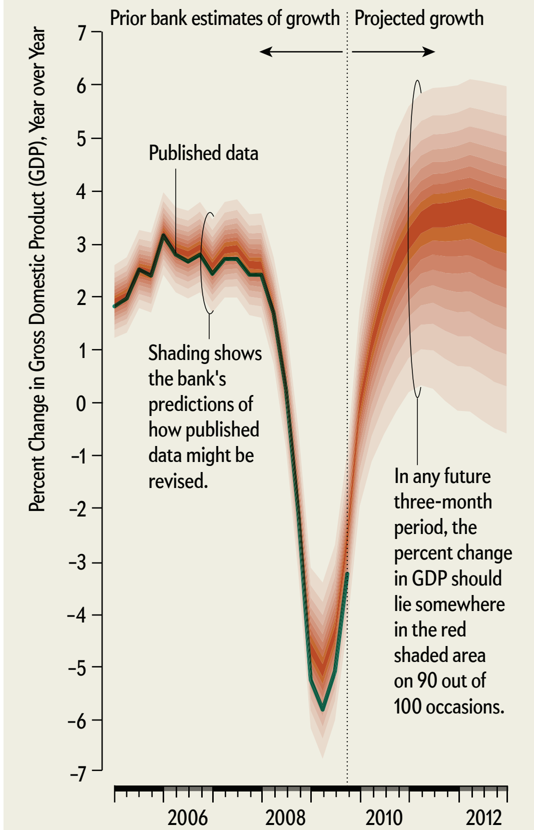
- The human visual system can estimate probability fairly accurately without having to deliberately count the items presented.
- Can be applied widely across different data types and visualization styles.
- Animation makes it possible to estimate probabilities involving multiple variables, which is difficult with static plots.

CONS

- Sampling introduces imprecision, especially if the distribution is heavily skewed by outliers.
- No guarantees on how many individual samples a user will pay attention to.
- Requires creating a dynamic or animated visualization, which some formats such as scientific papers may not yet easily support.

HYBRID APPROACHES

Designers can create effective uncertainty visualizations by combining different techniques rather than choosing a standard chart "type." One example is a fan chart, made famous by the Bank of England (o). It depicts data up to the present (t o ott), then projections into the future (t); uncertainty about the past is an important component in assessing uncertainty about the future. The fan chart presents probability from higher chance ( ) to lesser chance (t) in multiple bands that represent different levels of confidence, which the reader can choose from. Readers can perceive the information through the position of the edges of the bands, as well as lightness versus darkness. Some modern software packages for statistical graphics and modeling make it easy to combine uncertainty visualization approaches.



SOURCE: INFLATION REPORT. BANK OF ENGLAND, FEBRUARY 2010 (GDP chart)

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scientificamerican.com/magazine/sa

Illustration by Tiffany Farrant-Gonzalez (election needle)

SOCIAL PSYCHOLOGY

RADICAL CHANGE

UNCERTAINTY IN THE WORLD THREATENS OUR SENSE OF SELF. TO COPE, PEOPLE EMBRACE POPULISM

By Michael A. Hogg

Human societies are constantly rearranging themselves, causing profound disruptions in our social lives. The industrial revolution of the late 18th and early 19th century fragmented communities as people moved for work, the decay of empires in the early 20th century reconfigured nations and national identities, and the Great Depression of the 1930s shattered people's economic security and future prospects. But we are now in what is perhaps a time of unprecedented uncertainty. The early 21st century is characterized by rapid and overwhelming change: globalization, immigration, technological revolution, unlimited access to information, sociopolitical volatility, the automation of work and a warming climate.

People need to have a firm sense of identity and their place in the world, and for many the pace and magnitude of such change can be alienating. This is because our sense of self is a fundamental organizing principle for our own perceptions, feelings, attitudes and actions. Typically it is anchored in our close interpersonal relationships—our friends, family, partners—and in the variety of social groups and categories that we belong to and identify with—our nationality, religion, ethnicity, profession. It allows us to predict with some confidence how others will view us and treat us.

Imagine navigating all the situations and people we encounter in day-to-day life while continually feeling uncertain about who we are, how to behave and how

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Illustration by Wesley Allsbrook

social interactions will unfold. We would feel disorientated, anxious, stressed, cognitively depleted, and lacking agency and control. This self-uncertainty can, in fact, be experienced as an exciting challenge if we feel we have the material, social and psychological resources to resolve it. If we feel we do not have these resources, however, it can be experienced as a highly aversive threat to ourselves and our place in the world.

Generally, self-uncertainty is a sensation that people are motivated to reduce. When people are increasingly unsure about who they are and how they fit into this rapidly changing landscape, it can be—and indeed has become—a real problem for society. People are supporting and enabling authoritarian leaders, flocking to ideologies and worldviews that promote and celebrate the myth of a glorious past. Fearful of people who are different from themselves, they seek homogeneity and become intoxicated by the freedom to access only information that confirms who they are or who they would like to be. As a result, global populism is on the rise.

SEEKING SOCIAL IDENTITY

ONE POWERFUL SOURCE of identity resides in social groups. They can be highly effective at reducing a person's self-uncertainty—particularly if such groups are distinctive and have members who share a sense of interdependence.

Groups play this central role in anchoring who we are because they are social categories, and research shows that social categorization is ubiquitous. A person categorizes others as either "in-group" or "out-group" members. They assign the group's attributes and social standing to those others, thereby constructing a subjective world where groups are internally homogeneous and the differences between groups are exaggerated and polarized in an ethnocentric manner. And because we also categorize ourselves, we internalize shared in-group-defining attributes as part of who we are. To build social identity, we psychologically surround ourselves with those who are like us.

This psychological process that causes people to identify with groups and behave as group members is called social categorization. It anchors and crystallizes our sense of self by assigning us an identity that prescribes how we should behave, what we should think and how we should make sense of the world. It also makes interaction predictable, allows us to anticipate how people will treat and think about us, and furnishes consensual identity confirmation: people like us—the in-group members—validate who we are.

This self-uncertainty social-identity dynamic is not in itself a bad thing. It enables the collective organization that lies at the heart of human society. Human achievements that require the coordination of many in the service of common goals cannot be achieved by people on their own. Yet this dynamic becomes a problem when the sense of self-uncertainty and identity threat is acute, enduring and all-encompassing. People then

IN BRIEF

Ra i a o e hel i g change can threaten people's sense of self and identity.

el ce ai motivates people to seek out stronger group identification as well as leadership preferences that can encourage confirmation bias and populism.

o h he e ac o are facilitated and exacerbated by the availability of unlimited information and access to extremist groups on the Internet.

HOW A NEUROSCIENTIST SEARCHES FOR ANSWERS

Science does not search for truth, as many might think.

Rather the real purpose of science is to look for better questions. We run experiments because we are ignorant about something and want to learn more, and sometimes those experiments fail. But what we learn from our ignorance and failure opens new questions and new uncertainties. And these are better questions and better uncertainties, which lead to new experiments. And so on.

Take my field, neurobiology. For around 50 years the fundamental question for the sensory system has been: What information is being sent into the brain? For instance, what do our eyes tell our brain? Now we are seeing a reversal of that idea: the brain is actually asking questions of the sensory system. The brain may not be simply sifting through massive amounts of visual information from, say, the eye; instead it is asking the eye to seek specific information.

In science, there are invariably loose ends and little blind alleys. While you may think you have everything cleared up, there is always something new and unexpected. But there is value in uncertainty. It shouldn't create anxiety. It's an opportunity.

***Stuart Firestein,** a professor in the department of biological sciences at Columbia University, as told to Brooke Borel*

Illustration by Bud Cook

experience an overwhelming need for identity—and not just any identities but ones that are well equipped to resolve those disorienting, even scary, feelings.

REDUCING UNCERTAINTY THROUGH GROUP MEMBERSHIP

SOME FEATURES of groups and social identities are especially well suited to reducing self-uncertainty. Most important, groups need to be polarized from other groups and have unambiguous boundaries that distinguish between those who are "in" and those who are "out." Internally they need to be clearly structured, typically in a hierarchical way. These features make the group cohesive and homogeneous, such that members are interdependent and of one mind in sharing a common fate.

Diversity and dissent reinstate uncertainty and are therefore avoided. When these facets do occur, individuals and the group as a whole react decisively and harshly, creating an atmosphere of suspicion that lays the ground for persecution of alleged deviants. It breeds an opportunity for personal dislikes and vendettas to escalate under the guise of protecting cohesion.

That members are accepted and trusted fully is important not only for the group but also for the members themselves. After all, they desperately want to be included so that their identity is validated and their uncertainty thus reduced. Prospective and new members—and those who suspect they are viewed with suspicion or are uncertain about whether they are fully accepted—will go to extremes on behalf of the group to prove their membership credentials and loyalty. These individuals are vulnerable to zealotry and radicalization. Neo-Nazis and white supremacists who publicly engage in violent acts of terrorism and racial hatred are one example of this extremism.

The social identity embodied by such groups also needs to be uncomplicated so that it can be taken at face value as "the truth." Subtlety and nuance are anathema because they are an impediment to uncertainty reduction. Clarity on where the group stands allows its members to know how they should think and feel—as well as behave. Such identities are bolstered by having a strong ideology that identifies distasteful and morally bankrupt out-groups who can be demonized and cast in the role of "enemy." Conspiracy theories thrive in this environment because they establish these out-groups as agents of historical victimization by the in-group.

HOW UNCERTAINTY BREEDS POPULISM

IF SELF-UNCERTAINTY motivates people to identify with a group and internalize that identity as a key part of who they are, they need to be confident that they know exactly what the group's identity is. When you need what *you* consider to be reliable and trusted sources of identity information, where do you turn? The first port of call are those who you believe are consensually viewed by the group to be its leadership—typically it is a person whose leadership position is also formalized.

Recent research on how self-uncertainty affects the type of leaders that individuals prefer paints a potentially alarming picture. People just need someone to tell them what to do—and ideally those directives are coming from someone whom they can trust as "one of us." Self-uncertain people have also been shown to prefer leaders who are assertive and authoritarian, even autocratic, and who deliver a simple, black-and-white, affirmational message about "who we are" rather than a more open, nuanced and textured identity message.

Perhaps most troubling is that self-uncertainty can enable and build support for leaders who possess the so-called Dark Triad personality attributes: Machiavellianism, narcissism and psychopathy. Self-uncertainty, in other words, seems to fuel populism.

Another source of identity information is "people like you" who you feel embody the group's identity and see the world in the same way as you do. These can be people with whom you interact face-to-face or as friends or sources of information such as radio and television channels, particularly news outlets, that you watch. But nowadays these sources are overwhelmingly information and influence nodes on the Internet, such as Web sites, social media, Twitter feeds, podcasts, and so forth.

The Web is an ideal place to decrease the discomfort of self-uncertainty because it provides nonstop access to unlimited information that is often cherry-picked by individuals themselves and algorithms that do it discreetly. Therefore, people are only accessing identity-confirming information. Confirmation bias, a powerful and universal human bias that is especially strong under uncertainty, separates information and identity universes that fragment and polarize society. Online, people can easily seek out groups that may not be readily available in their physical lives.

The Internet further empowers confirmation bias under uncertainty because people want to be surrounded by those who think alike so that their identities and worldview are continuously confirmed. The contours of "truth" then map onto these self-contained social-identity universes. In this scenario, there are no absolute truths and no motivation to seriously explore and incorporate alternative viewpoints because that would be kryptonite to social identity's power to reduce self-uncertainty. This dynamic helps to explain why people dwell in increasingly homogeneous echo chambers that confirm their identity. SA

MORE TO EXPLORE

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C MM NICA I N

A NE RLD DI RDER

OUR WILLINGNESS TO SHARE CONTENT WITHOUT THINKING IS EXPLOITED TO SPREAD DISINFORMATION

By Claire Wardle

Clai e a le is U.S. director at the nonprofit First Draft, where she researches, leads projects and trains groups on understanding and tackling misinformation. Previously she was a research fellow at the Shorenstein Center on Media, Politics and Public Policy at Harvard University. She has a Ph.D. in communication from the University of Pennsylvania.

As someone who studies the impact of misinformation on society, I often wish the young entrepreneurs of Silicon Valley who enabled communication at speed had been forced to run a 9/11 scenario with their technologies before they deployed them commercially.

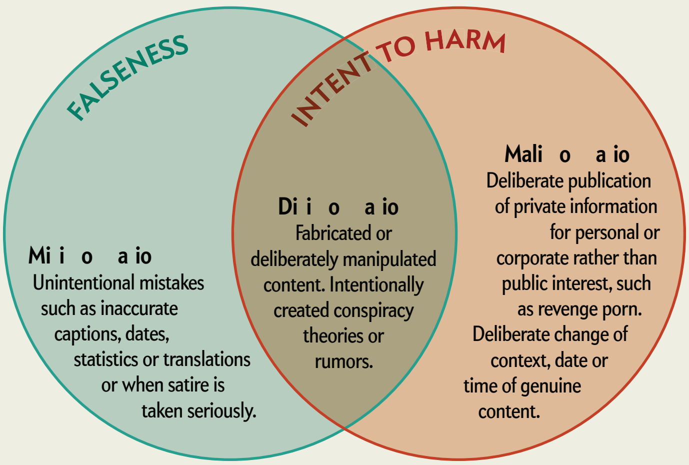
One of the most iconic images from that day shows a large clustering of New Yorkers staring upward. The power of the photograph is that we know the horror they're witnessing. It is easy to imagine that, today, almost everyone in that scene would be holding a smartphone. Some would be filming their observations and posting them to Twitter and Facebook. Powered by social media, rumors and misinformation would be rampant. Hate-filled posts aimed at the Muslim community would proliferate, the speculation and outrage boosted by algorithms responding to unprecedented levels of shares, comments and likes. Foreign agents of disinformation would amplify the division, driving wedges between communities and sowing chaos. Meanwhile those stranded on the tops of the towers would be livestreaming their final moments.

Stress testing technology in the context of the worst moments in history might have illuminated what social scientists and propagandists have long known: that humans are wired to respond to emotional triggers and share misinformation if it reinforces existing beliefs and prejudices. Instead designers of the social platforms fervently believed that connection would drive tolerance and counteract hate. They failed to see how technology

Illustration by Wesley Allsbrook

THREE CATEGORIES OF INFORMATION DISORDER

To understand and study the complexity of the information ecosystem, we need a common language. The current reliance on simplistic terms such as "fake news" hides important distinctions and denigrates journalism. It also focuses too much on "true" versus "fake," whereas information disorder comes in many shades of "misleading."



IN BRIEF

Ma e o i o a io i o e exist online, from fabricated videos to impersonated accounts to memes designed to manipulate genuine content.

A o a io a ic o a ge i g tactics have made it easier for agents of disinformation to weaponize regular users of the social web to spread harmful messages.

M ch e ea ch i ee e to understand the effects of disinformation and build safeguards against it.

would not change who we are fundamentally—it could only map onto existing human characteristics.

Online misinformation has been around since the mid-1990s. But in 2016 several events made it broadly clear that darker forces had emerged: automation, microtargeting and coordination were fueling information campaigns designed to manipulate public opinion at scale. Journalists in the Philippines started raising flags as Rodrigo Duterte rose to power, buoyed by intensive Facebook activity. This was followed by unexpected results in the Brexit referendum in June and then the U.S. presidential election in November—all of which sparked researchers to systematically investigate the ways in which information was being used as a weapon.

During the past three years the discussion around the causes of our polluted information ecosystem has focused almost entirely on actions taken (or not taken) by the technology companies. But this fixation is too simplistic. A complex web of societal shifts is making people more susceptible to misinformation and conspiracy. Trust in institutions is falling because of political and economic upheaval, most notably through ever widening income inequality. The effects of climate change are becoming more pronounced. Global migration trends spark concern that communities will change irrevocably. The rise of automation makes people fear for their jobs and their privacy.

Bad actors who want to deepen existing tensions understand these societal trends, designing content that they hope will so anger or excite targeted users that the audience will become the messenger. The goal is that users will use their own social capital to reinforce and give credibility to that original message.

Most of this content is designed not to persuade people in any particular direction but to cause confusion, to overwhelm and to undermine trust in democratic institutions from the electoral system to journalism. And although much is being made about preparing the U.S. electorate for the 2020 election, misleading and conspiratorial content did not begin with the 2016 presidential race, and it will not end after this one. As tools designed to manipulate and amplify content become cheaper and more accessible, it will be even easier to weaponize users as unwitting agents of disinformation.

WEAPONIZING CONTEXT

GENERALLY, THE LANGUAGE used to discuss the misinformation problem is too simplistic. Effective research and interventions require clear definitions, yet many people use the problematic phrase "fake news." Used by politicians around the world to attack a free press, the term is dangerous. Recent research shows that audiences increasingly connect it with the mainstream media. It is often used as a catchall to describe things that are not the same, including lies, rumors, hoaxes, misinformation, conspiracies and propaganda, but it also papers over nuance and complexity. Much of this content does not even masquerade as news—it appears as memes, videos and social posts on Facebook and Instagram.

In February 2017 I created seven types of "information disorder" in an attempt to emphasize the spectrum of content being used to pollute the information ecosystem. They included, among others, satire, which is not intended to cause harm but still has the potential to fool; fabricated content, which is 100 percent false and designed to deceive and do harm; and false context, which is when genuine content is shared with false contextual information. Later that year technology journalist Hossein Derakhshan and I published a report that mapped out the differentiations among disinformation, misinformation and malinformation.

Purveyors of *dis*information—content that is intentionally false and designed to cause harm—are motivated by three distinct goals: to make money; to have political influence, either foreign or domestic; and to cause trouble for the sake of it.

Those who spread *mis*information—false content shared by a person who does not realize it is false or misleading—are driven by sociopsychological factors. People are performing their identities on social platforms to feel connected to others, whether the "others" are a political party, parents who do not vaccinate their children, activists who are concerned about climate change, or those who belong to a certain religion, race or ethnic group. Crucially, disinformation can turn into misinformation when people share disinformation without realizing it is false.

We added the term "*mal*information" to describe genuine information that is shared with an intent to cause harm. An example of this is when Russian agents hacked into e-mails from the Democratic National Committee and the Hillary Clinton cam-

GRAPHIC BY JEN CHRISTIANSEN; SOURCE: *INFORMATION DISORDER: TOWARD AN INTERDISCIPLINARY FRAMEWORK FOR RESEARCH AND POLICYMAKING*, BY CLAIRE WARDLE AND HOSSEIN DERAKHSHAN. COUNCIL OF EUROPE, OCTOBER 2017

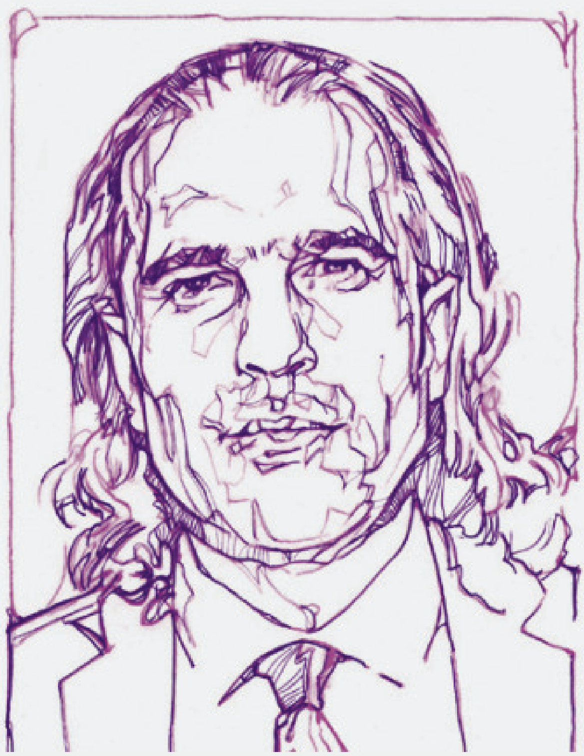
paign and leaked certain details to the public to damage reputations.

Having monitored misinformation in eight elections around the world since 2016, I have observed a shift in tactics and techniques. The most effective disinformation has always been that which has a kernel of truth to it, and indeed most of the content being disseminated now is not fake—it is misleading. Instead of wholly fabricated stories, influence agents are reframing genuine content and using hyperbolic headlines. The strategy involves connecting genuine content with polarizing topics or people. Because bad actors are always one step (or many steps) ahead of platform moderation, they are relabeling emotive disinformation as satire so that it will not get picked up by fact-checking processes. In these efforts, context, rather than content, is being weaponized. The result is intentional chaos.

Take, for example, the edited video of House Speaker Nancy Pelosi that circulated this past May. It was a genuine video, but an agent of disinformation slowed down the video and then posted that clip to make it seem that Pelosi was slurring her words. Just as intended, some viewers immediately began speculating that Pelosi was drunk, and the video spread on social media. Then the mainstream media picked it up, which undoubtedly made many more people aware of the video than would have originally encountered it.

Research has found that traditionally reporting on misleading content can potentially cause more harm. Our brains are wired to rely on heuristics, or mental shortcuts, to help us judge credibility. As a result, repetition and familiarity are two of the most effective mechanisms for ingraining misleading narratives, even when viewers have received contextual information explaining why they should know a narrative is not true.

HOW A THEORETICAL PHYSICIST SEARCHES FOR ANSWERS



Physics is the most mature science, and physicists are obsessive on the subject of truth. There is an actual universe out there. The central miracle is that there are simple underlying laws, expressed in the precise language of mathematics, which can describe it. That said, physicists don't traffic in certainties but in degrees of confidence. We've learned our lesson: throughout history, we have again and again found out that some principle we thought was central to the ultimate description of reality isn't quite right.

To figure out how the world works, we have theories and build experiments to test them. Historically, this method works. For example, physicists predicted the existence of the Higgs boson particle in 1964, built the Large Hadron Collider (LHC) at CERN in the late 1990s and early 2000s, and found physical evidence of the Higgs in 2012. Other times we can't build the experiment—it is too massive or expensive or would be impossible with available technology. So we try thought experiments that pull from the existing infrastructure of existing mathematical laws and experimental data.

Here's one: The concept of spacetime has been accepted since the early 1900s. But to look at smaller spaces, you have to use more powerful resolution. That's why the LHC is 17 miles around—to produce the huge energies needed to probe tiny distances between particles. But at some point, something bad happens. You'll put out such an enormous amount of energy to look at such a small bit of space that you'll actually create a black hole instead. Your attempt to see what is inside makes it impossible to do so, and the notion of spacetime breaks down.

At any moment in history, we can understand some aspects of the world but not everything. When a revolutionary change brings in more of the larger picture, we have to reconfigure what we knew. The old things are still part of the truth but have to be spun around and put back into the larger picture in a new way.

Nima Arkani-Hamed, a professor in the School of Natural Sciences at the Institute for Advanced Study in Princeton, N.J., as told to Brooke Borel

Bad actors know this: In 2018 media scholar Whitney Phillips published a report for the Data & Society Research Institute that explores how those attempting to push false and misleading narratives use techniques to encourage reporters to cover their narratives. Yet another recent report from the Institute for the Future found that only 15 percent of U.S. journalists had been trained in how to report on misinformation more responsibly. A central challenge now for reporters and fact checkers—and anyone with substantial reach, such as politicians and influencers—is how to untangle and debunk falsehoods such as the Pelosi video without giving the initial piece of content more oxygen.

MEMES: A MISINFORMATION POWERHOUSE

IN JANUARY 2017 the NPR radio show *This American Life* interviewed a handful of Trump supporters at one of his inaugural events called the DeploraBall. These people had been heavily involved in using social media to advocate for the president. Of Trump's surprising ascendance, one of the interviewees explained: "We memed him into power.... We directed the culture."

Of Trump's surprising ascendance, one of the DeploraBall interviewees explained: "We memed him into power.... We directed the culture."

The word "meme" was first used by theorist Richard Dawkins in his 1976 book, *The Selfish Gene,* to describe "a unit of cultural transmission or a unit of imitation," an idea, behavior or style that spreads quickly throughout a culture. During the past several decades the word has been appropriated to describe a type of online content that is usually visual and takes on a particular aesthetic design, combining colorful, striking images with block text. It often refers to other cultural and media events, sometimes explicitly but mostly implicitly.

This characteristic of implicit logic—a nod and wink to shared knowledge about an event or person—is what makes memes impactful. Enthymemes are rhetorical devices where the argument is made through the absence of the premise or conclusion. Often key references (a recent news event, a statement by a political figure, an advertising campaign or a wider cultural trend) are not spelled out, forcing the viewer to connect the dots. This extra work required of the viewer is a persuasive technique because it pulls an individual into the feeling of being connected to others. If the meme is poking fun or invoking outrage at the expense of another group, those associations are reinforced even further.

The seemingly playful nature of these visual formats means that memes have not been acknowledged by much of the research and policy community as influential vehicles for disinformation, conspiracy or hate. Yet the most effective misinformation is that which will be shared, and memes tend to be much more shareable than text. The entire narrative is visible in your feed; there is no need to click on a link. A 2019 book by An Xiao Mina, *Memes to Movements,* outlines how memes are changing social protests and power dynamics, but this type of serious examination is relatively rare.

Indeed, of the Russian-created posts and ads on Facebook related to the 2016 election, many were memes. They focused on polarizing candidates such as Bernie Sanders, Hillary Clinton or Donald Trump and on polarizing policies such as gun rights and immigration. Russian efforts often targeted groups based on race or religion, such as Black Lives Matter or Evangelical Christians. When the Facebook archive of Russian-generated memes was released, some of the commentary at the time centered on the lack of sophistication of the memes and their impact. But research has shown that when people are fearful, oversimplified narratives, conspiratorial explanation, and messages that demonize others become far more effective. These memes did just enough to drive people to click the share button.

Technology platforms such as Facebook, Instagram, Twitter and Pinterest play a significant role in encouraging this human behavior because they are designed to be performative in nature. Slowing down to check whether content is true before sharing it is far less compelling than reinforcing to your "audience" on these platforms that you love or hate a certain policy. The business model for so many of these platforms is attached to this identity performance because it encourages you to spend more time on their sites.

Researchers are now building monitoring technologies to track memes across different social platforms. But they can investigate only what they can access, and the data from visual posts on many social platforms are not made available to researchers. Additionally, techniques for studying text such as natural-language processing are far more advanced than techniques for studying images or videos. That means the research behind solutions being rolled out is disproportionately skewed toward text-based tweets, Web sites or articles published via URLs and fact-checking of claims by politicians in speeches.

Although plenty of blame has been placed on the technology companies—and for legitimate reasons—they are also products of the commercial context in which they operate. No algorithmic tweak, update to the platforms' content-moderation guidelines or regulatory fine will alone improve our information ecosystem at the level required.

PARTICIPATING IN THE SOLUTION

IN A HEALTHY INFORMATION commons, people would still be free to express what they want—but information that is designed to mislead, incite hatred, reinforce tribalism or cause physical harm would not be amplified by algorithms. That means it would not be allowed to trend on Twitter or in the YouTube content recommender. Nor would it be chosen to appear in Facebook feeds, Reddit searches or top Google results.

Until this amplification problem is resolved, it is precisely our willingness to share without thinking that agents of disinformation will use as a weapon. Hence, a disordered information environment requires that every person recognize how he or she, too, can become a vector in the information wars and develop a set of skills to navigate communication online as well as offline.

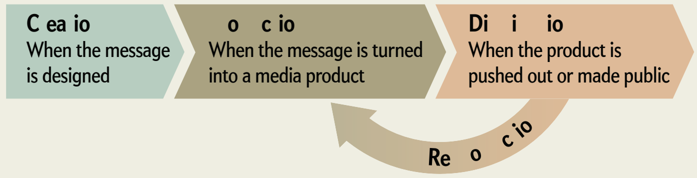
Currently conversations about public awareness are often focused on media literacy and often with a paternalistic framing that the public simply needs to be taught how to be smarter consumers of information. Instead online users would be better taught to develop cognitive "muscles" in emotional skepticism and trained to withstand the onslaught of content designed to trigger base fears and prejudices.

Anyone who uses Web sites that facilitate social interaction would do well to learn how they work—and especially how algorithms determine what users see by "prioritiz[ing] posts that spark conversations and meaningful interactions between people," in the case of a January 2018 Facebook update about its rankings. I would also recommend that everyone try to buy an advertisement on Facebook at least once. The process of setting up a campaign helps to drive understanding of the granularity of information available. You can choose to target a subcategory of people as specific as women, aged between 32 and 42, who live in the Raleigh-Durham area of North Carolina, have preschoolers, have a graduate degree, are Jewish and like Kamala Harris. The company even permits you to test these ads in environments that allow you to fail privately. These "dark ads" let organizations target posts at certain people, but they do not sit on that organization's main page. This makes it difficult for researchers or journalists to track what posts are being targeted at different groups of people, which is particularly concerning during elections.

Facebook events are another conduit for manipulation. One of the most alarming examples of foreign interference in a U.S. election was a protest that took place in Houston, Tex., yet was entirely orchestrated by trolls based in Russia. They had set up two Facebook pages that looked authentically American. One was named "Heart of Texas" and supported secession; it created an "event" for May 21, 2016, labeled "Stop Islamification of Texas." The other page, "United Muslims of America," advertised its own protest, entitled "Save Islamic Knowledge," for the exact same time and location. The result was that two groups of people came out to protest each other, while the real creators of the protest celebrated the success at amplifying existing tensions in Houston.

HOW DISINFORMATION BECOMES MISINFORMATION

The spread of false or misleading information is often dynamic. It starts when a disinformation agent engineers a message to cause maximum harm—for example, designing real-life protests that put opposing groups in public conflict. In the next phase, the agent creates "Event" pages on Facebook. The links are pushed out to communities that might be intrigued. People who see the event are unaware it is a false premise and share it with their communities, using their own framing. This reproduction continues.



GRAPHIC BY JEN CHRISTIANSEN; SOURCE: *INFORMATION DISORDER: TOWARD AN INTERDISCIPLINARY FRAMEWORK FOR RESEARCH AND POLICYMAKING,* BY CLAIRE WARDLE AND HOSSEIN DERAKHSHAN. COUNCIL OF EUROPE, OCTOBER 2017

Another popular tactic of disinformation agents is dubbed "astroturfing." The term was initially connected to people who wrote fake reviews for products online or tried to make it appear that a fan community was larger than it really was. Now automated campaigns use bots or the sophisticated coordination of passionate supporters and paid trolls, or a combination of both, to make it appear that a person or policy has considerable grassroots support. By making certain hashtags trend on Twitter, they hope that particular messaging will get picked up by the professional media and direct the amplification to bully specific people or organizations into silence.

Understanding how each one of us is subject to such campaigns—and might unwittingly participate in them—is a crucial first step to fighting back against those who seek to upend a sense of shared reality. Perhaps most important, though, accepting how vulnerable our society is to manufactured amplification needs to be done sensibly and calmly. Fearmongering will only fuel more conspiracy and continue to drive down trust in quality-information sources and institutions of democracy. There are no permanent solutions to weaponized narratives. Instead we need to adapt to this new normal. Just as putting on sunscreen was a habit that society developed over time and then adjusted as additional scientific research became available, building resiliency against a disordered information environment needs to be thought about in the same vein. SA

MORE TO EXPLORE

I o aio Dio e o a a l e ici li a a e o o Re ea cha olic Ma i g. Claire Wardle and Hossein Derakhshan. Council of Europe, October 2017.

Ne o o aga a Ma i la io Di i o a io a Ra icali a io i A e ica oli ic . Yochai Benkler, Robert Faris and Hal Roberts. Oxford University Press, 2018.

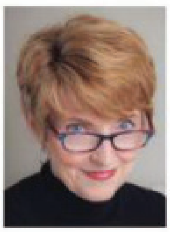
Me e o Mo e e Ho he o l Mo i al Me ia l Cha gi g ocial o e a o e. An Xiao Mina. Beacon Press, 2019.

Priming and Fake News: The Effects of Elite Discourse on Evaluations of News Media. Emily Van Duyn and Jessica Collier in *Mass Communication and Society,* Vol. 22, No. 1, pages 29–48; 2019.

FROM OUR ARCHIVES

Clic Lie a i eo a e. Brooke Borel; October 2018.

scientificamerican.com/magazine/sa



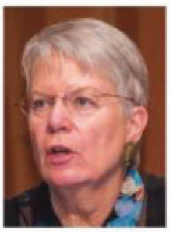
Millie Hughes-Fulford, Ph.D.

Professor of Medicine University of California Medical Center

Millie Hughes-Fulford was selected as a Scientist-Astronaut on the first Spacelab mission dedicated to biomedical studies in 1991 and has since continued her research into the mechanisms of cell growth and activation in spaceflight, winning an award from NASA in 2012 for discovering why the immune system is weakened in zero gravity.

Space: An Astronaut's Perspective

- Living and Working in Space
- ISS and Science
- The Right Stuff — Revised 2020 Edition
- The Future



Jill Tarter, Ph.D.

Emeritus Chair for SETI Research, SETI Institute

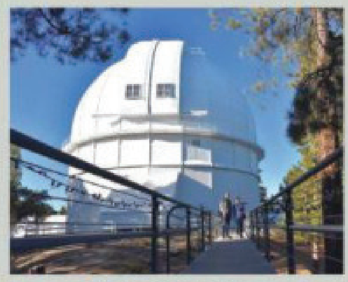
Jill Tarter achieved recognition for her work searching for evidence of extraterrestrial life, which entered public consciousness through the movie *Contact*, and has won several awards including the Lifetime Achievement Award from Women in Aerospace, two NASA Public Service Medals, *Time* Magazine's Top 100 Most Influential People in 2004 and many more for her dedication to communicating science to the public.

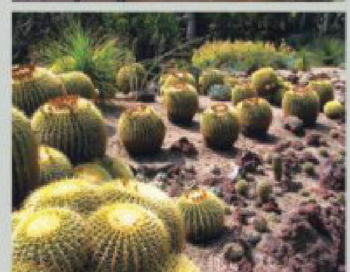
Habitable Worlds: The Search for Life

- Extremophiles on Earth
- Exoplanets
- Biosignatures
- Technosignatures

Post-Cruise Land Tour March 30 – April 3, 2020

Join us in Los Angeles to visit the most exciting science sites that SoCal has to offer. We'll go behind the scenes into the prep lab at the Natural History Museum to learn how scientists process fossils. We'll also enjoy private tours at NASA's Jet Propulsion Lab, CalTech and the Mount Wilson Observatory, where we'll stay until after dark to observe the stars through the same Hooker telescope that Edwin Hubble used in 1923 to discover the Andromeda galaxy.*





NOTES: Maximum of 40 for our private telescope reservation. Mt. Wilson Observatory is at 5,700 feet of elevation and not ADA compliant.

For speakers' complete bios, visit http://InsightCruises.com/events/sa39/#SPEAKERS.html

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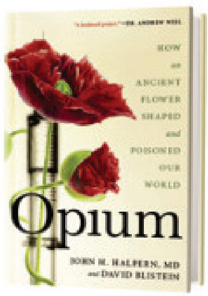
CST# 2065380-40

By Andrea Gawrylewski

Opium: How an Ancient Flower Shaped and Poisoned Our World

by John H. Halpern and David Blistein. Hachette Books, 2019 ($29)

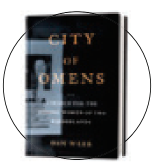


REBEL soldiers in an opium poppy field in Myanmar (formerly Burma).

Humanity's complicated relationship with the opium poppy dates back to our earliest civilizations. Psychiatrist Halpern and writer Blistein trace the plant's origins from ancient Mesopotamia to Greece to China, exploring how it became an effective medicine—and deadly drug. They weave together a history of the flower's medicinal uses, the origins of the opium trade and drug wars, and the modern opioid crisis. It's a story peppered with colorful anecdotes about Hippocrates' use of the drug to treat pain and other ailments, the brazen drug abuser Alexander the Great, and the notorious 19th-century opium dens of San Francisco. Halpern and Blistein decry the view of addiction as a moral failing instead of a disease and detail a long history of misguided and racist drug-enforcement efforts. Although we may never completely stop opioid deaths, they write, better prevention strategies can still save thousands of lives. *—Tanya Lewis*

City of Omens: A Search for the Missing Women of the Borderlands

by Dan Werb. Bloomsbury Publishing, 2019 ($28)



Throughout the past decade Tijuana has earned a reputation as one of the world's deadliest cities. Violence, sex trafficking and drug addiction have plagued the region and have made it vulnerable to rapid disease transmission. Epidemiologist Werb joined a research project in 2013 to help investigate the spread of two relentless epidemics in the border town: HIV and homicide. Women in particular were being killed at a staggering rate. In this riveting scientific detective story, Werb investigates the causes of the femicide. He discovers that the virus and murder were symptoms of a larger, more ferocious epidemic targeting Tijuana's women. "It was a multifaceted pathological process closing in on them from all sides simultaneously," Werb writes. *—Sunya Bhutta*

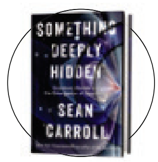
The Deep History of Ourselves: The Four-Billion-Year Story of How We Got Conscious Brains

by Joseph LeDoux. Viking, 2019 ($30)

Scientists often don't explain their work clearly. Neuroscientist LeDoux is unlikely to be accused of such neglect in his book, which sets out the entire history of life on Earth. He describes how all living organisms respond to basic needs: threats, food, reproduction, and so on. Survival behaviors, though, are distinct from emotional responses. A true feeling, LeDoux contends, emerges when, say, a threat from the brain's survival circuits is conveyed to "prefrontal" areas, which evolved quite recently in humans to produce an awareness of fear or anxiety, among other emotions. The definition of emotion that LeDoux puts forth raises the provocative question of whether any other animal but humans experiences conscious feelings. *—Gary Stix*

Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime

by Sean Carroll. Dutton, 2019 ($29)



Physicists are afraid of quantum mechanics, explains theorist and author Carroll, because they do not understand it—even though it lies at the heart of their discipline. This book is Carroll's unflinching attempt to face that fear, forgoing any mystical hand waving in favor of simply describing what is actually known. It is also an argument for one of the more mind-boggling interpretations of quantum mechanics, the many-worlds theory, which posits that the simplest solution to quantum paradoxes is to assume we live in an ever expanding, many-branched multiverse where every possibility is realized. *Something Deeply Hidden* is enlightening and refreshingly bold. Is it right? No one yet knows. *—Lee Billings*

THIERRY FALISE *Getty Images*

eynep Tufe ci is an associate professor at the University of North Carolina School of Information and Library Science and a regular contributor to the *New York Times*. Her book, *Twitter and Tear Gas: The Power and Fragility of Networked Protest*, was published by Yale University Press in 2017.

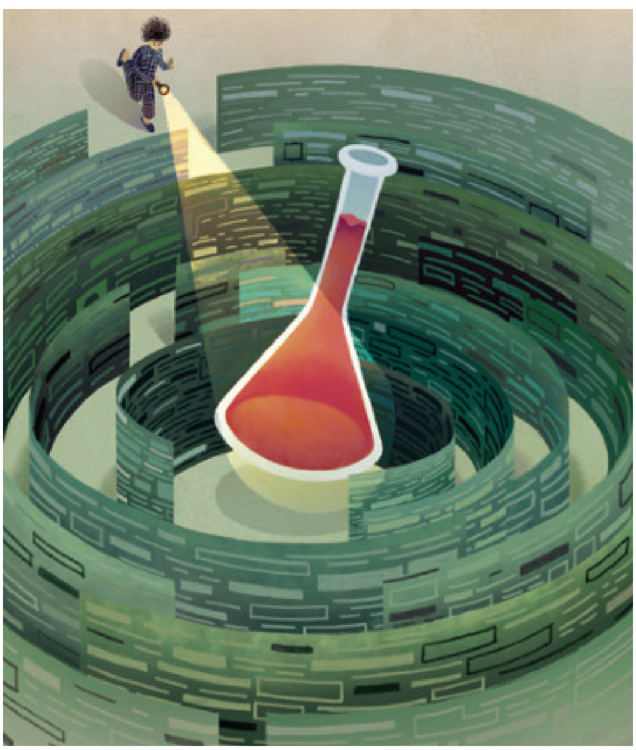
Beware of Medical Web Searches

You can find good information, but there's a lot more bad

By Zeynep Tufekci

When a sharp chest pain woke me up around 3 A.M., I had the obvious question: Was this truly panic-worthy? This had never happened to me before, and I'm in fairly good health—but I had lost one parent to a sudden, early death that may have been a cardiac event (we never learned for sure).

I may have the word "doctor" in my title, but I'm not that kind of doctor. I thought about dialing 911, but then I noticed that … well, the pain was on the right side of my chest rather than the left. My breathing wasn't labored. My heart wasn't pounding. So like millions before me, I Googled my symptoms. On top of the screen was an article entitled "16 Causes of Right Side Chest Pain." Bingo, I thought—except it was an ad. I moved on to the actual search results, which were headlined "17 Causes of Pain in the Right Side of the Chest" and "26 Causes of Chest Pain & Tightness." When I got to "3 Types of Chest Pain That Won't Kill You," I started wondering: What were all these bizarre articles?



Suddenly, my medically useless doctorate seemed to be more and more relevant. The titles were about gaming Google's search algorithm to grab people's attention at their vulnerable moments. This is called search-engine optimization, or SEO: the art and science of engineering for higher placement in Google search results and getting people to click on the links.

Unlike a lot of "medical information" online, SEO itself is steeped in the scientific method, which shows that this number-heavy format plays to a human cognitive bias called stand-out. We notice things that stand out—like oddly precise numbers. When I was a child in Turkey, my grandmother loved various over-the-counter remedies for maladies from the most minor to the serious, and many of them contained menthol. Menthol may not always have been the active ingredient, but it gave a soothing, medicinal aura to the lotions and rubs that filled her cupboard. Similarly, these odd, specific numbers add a scientific aura to the headlines.

I still needed information, though, so I clicked on a result from WebMD. I had seen that site before, and it didn't seem like it was quackery. I was barely a paragraph or two in when I noticed links about lung cancer symptoms. Huh? Lung cancer often causes no pain until its later stages. Then I realized that the information about lung cancer was an ad, but the "ad" notation was barely noticeable. During an emergency is obviously not the best time to scare people into clicking links for unlikely diseases. Indeed, if you clicked on these "lung cancer symptoms," the browser took you eventually to a site advertising a lung cancer medication from Merck. Ugh.

Using inappropriate screenings and symptoms to advertise for drugs is not new at all. As early as 2010, WebMD had gotten in hot water for a depression screener consisting of 10 questions that, no matter how you answered, spat out the same answer: "You may be at risk for major depression." You can almost smell the legalese: we all *may be* at risk for major depression anyway. No need for a quiz sponsored by Eli Lilly, a company that just happens to manufacture the antidepressant Cymbalta.

Having medical information online be financed by advertisers or pharmaceutical companies—or supplement manufacturers—is certainly not healthy. They often have an incentive to scare us. It's a lose-lose situation. Sometimes we do need to be worried and seek medical care. Other times it's just fearmongering for clicks. But who can tell when one is in crisis?

Finally, I looked up whether my own university had a health information site. Sure enough, there was a site with precise answers for exactly my question, the first statement being that "pinpointed chest pain" like mine was unlikely to be heart-related. Just then I remembered that I'd had a glass of carbonated water right before going to bed—a common cause of random but pinpointed chest and abdominal pain. My own "emergency" faded away, but the state of health information online remains dire. SA

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Illustration by Enan Liang

Steve irs y has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Ya Know?

Beyond the unknown unknowns is what's unknowable

By Steve Mirsky

In the 1954 World Series, Willie Mays of the New York Giants made what many consider the greatest catch in baseball history on a long fly ball to straightaway center-field hit by Vic Wertz of the Cleveland Indians. Broadcaster Bob Costas talked about the catch for the Ken Burns documentary series *Baseball:* "It was more than just a great catch. It was a catch no one had ever seen before … it was a play that until that point was outside the realm of possibility in baseball." Mays in that moment thus expanded baseball into previously nonexistent territory, much like the universe expands—and not *into* anything, for there was nothing there before.

On the other hand, nah. Indians' pitcher Bob Feller, who watched the play from the dugout, followed Costas on the episode. "It was far from the best catch I've ever seen," he says. "It was a very good catch. We knew Willie had the ball all the way."

I thought of this sequence more than once when I attended an April conference at the New School's Center for Public Scholarship here in New York City billed as "Unknowability: How Do We Know What Cannot Be Known?" Filled with doubt, I felt fortunate to simply find the auditorium.

Discussing the unknown, Columbia University biologist Stuart Firestein cited what he called an apocryphal saying: "It's very hard to find a black cat in a dark room, especially when there is no cat." He continued, "I think this is exactly how science works and how it deals with the so-called unknowable. We stomp around in black rooms and eventually … we may find this critter or we may find some other critter entirely. But once having decided the room is either empty or full of a cat, we simply move on to the next dark room."

He also cited James Clerk Maxwell as having said, "'Thoroughly conscious ignorance is the prelude to every real advance in science.'" Firestein went on, "And so this is the kind of ignorance that I'm talking about, not the common usage of the word 'ignorance,' not stupidity or willful indifference to fact or logic—you know who I'm talking about. But rather this thoroughly conscious kind of ignorance that can be developed …. The big question for me really is we've gained some knowledge, what does one do with that knowledge? And the purpose of that knowledge in my opinion is to create better ignorance, if you will. Because there's low-quality ignorance and high-quality ignorance … science, in my opinion, is the search for better ignorance." Presumably, as the quality of ignorance increases, so does the level of associated bliss.

After University of Cambridge mathematician John Barrow pointed out that "the unknown … is of course a vast, untapped field—rather like studying everything that is not a banana," he mentioned that beyond unknown unknowns lies the truly unknowable. "[Kurt] Gödel announced that … if you have a system that's got a finite number of axioms ... and if it's complicated enough to include arithmetic … and if it's consistent … then there are statements of arithmetic which you can neither show to be true nor false using the rules and axioms of arithmetic."

Gödel's knack for deep insights led to a famous story about his U.S. citizenship interview. He allegedly cheerfully announced that he had discovered a way to apply the Constitution that would turn the U.S. into a dictatorship. (See above, "You know who I'm talking about.") Legend has it that his friend Einstein, on hand for the happy day, jumped in to change the subject.

Uncertainty and unknowability may feel discouraging. But Firestein thought they could be a source of optimism, as in the story of the condemned prisoner who convinces the king to give him a year's reprieve in return for the promise that the inmate will teach the monarch's horse to talk.

Another prisoner asks the saved man what possessed him to make such a crazy bargain. "The fellow says, 'A lot can happen in a year. The horse might die. The king might die. I might die. The horse might learn to talk.'" That last option may seem overly optimistic. But it certainly beats the alternative. SA

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Illustration by Matt Collins

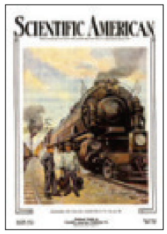
50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

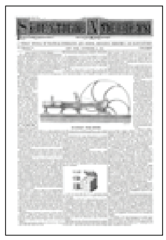
Compiled by Daniel C. Schlenoff

SEPTEMBER

1969



1919



1869

1969 Restless Moon

"The seismometer package left on the moon by the astronauts began reporting tremors as soon as it was installed. The first signals were produced by Armstrong and Aldrin as they walked about completing their tasks. The takeoff of the lunar module *Eagle* was also recorded clearly. The first group of high-frequency events seemed mysterious, but they were finally attributed to various venting processes. 'We had no idea [the module] would be such a living, breathing monster,' said Gary Latham of the Lamont-Doherty Observatory, the designer of the seismometer. The second group of events evidently represent rock sliding down the steep sides of craters. The most revealing class of events, more than 20 in all, are thought to be genuinely tectonic, meaning events caused by activity below the moon's surface."

"Polywater"

"The existence of a stable polymeric form of water with properties very different from those of ordinary water has been verified by a joint research group from the National Bureau of Standards and the University of Maryland. The 'new' substance, which has been given the name polywater, had first been reported in the early 1960s by Russian chemists. The new findings indicate that polywater is a stable polymer chain based on ordinary water molecules. In contrast to normal water, polywater maintains its molecular structure up to about 500 degrees Celsius. But if polywater is so stable, why has it never been found in nature?"

Polywater proved to be ordinary water contaminated by organic compounds (possibly including sweat).

1919 Mules Bring the Goods

"The Tieton Irrigation Canal, in the State of Washington, was constructed in 1907–1909 by the United States Reclamation Service, and has been carrying irrigation water for the past eight years. After 8,000 acres were added to the irrigation district, it was necessary to increase the water-carrying capacity of the canal. To enlarge the canal, a new top segment was cast in place on each side, after removing the cross-braces. The outstanding problem was the delivery of construction material to the local working points. It was necessary to employ the canal itself as a highway for further distribution of material to the workmen. Mules hauled good loads in very satisfactory time [*see illustration*]."

Hi-Tech Aviation

"During the war, black walnut and mahogany were practically the only species used for propellers. Since the available supply of these species in the U.S. was not sufficient to keep up the necessary production, other species had to be substituted. The U.S. Forest Products Laboratory at Madison, Wis., was able to suggest several native woods which appeared suitable for propellers. Quarter-sawn white oak combat propellers were put into production and other native species, such as birch and maple, were used on training planes, but not for combat propellers. At the present time almost all propellers are made up with hide glue. It is not waterproof, and under extreme conditions of humidity the joints may open."

1919: A mule hauls supplies up the bed of an old irrigation canal undergoing renovation.

SCIENTIFIC AMERICAN, V L C I, N .13 SEPTE BER 2, 1919

1869 A Fair Fare

"An invention has been produced in Paris for settling disputes between cab hirers and cab drivers, which seems to deserve attention. According to the account of it, the 'compteur mécanique,' or calculating machine, not only reckons the distance traversed, but indicates as well the exact sum of money due to the driver. Two dials are fixed on the back of the driving seat; one contains a clock, while on the other the distance traveled."

Heaven Found

"Theological writers have always been puzzled to fix upon any very definite idea in regard to the geographical—so to speak—location of heaven. But at last we have a philosopher sufficiently bold who undertakes to remove our perplexity, D. Mortimer, M.D. According to his theory, 'there is a vast globe or world far within the surrounding photosphere of ethereal fire, the sun.' Dr. Mortimer states that he has brought divine revelation to bear on this vast central globe, and is plainly convinced 'that the globe thus discerned is the Heavenly Empire wherein the righteous from this earth find their future home,' for all of which information, doubting and believing souls will forever thank the learned doctor."

Text and Graphics by Alberto Cairo

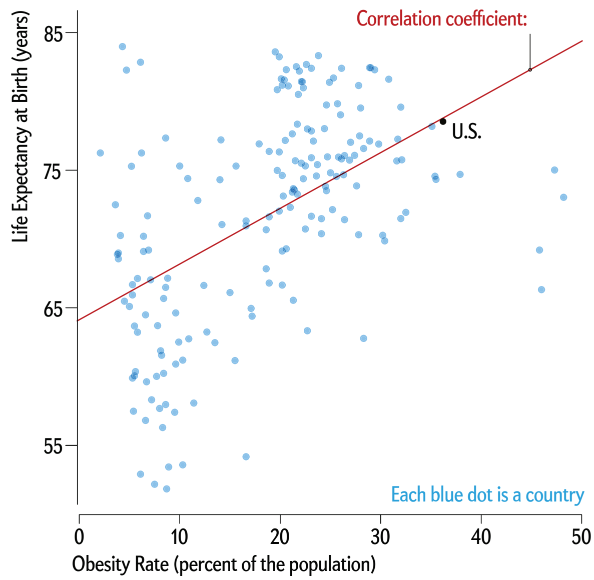
Does Obesity Shorten Lives?

Misreading data visualizations can reinforce biased perceptions

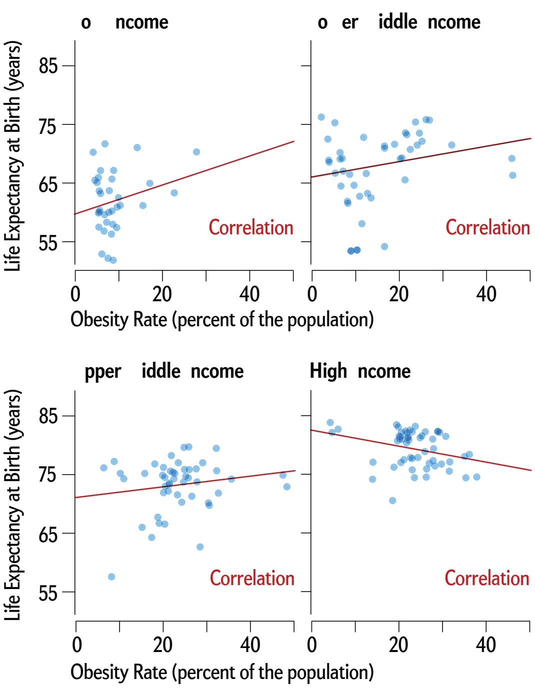
"A picture is worth a thousand words." That saying leads us to believe that we can readily interpret a chart correctly. But charts are visual arguments, and they are easy to misunderstand if we do not pay close attention. Alberto Cairo, chair of visual journalism at the University of Miami, reveals pitfalls in an example diagrammed here. Learning how to better read graphics can help us navigate a world in which truth may be hidden or twisted.

Say that you are obese, and you've grown tired of family, friends and your doctor telling you that obesity may increase your risk for diabetes, heart disease, even cancer—all of which could shorten your life. One day you see this chart (*right*). Suddenly you feel better because it shows that, in general, the more obese people a country has (*right side of chart*), the higher the life expectancy (*top of chart*). Therefore, obese people must live longer, you think. After all, the correlation (*red line*) is quite strong.

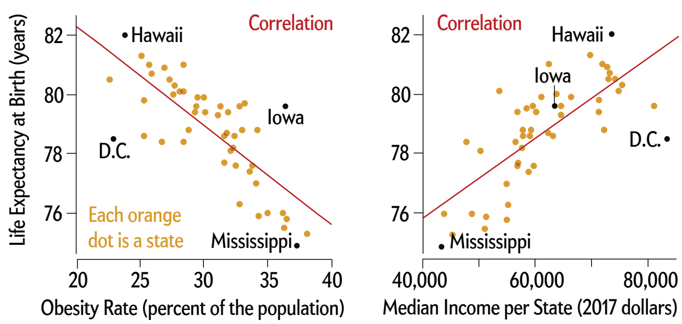
The chart itself is not incorrect. But it doesn't really show that the more obese people are, the longer they live. A more thorough description would be: "At the national level—country by country—there is a positive association between obesity rates and life expectancy at birth, and vice versa." Still, this does not mean that a positive association will hold at the local or individual level or that there is a causal link. Two fallacies are involved.



First, a pattern in aggregated data can disappear or even reverse once you explore the numbers at different levels of detail. If the countries are split by income levels, the strong positive correlation becomes much weaker as income rises. In the highest-income nations (*chart on bottom right*), the association is negative (higher obesity rates mean lower life expectancy).



The pattern remains negative when you look at the U.S., state by state: life expectancy at birth drops as obesity rises (*left*). Yet this hides the second fallacy: the negative association can be affected by many other factors. Exercise and access to health care, for example, are associated with life expectancy. So is income (*right*). The fallacy is trying to determine something about your individual risk by looking at aggregated data that do not reflect individual circumstances. If instead you saw data on individuals within a large sample of randomly selected people, you might discover that obesity may, or may not, relate to life expectancy for someone in your situation.



What to Do

1. Try to see not just what a chart shows but what it may not be showing.
2. Don't jump to conclusions, particularly if a chart seems to confirm what you already believe.
3. Question whether you are correctly verbalizing the chart's content.
4. Consider whether the data represent the level required to make the inferences you want. If you want to learn about countries, say, consult data at the country level, but if you want to learn about your own health risks, find data about individuals. And either way, always remember that, in a chart or among any data, correlation is not the same as causation.

C NS LTANT: HEATHER RA SE *Datassist* S RCES: "ASS CIATI N BETWEEN CLASS III BESITY (B I F 0 9 G 2) AND RTALITY: A P LED ANALYSIS F 20 PR SPECTIVE ST DIES," BY CARI . ITAHARA ET AL., IN *PLOS MEDICINE;* J LY 8, 201 CIA W RLD FACTB *(worldwide obesity rates, 2016)* W RLD BAN *(life expectancy at birth rates and income group classification, 2016)* CDC *(U.S. obesity rates, 2017) HOW CHARTS LIE: GETTING SMARTER ABOUT VISUAL INFORMATION*, BY ALBERT CAIR , W. W. N RT N (IN PRESS) DATA F R WISC NSIN AND AINE N T AVAILABLE

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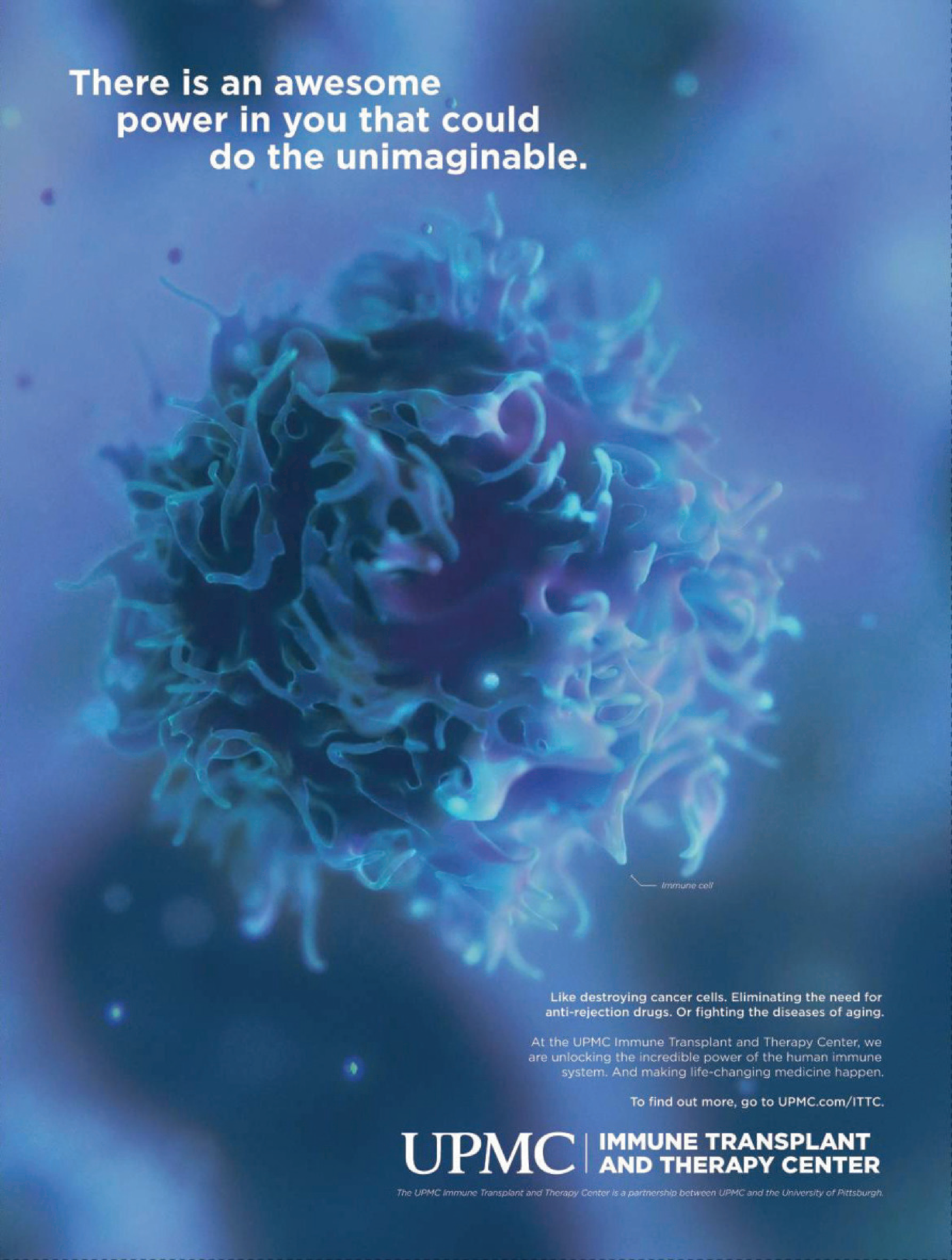
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