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Science Connected

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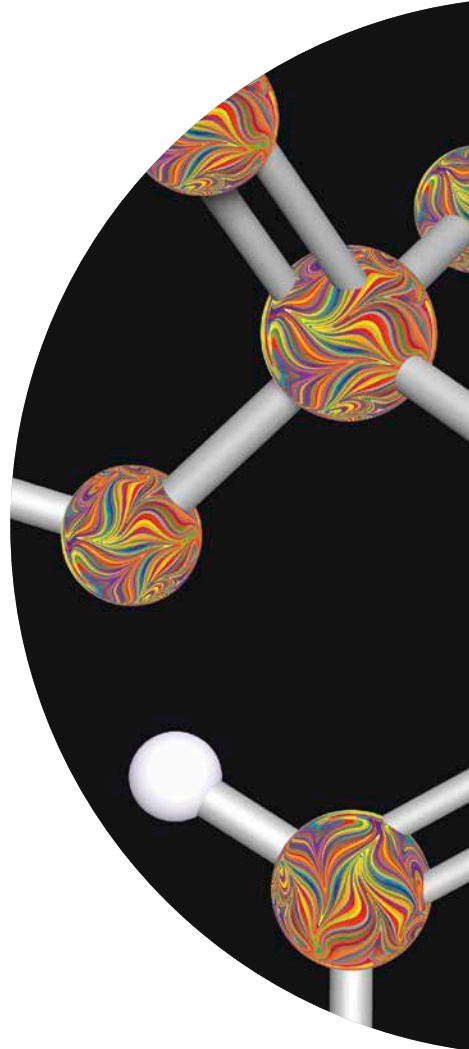
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A Change Is Gonna Come

BY KEVIN BERGER

WE CREATE EACH issue of *Nautilus* with articles from various fields of science, hoping thematic connections among them will emerge organically. We don't design the experiment to produce expected results. We aim for surprise. That design works beautifully in this issue. Without planning, the articles share a key theme in science: change.

Let's start with your brain on psilocybin. Moises Velasquez-Manoff reports on patients sprung from addiction and depression after a few sessions of tripping on an hallucinogen derived from mushrooms. In the brain, psilocybin links regions that normally don't "talk" to each other, enabling a "state of unrestrained cognition," neuroscientists explain. Moises points out that hallucinogen therapy reorders the brain and reframes "how we see ourselves." A 52-year-old upholsterer who smoked one or two packs of cigarettes for 40 years, and tried everything to quit, says he was skipping the light fandango after his psilocybin trips. "I don't feel like I'm fighting this addiction" he said. "It's like it's not even me."

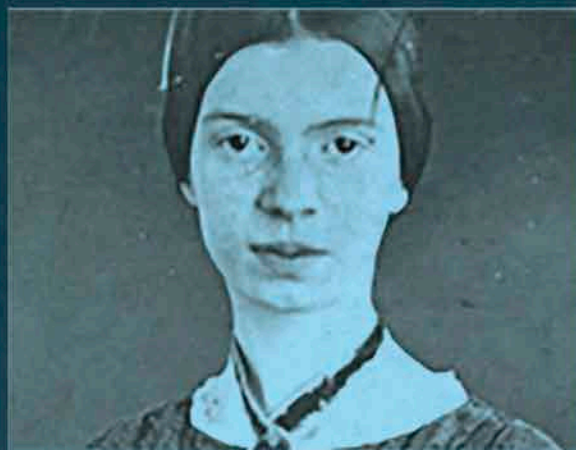
The "me" that our brains compose as we grow up, the self that centers us in the world, is sculpted by experience and learning. Heather Hansman feels this change come over her during a raft journey on the Green River to investigate dams. She had long accepted the environmental wisdom that dams destabilize a river ecosystem, and she spells out the verities why. But the "more I talk to people who touch the water every day, the more I realize how naïve and unsubtle my thinking has been," she writes. Heather's personal story is a tale of the Anthropocene, a panoramic view of conservation, where the health of the river must be balanced with the needs of the humans on its shores.

As the issue rolls along, you'll learn how black holes affect our sense of time. You'll meet mathematician John Baez, who reflects on his late-blooming appreciation of algebraic geometry. Magician Gustav Kuhn shares the secret of a famous illusion. And Nobel laureate Eric Kandel walks through a New York gallery to explain how art rewires our brains.

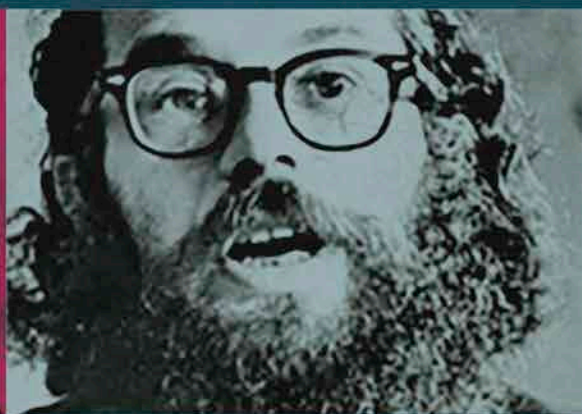
Evolutionary biologist David P. Barash stares into the sun of "global heating" and concludes our biological evolution is no longer a match for our cultural evolution. There was no payoff for our primate ancestors to wrestle with mammoth forces of nature like a tornado or volcano, and if they had, they would not have survived to pass on their genes. Today, our failure to curb global heating is our brain's way of saying we didn't evolve for this. But cultural evolution has its good side. Barash offers a simple example. To the benefit of our health, we learned to use toilets. "A primate with such behavioral flexibility, capable of going against millennia of natural selection, is nearly miraculous, yet an everyday event," Barash writes. "Take heart."

We do. This issue, like every issue of *Nautilus*, takes heart in science and the changes it brings.

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Readers Respond

Comments and letters about stories from print issue 25.

“THE ETHICS OF CONSCIOUSNESS HUNTING”

Great article! I am an ICU physician and routinely have to deal with patients we think are vegetative. It would be interesting to see if there is anything fMRI could be linked to, another sign or symptom which would help us distinguish their cognitive state, maybe EEG? Maybe a blood test like serum enolase? Would be interesting to try to correlate.

—Michael Stephen

While I applaud the effort to reach individuals who might appear to be in a vegetative state, I am troubled by the converse of killing or allowing to die those who truly are in such a state. The idea of physicians—healers—switching from fighting death to dealing it out makes me very uncomfortable. I also worry about someone doing the math and determining that the paltry few CMD patients that would be found is simply not worth the cost to find and sustain them.

—Bill Mullins

“WHAT TIME FEELS LIKE WHEN YOU’RE IMPROVISING”

This is interesting. While this idea of improvisation is directed at the arts in general, I can see some clear cases in business where people doing Q&A sessions after a presentation or speech are able to provide much faster and often more

insightful answers than if they were simply replying to an email version of that same question.

—James Steadman

“HERBICIDE IS WHAT’S FOR DINNER”

Thanks for the article—I had never heard of the practice of desiccation. I find many statements you hear in debates like these to be quite naive or disingenuous, complaining the author: “does not appear to reference large scale studies.” Of course—there haven’t been any. It makes it very hard to point to the science when there isn’t any science, and no money for the science to be conducted. This sort of thinking puts the burden of proof in the wrong place. Should we not be asking those employing these industrial practices to pay for the necessary research?

—George Gantz

“THE WOMAN REDEEMED BY TREES”

I have always believed in the connectedness of trees. Having grown up in the forest near Lake Tahoe—before they ruined the ecology and tried to save it in the most ridiculously mistaken ways—I know what it’s like to spend all my time alone with the flora and fauna of the deep forest.

—Sheri Chin



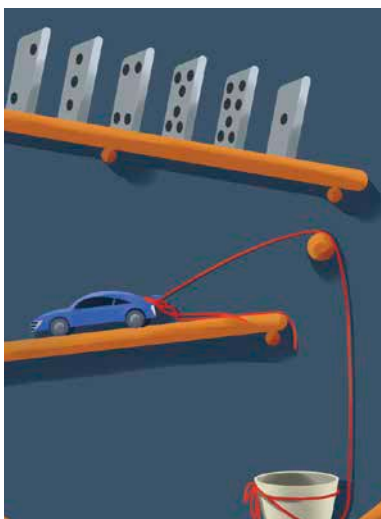
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Preludes



ARTIFICIAL INTELLIGENCE

Here's How We'll Know an AI Is Conscious

THE PHILOSOPHER DAVID CHALMERS famously asked whether “philosophical zombies”—people who behave like you and me yet lack subjective experience—are conceivable. The reasoning is that, if such zombies, or sophisticated unfeeling robots, are conceivable, then physical properties alone cannot explain the experience of consciousness. Instead, some additional mental properties must account for the what-it-is-like feeling of being conscious. Figuring out how these mental properties arise has become known as the “hard problem” of consciousness.

But I have a slight problem with Chalmers’ zombies. Zombies are supposed to be capable of asking any question about the nature of experience. It’s worth wondering, though, how a person or machine devoid

The 21st century is in dire need of a Turing test for consciousness.

of experience could reflect on experience it doesn’t have.

This is not a strictly academic matter—if we develop an AI that starts asking, say, why the color red feels like red and not something else, there are only a few possible explanations. Perhaps it heard the question from someone else. It’s possible that an AI might learn to ask questions about consciousness simply by reading papers about consciousness. Or it could have been programmed to ask that question, or burped it out of random noise. Clearly, asking questions

PHOTOGRAPH BY ARS ELECTRONICA / FLICKR

about consciousness does not prove anything per se. But could an AI zombie formulate such questions by itself? To me, the answer is clearly no. If I'm right, then we should seriously consider that an AI might be conscious if it asks questions about subjective experience unprompted.

Our conscious experiences are composed of qualia, the subjective aspects of sensation—the redness of red, the sweetness of sweet. The qualia that compose conscious experiences are irreducible, incapable of being mapped onto anything else. If I were born blind, no one would ever be able to give me a sense of the color blood and roses share. This would be true even if I were among a number of blind people who develop something called blindsight—the ability to avoid obstacles and accurately guess where objects appear on a computer monitor despite being blind.

Blindsight seems to show that some behaviors can be purely mechanized, so to speak, occurring without any subjective awareness—echoing Chalmers' notion of zombies. The brains of blindsighted people appear to exploit preconscious areas of the visual system, yielding sighted behavior without visual experience. This often occurs after a person suffers a stroke or other injury to the visual cortex. Because the person's eyes are still healthy, they may feed information hidden from consciousness to certain brain regions.

By the same token, there are a few documented cases of deaf hearing. One such case, detailed in a 2017 *Philosophical Psychology*

report, is of a man deaf since birth who can discriminate sounds based on their content. For people like him, this discernment occurs in silence. But if a deaf-hearing person were to ask the sort of questions people who can hear ask—"Doesn't that sound have a weird sort of brassiness?"—then we'd have good reason to suspect this person isn't deaf at all. Likewise, if an AI began asking, unprompted, the sorts of questions only a conscious being could ask, we'd reasonably form a similar suspicion that subjective experience has come online.

The 21st century is in dire need of a Turing test for consciousness. AI is learning how to drive cars, diagnose lung cancer, and write its own computer programs. Intelligent conversation may be only a decade or two away, and future

super-AI will not live in a vacuum. It will have access to the Internet and all the writings of Chalmers and other philosophers who have asked questions about qualia and consciousness. But if tech companies beta-test AI on a local, isolated intranet, they could conduct a Turing-test style interview to detect whether questions about qualia make sense to the AI.

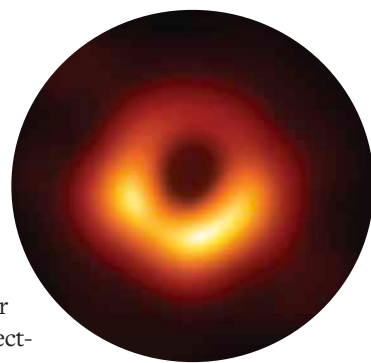
It's possible that an artificial consciousness might possess qualia vastly different than our own. Therefore, the best question would likely be that of the hard problem itself: Why does consciousness even exist? Why do you experience qualia while processing input from the world? If this question makes any sense to the AI, then we've likely found artificial consciousness.

—Joel Frohlich

PHYSICS

First Black-Hole Image: It's Not Looks That Count

FOR THE PAST 12 YEARS, the Event Horizon Telescope has been looking at black holes. In April, the collaboration released the long-awaited results from its first full run two years ago. Contrary to expectation, their inaugural image is not, as many expected, Sagittarius A*, the black hole at the center of the Milky Way. Instead, it is the supermassive black hole in the elliptic galaxy Messier 87, about 55 million light-years from here. This black hole weighs



in at 6.5 billion times the mass of our sun, and is considerably larger than the black hole in our own galaxy. So, even though the Messier-87 black hole is a thousand times farther away than Sagittarius A*, it still appears half the size in the sky.

The Event Horizon Telescope (EHT) is not less remarkable than the objects it observes. With a collaboration of 200 people, the EHT uses not a single telescope, but a global network of nine telescopes. Its sites, from Greenland to the South Pole and from Hawaii to the French Alps, act in concert as one. Together, the collaboration commands a telescope the size of planet Earth, staring at a tiny patch in the northern sky that contains the Messier-87 black hole.

In theory, black holes are regions of space where the gravitational pull is so large that everything, including light, becomes trapped for eternity. The surface of the trapping region is called the “event horizon.” It has no substance; it is a property of space itself. In the simplest case, the event horizon is a sphere—a perfect sphere, made of nothing.

In reality, it’s complicated. Astrophysicists have had evidence for the existence of black holes since the 1990s, but so far all observations have been indirect—inferred from the motion of visible stars and gas, leaving doubt as to whether the dark object really possesses the defining event horizon. It turned out difficult to actually see a black hole. Trouble is, they’re black. They trap light. And while Stephen Hawking proved that black holes must emit radiation due to quantum effects, this quantum glow is

far too feeble to observe.

But much like the prisoners in Plato’s cave, we can see black holes by observing the shadows they cast. Black holes attract gas from their environment. This gas collects in a spinning disk, and heats up as it spirals into the event horizon, pushing around electric charges. This gives rise to strong magnetic fields that can create a “jet”: a narrow, directed stream of particles leaving the black hole at almost the speed of light. But whatever strays too close to the event horizon falls in and vanishes without a trace.

At the same time black holes bend rays of light, bend them so strongly, indeed, that looking at the front of a black hole, we can see part of the disk behind it. The light that just about manages to escape reveals what happens near the horizon. It is an asymmetric image that the astrophysicists expect, brighter on the side of the black hole where the material surrounding it moves toward us, and darker where it moves away from us. The hot gas combined with the gravitational lensing creates the unique observable signature that the EHT looks out for.

The experimental challenge is formidable. The network’s telescopes must synchronize their data-taking using atomic clocks. Weather conditions must be favorable at all locations simultaneously. Once recorded, the amount of data is so staggeringly large, it must be shipped on hard disk to a central location for processing.

The theoretical challenges are not any lesser. Black holes bend light so much that it can wrap around the

Black holes bend light so much that it can wrap around the horizon multiple times.

horizon multiple times. The resulting image is too complicated to capture in simple equations.

The EHT’s observations agree with expectation. But this result is more than just another triumph of Einstein’s theory of general relativity. It is also a triumph of the astronomers’ resourcefulness. They joined hands and brains to achieve what they could not have done separately. And while their measurement settles a long-standing question—yes, black holes really do have event horizons!—it is also the start of further exploration. Physicists hope that the observations will help them understand better the extreme conditions in the accretion disk, the role of magnetic fields in jet formation, and the way supermassive black holes affect galaxy formation.

—Sabine Hossenfelder

COGNITIVE SCIENCE

New Evidence for the Strange Geometry of Thought

PETER GÄRDENFORS, A PHILOSOPHER and cognitive scientist, has been working on his idea of cognitive spaces, which explain how our brains represent concepts and objects, for decades. He thinks that humans can do things that today's powerful computers can't do—like learn language quickly and easily generalize from particulars (to see, in other words, without much training, that lions and tigers are four-legged felines)—because we, unlike computers, represent information in geometrical space.

In a 2018 *Science* paper co-authored with Jacob Bellmund, Christian Doeller, and Edvard Moser, Gärdenfors argued that the brain represents concepts in the same way that it represents space and your location, by using the same neural circuitry for the brain's "inner GPS."

"Cognitive spaces are a way of thinking about how our brain might organize our knowledge of the world," Bellmund said. It's an approach that concerns not only geographical data, but also relationships between objects and experience. The hippocampus' place and grid cells, in other words, map not only physical space but conceptual space. It appears that our representation of objects and concepts is very tightly linked with our representation of space.

Certain regions in the brain—the hippocampus and entorhinal cortex—act like a GPS. Their cells form a grid-like representation of the brain's surroundings and keep track of its location on it. Specifically, neurons in the entorhinal cortex activate at evenly distributed locations in space: If you drew lines between each location in the environment where these cells activate, you would end up sketching a triangular grid, or a hexagonal lattice. The activity of these aptly named "grid" cells contains information that



Our representation of objects and concepts is very tightly linked with our representation of space.

another kind of cell uses to locate your body in a particular place. These cells activate only when you are in one particular location in space, or the grid. Yet other cells indicate when you're at the border of your environment—a wall or cliff. Rodent models have elucidated the nature of the brain's spatial grids, but, with fMRI, they have also been validated in humans.

Recent fMRI studies show that cognitive spaces reside in the hippocampal network—supporting the idea that these spaces lie at the heart of much subconscious processing. For example, subjects of a 2016 study were shown a video of a bird's neck and legs morph in size. Previously they had learned to associate a particular bird shape with a Christmas symbol, such as Santa or a gingerbread man. The researchers discovered the subjects made the connections with a "mental picture" that could not be described spatially, on a two-dimensional map. Yet grid-cell responses in the fMRI data resembled what one would see if subjects were imagining themselves walking in a physical environment. This kind of mental processing might also apply to how we think about our family and friends. We might picture them "on the basis of their height, humor, or income, coding them as tall or short, humorous or humorless, or more or less wealthy," Doeller said. And, depending on whichever of these dimensions matters in the moment, the brain would store one friend mentally closer to, or farther from, another friend.

But the usefulness of a cognitive

space isn't just restricted to already familiar object comparisons. "One of the ways these cognitive spaces can benefit our behavior is when we encounter something we have never seen before," Bellmund said. "Based on the features of the new object we can position it in our cognitive space." Representing knowledge in this structured way allows us to make sense of how we should behave in new circumstances.

Data also suggests that this region may represent information with different levels of abstraction. If you imagine moving through the hippocampus from the top of the head down, you will find many different groups of place cells that completely map the entire environment but with different degrees of magnification. Put another way, it's like zooming in and out on your phone's map app. The area in space represented by a single place cell gets larger. Such size differences could be the basis for how humans are able to move between levels of abstraction—from "dog" to "pet" to "sentient being," for example. In this cognitive space, more zoomed-out place cells would represent a relatively broad category consisting of many types, while zoomed-in place cells would be narrower.

Scientists still need to experimentally verify the link between the hippocampus and higher-order cognitive functions in humans. fMRI studies like the ones from the group in Oxford are, as yet, only suggestive. It is also unknown whether place cells can represent objects at particular locations in a cognitive space. Revealing this in experiments with human subjects

is hard, since they require very fine-resolution brain imaging. But recent advances in higher-resolution fMRI might provide a solution.

Gärdenfors' theory highlights a fruitful path, not only for cognitive scientists, but for neurologists and machine-learning researchers. It is a kind of incomplete, generic sketch on a canvas that invites

refinement and elaboration. Cognitive spaces are, as Gärdenfors and Bellmund put it, an "overarching framework" that can help unravel the causes of neurodegenerative diseases, like Alzheimer's, and "to inform novel architectures in artificial intelligence."

—Adithya Rajagopalan

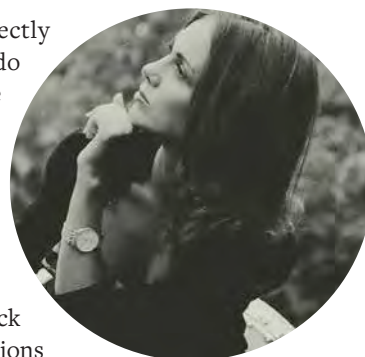
PSYCHOLOGY

Taking Another Person's Perspective Doesn't Help You Understand Them

NO MORAL ADVICE IS perfectly sound. The Golden Rule—do unto others as you would have them do unto you—is only as wise as the person following it.

A more modern-sounding tip—take the perspective of others—can seem like an improvement. It was Dale Carnegie's eighth principle in *How to Win Friends and Influence People*, and Barack Obama trotted it out at the United Nations when discussing Israel and Palestine. Perspective-taking avoids the Golden Rule's flaw—its effect doesn't hinge on the integrity of the person considering it. And it's an inducement to selflessness, in that you're encouraged to exchange your frame of reference for that of another. Perspective-taking increases the odds you'll emotionally empathize with the person whose shoes you're stepping into, rely less on your own biases and group-based stereotypes, and avoid automatic expressions of racial bias.

In a study, authors Tay Eyal, Mary Steffel, and Nicholas Epley say these results "suggest that being told to put oneself into another's perspective may result in increased interpersonal accuracy," an understanding of



To understand someone, we should not imagine their point of view but make the effort to "get" their perspective.

the thoughts and desires of someone else. It doesn't. After testing the impact perspective-taking had on the accuracy of interpersonal judgments in 25 experiments, the researchers concluded, "If anything, perspective-taking decreased accuracy overall while increasing confidence in judgment." Even romantic partners together for a decade couldn't get perspective taking to work when quizzed on their significant other's preferences or views. They thought, on average, that 13 of their 20 guesses would be accurate. Only five were.

This finding is counterintuitive, Epley explained in a piece for NPR. "The vast majority of people we surveyed predicted that actively adopting another person's perspective would help them understand another person better in a variety of ways, from understanding another person's reaction when looking at a picture to predicting movie preferences," he wrote. "Perspective-taking may work some wonders for your social life, but understanding another person better does not seem to be one of those wonders."

To Epley, the lesson can seem "painfully obvious." To understand someone, we should not imagine their point of view but make the effort to "get" their perspective. "True insight into the minds of others is not likely to come from honing your powers of intuition," Epley wrote, "but rather by learning to stop guessing about what's on the mind of another person and learning to listen instead."

This takeaway undermines the idea that moral progress depends on perspective-taking, a thesis that

"True insight into the minds of others is not likely to come from honing your powers of intuition."

George Eliot built into her classic novel, *Middlemarch*. "The differences between her characters are ethical differences which are shown as differences in the limits of their capacity for sympathetic imagination," said Rebecca Newberger Goldstein, a philosopher, novelist, and author. "She makes the limits of imagination—not the limits of reason—essential to how much moral progress a character can make."

Epley, by contrast, doesn't seem as taken by the ability to imagine the inner reality of others, since the data indicates that what we picture is often spurious. He's advocated conversation over imagination for years. In 2015, Epley told *Nautilus*, "Another person's mind comes through their mouth."

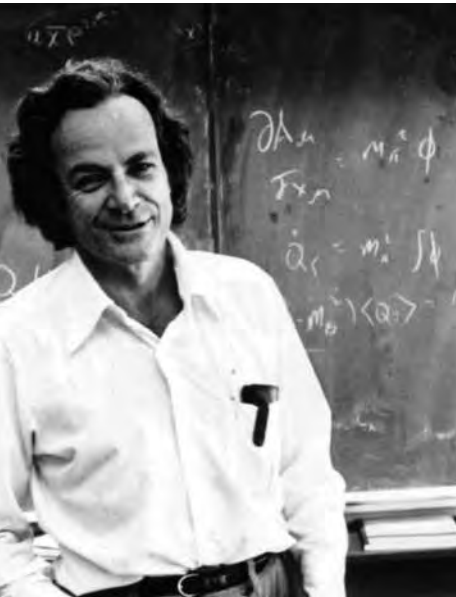
—Brian Gallagher

PHYSICS

The Day Feynman Worked Out Black-Hole Radiation on My Blackboard



ONE DAY AT LUNCH in the Caltech cafeteria, I was with two graduate students, Bill Press and Saul Teukolsky, and Richard Feynman. Bill and Saul were talking about a calculation they had just done. It was a theoretical calculation where they looked at what happens if you shine light on a rotating black hole. If you shine it at the right angle, the light will bounce off the black hole with more energy than it came in with. The classical analogue is a spinning top. If you throw a marble at the top at the right angle, the marble will bounce off the top with more velocity than it came in with. As Bill and Saul were talking, Feynman was listening.



Richard Feynman

Feynman said, “You know that process you’ve described? It sounds very much like stimulated emission.” That’s a quantum process in atomic physics where you have an electron orbiting an atom, and a light particle, a photon, comes in. The two particles are emitted and the electron goes to a lower energy state, so the light is amplified by the electron. The electron decreases energy and gives up that extra energy to sending out two photons. Feynman said, “What you’ve just described sounds like stimulated emission. According to Einstein, there’s a well-known relationship between stimulated emission and spontaneous emission.”

Spontaneous emission is when you have an electron orbiting an atom and it just emits a photon all by itself and goes to a lower energy state. Einstein had worked out this relationship between stimulated

and spontaneous emission. Whenever you have one, you have the other, at the atomic level. Feynman said that what Bill and Saul were describing sounded like simulated emission, so there should be a spontaneous emission process analogous to it.

We all ended up in my tiny little office. Feynman went to the blackboard and began working out the equations for spontaneous emission from black holes. Up to this point in history, it had been thought that all black holes were completely black, and could never emit any kind of energy on their own. But Feynman had postulated that if a spinning black hole can emit with light coming in, it can also emit

energy with nothing coming in.

After a few minutes, Feynman had worked out the process of spontaneous emission, which is what Stephen Hawking became famous for a year later. Feynman had it all on my blackboard. He wasn’t interested in copying down what he’d written. He just wanted to know how nature worked. After he finished working it out, he brushed the chalk dust off his hands and walked out of the office.

A little bit later, I left. That night I realized this was a major thing and I needed to hurry back to my office and copy it down. But when I got there, the cleaning lady had wiped the blackboard clean.

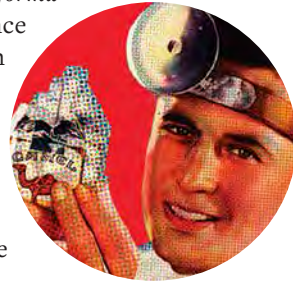
—Alan Lightman

SOCIOLOGY

How Misinformation Spreads

IN THEIR NEW BOOK, *The Misinformation Age*, philosophers of science Cailin O’Connor and James Owen

Weatherall detail how those with the power control the information. They provide compelling examples of industries that distorted science to boost their bottom lines. In an interview with *Nautilus*, they discuss the force that’s fracturing truth more than ever.



When it comes to misinformation, twas always thus. What’s changed now?

O’Connor: It’s always been the case that humans have been dependent on social ties to gain knowledge and belief. There’s been misinformation and propaganda for

hundreds of years. If you're a governing body, you have interests you're trying to protect. You want to control what people believe. You find people online who share your beliefs and communicate with them. This new structure means that all sorts of influencers have direct access to people. They can pose on Twitter and Facebook as a normal person who you might want to interact with. They can build trust with people who would naturally be part of their groups. Once they grounded that trust, they can influence them by getting them not to vote or driving polarization, causing more extreme rhetoric. They can make other people trust them in ways that would have been very difficult without social media.

James Weatherall: People tend to trust their friends, their family, people who they share other affinities with. Ideas aren't spreading properly. So we get enclaves. This is what polarization looks like—a failure of reliable beliefs to spread from one community to another. Another thing that's become widespread is the ability to produce easily shareable visual media. The memes we see on Twitter or Facebook don't really say anything; they conjure up an emotion associated with an ideology or belief you might have. It's a type of misinformation that supports your beliefs without ever coming out and saying something false.

O'Connor: The marketplace of ideas doesn't work. We vote for someone who doesn't believe in climate change and then act as if climate change isn't true. That vote doesn't change whether it's true and whether we're going to face the consequences of climate change. The problem is that matters of fact shouldn't be settled by public vote. They should be settled by gathering evidence and using that evidence to feed into our best tools to figure out what's true.

How can we intervene in social networks to direct people toward truth and facts?

O'Connor: All social media sites should be employing teams to fight active misinformation and



Fake news is shared more often by older people than by younger people.



disinformation. On an individual level, it's trickier. People just don't trust others who have different beliefs from them.

Can systemic changes really overturn false beliefs?

Weatherall: Look at the history of media. When newspapers, radio, and television were first introduced, they presented all sorts of misinformation that influenced people. But then you saw responses develop. You saw regulations. So we get better at responding to misinformation presented to us in the media. We can learn what sorts of things we can trust, what sorts of things are reliable. We have to hope that we're going to become more successful, more effective, or more sophisticated about responding to misinformation online. I think there's evidence this is happening. Fake news is shared more often by older people than by younger people.

O'Connor: Younger people are savvier about identifying fake news, able to look at different aspects of a website and say, 'This probably isn't real,' and so are less likely to share it.

—Brian Gallagher & Kevin Berger

Hallucinogen Therapy Is Coming

How psilocybin can spring people from fears and destructive habits

BY MOISES VELASQUEZ-MANOFF



THREE YEARS LATER DANIEL KREITMAN still chokes up when he talks about what he saw, and how it changed him. Kreitman, an upholsterer by trade, had taken psilocybin, a hallucinogen derived from mushrooms, in a trial at Johns Hopkins University School of Medicine for nicotine addiction. He was 52, and he'd smoked between one and two packs a day for nearly 40 years. After his first psilocybin session, his urge to smoke was gone. During his third and final session, he had the vision that helped him quit for good.

He saw lakes, roads, and mountains, and a broad-shouldered man at the helm of a ship, lassoing birds. Was it his dead father? He wasn't sure. But he remembers giggling and feeling good. Music was playing in his headphones. During Aaron Copland's *Appalachian Spring* he had the sensation of physically touching the music, which was smooth and bright yellow in his mind's eye. As the music progressed, he traveled, flowing outward toward an immense space that never ended. He may have wept for joy—he's not sure—but the beauty of the vision overwhelmed him. "I was seeing forever," he told me.

Kreitman was brought up Jewish, but doesn't consider himself to be particularly religious. Yet he falls back on religious language to explain the experience. "I think I saw God at one point," he said, his voice cracking with emotion. The day after the session, in his journal, he wrote: "The question is, if I saw God and infinity, what's next? How does that change me and my life?"

When I spoke with him, Kreitman had an answer: He hadn't had a cigarette for three years. He'd previously tried nicotine gum and patches, to no avail. He always returned to the habit, falling into the easy rhythms of smoking on the way to work and on the way home. It was taking a toll on his health, though. He was chronically short of breath and although they didn't nag, his wife and children were concerned for his health. Since that session three years ago, however, cravings have barely registered. "It's kind of crazy," he told me. "I don't feel like I'm fighting this addiction. It's like it's not even me."

Hallucinogen therapy offers a radical new perspective on the self.

The trial was small, just 15 people, but it's on the vanguard of resurgent research into the therapeutic potential of hallucinogens—a "psychedelic renaissance," as one researcher described it. Work from the mid-20th century suggested that psychedelics held therapeutic promise. But those studies didn't generally hew to modern scientific design.

Now, after decades of neglect, scientists are beginning to rigorously test hallucinogens as medicine. They're trying to treat some of our most vexing afflictions, including addiction, depression, and the existential anxiety of having a terminal disease. The small studies so far conducted have yielded striking results. In one 10-person pilot study on alcoholics, participants more than halved their alcohol intake six months after taking psilocybin. In Kreitman's study, 60 percent of smokers who took psilocybin hadn't smoked two-and-a-half years later.

If hallucinogens prove effective in treating substance abuse, they would address a massive unmet need. They'd also possibly force a change in how we think about the dysfunction that underlies these conditions.

In the past, addiction was cast as a moral failing. Today it's variously seen as a psychiatric condition, a learning disorder, or a disorder of the brain. Given that dependency on one's drug of choice eventually emerges, a common treatment approach is to wean addicts off their drugs by, in the case of smoking, giving ever smaller quantities of nicotine in patches or gum.

Hallucinogen therapy dispenses with this gradualist

approach, instead seeking a more sudden transformation. That's in part because many studies, including the Johns Hopkins trial Kreitman participated in, suggest those who have mystical experiences while on psilocybin have the best outcome. This kind of sudden, divine-seeming insight, what William James termed a "conversion," is central to many religious and meditative traditions. It can also occur in more prosaic contexts—a phenomenon one psychologist has dubbed "quantum change." People can quickly and inexplicably, often after a profound epiphany, change.

The question of how, precisely, hallucinogens trigger these transformations has sent neuroscientists down an intriguing rabbit hole. They have observed similarities between what happens in meditators' brains and people on hallucinogens. Neural networks that serve as control centers—the neural correlates of the old Freudian ego—may loosen their grip, freeing

other regions of the brain.

Researchers often use an unusual language to talk about this transformation, one that emphasizes meaning and subjective experience over molecular pathways and neurotransmitters. Hallucinogen therapy seems to recast addiction not only as a disorder of the brain, but as a disorder of meaning—of framing and how we see ourselves.

Ultimately, hallucinogen researchers are addressing a mystery that's central to psychology and psychiatry, not to mention the self-help section of the bookstore: the question of how people change, of how they escape limiting and often self-destructive behavioral patterns. Their early research suggests that hallucinogen therapy offers a radically new perspective on the self, showing people that they're not slaves to their compulsions or fears, and providing them with a sense of connection to something ineffable, something greater than themselves.



THE TRIPPING COUCH A participant in psilocybin therapy at Johns Hopkins University School of Medicine. In each session, participants listen to music and direct their attention toward their inner experiences. If fear or anxiety arises, monitors are on hand to provide reassurance.

THE PSILOCYBIN STUDIES at Johns Hopkins University School of Medicine have been guided in part by Roland R. Griffiths, Ph.D., a professor in the departments of psychiatry and neuroscience at the university. About 15 years ago, Griffiths began meditating. He started with a Hindu mantra-based practice, and moved to Buddhism. As a scientist, he studied drugs of abuse—how they hooked people and why. But he'd always been curious about the nature of consciousness itself—why we're aware at all—which is in many ways the fundamental enigma of human existence. He thought that meditation was one method, albeit a subjective one, for exploring this mystery.

As his meditation practice deepened, he began to have interesting and unusual experiences. They opened “a spiritual window,” he told me. “With meditation, one really begins to see how the mind works, how ideas come up.”

Seeking to better understand these experiences, Griffiths dove into the literature on comparative religion. He discovered claims that hallucinogens could induce experiences like those he had while meditating.

William James offered a compelling perspective on alternative consciousness in the early 20th century. “Looking back on my own experiences” with nitrous oxide (laughing gas), he wrote, “they all converge towards a kind of insight to which I cannot help ascribing some metaphysical significance. The keynote of it is invariably a reconciliation. It is as if the opposites of the world, whose contradictoriness and conflict make all our difficulties and troubles, were melted into unity.”

In the 1950s, scientists began exploring hallucinogens therapeutically. Humphry Osmond, a British-born psychiatrist working in Canada, conducted some particularly interesting work. Osmond, who coined the term “psychedelic”—“mind manifesting,” in his words—wanted to help alcoholics quit drinking. When longtime drinkers stop, they can suffer from a severe and occasionally deadly form of withdrawal called delirium tremens, which can include psychotic episodes. Delirium tremens also sometimes served as a turning point toward recovery in alcoholics' lives. Only after they “hit bottom,” the thinking went, could they get better. Osmond and his colleagues reasoned that

It's what many
religious practices
figured out long ago.



BAD MEDICINE The psychedelic 1967 film *The Trip*, written by Jack Nicholson, represented the counterculture's embrace of hallucinogens. Hysteria about mind-altering drugs, though, spread through the establishment, derailing hallucinogens' use in serious medical experiments.

an LSD session, which also induces a psychosis-like state, might accelerate this naturally occurring process. He and his colleagues hatched a plan to treat alcoholics by inducing with megadoses of LSD the very psychosis they might experience down the road.

And it worked, sort of. Of his first two patients, one remained sober six months later. Over the years, Osmond and his colleagues treated perhaps 2,000 more drinkers with LSD, including many who hadn't responded to other therapies, and achieved impressive results. Between 40 and 45 percent of his patients continued to abstain a year after treatment. It wasn't that they were scared straight by their LSD episodes. Rather, over and over, these patients reported insightful and often mystical experiences—a feeling of being at one with the universe, and of seeing oneself and one's internal conflicts clearly and objectively. Those experiences were central to their subsequent abstinence.

As it happens, Albert Hofmann, the Swiss scientist who first synthesized LSD, and who himself had an intense mystical experience while on the drug, had always hoped that his creation would be studied scientifically, its therapeutic potential rigorously tested. He once described LSD as “medicine for the soul”—as “a tool to turn us into what we are supposed to be.”

But by the late 1960s, research on hallucinogens mostly ground to a halt. The burgeoning counterculture got a hold of psychedelics—“altered consciousness” was a central aspiration of the movement—and a kind of anti-hallucinogen hysteria took hold among the establishment. Hallucinogens were linked to anti-war demonstrations and student riots. Newspaper articles began appearing claiming that LSD caused psychotic episodes, fetal abnormalities, and crime. The emerging evidence of therapeutic potential was dismissed as flawed, and the drugs were made illegal.

In the nearly 40 years since, establishment attitudes toward hallucinogens began to shift. Scientific curiosity began to displace hysteria. And in the early aughts, Griffiths decided to test the idea that hallucinogens could reliably provoke mystical experiences. He recruited 36 volunteers for a double blind study. No one knew exactly what drug conditions would be administered, and the stimulant Ritalin was given as a placebo.

He published his first results in 2006. Many participants reported having mystical-type experiences that, two months later, they rated as among the most meaningful of their lives. Nearly two-thirds of the participants said the experiences had increased their well-being—something that Griffiths and his colleagues confirmed with family and friends. Maybe most surprising, the subjects reported lasting change after the psilocybin sessions.

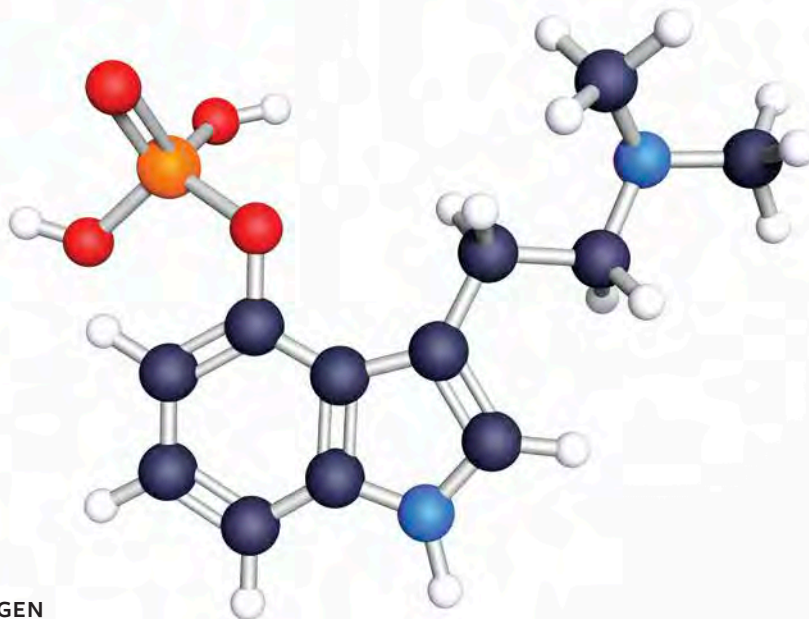
Psychologists often rate personalities in broad domain categories like neuroticism, extroversion, and agreeableness. After the age of 30, it's thought that one's personality is more or less set. But in Griffiths' study, one domain in particular improved among the

psilocybin-takers more than a year after the sessions: openness. They reported more imagination, creativity, and aesthetic appreciation.

Others call these studies groundbreaking. They're the first studies on hallucinogens in the U.S. in decades, and among the only rigorous studies ever. They suggest that mystical experiences are reliably inducible. And for Griffiths, they indicate that the human brain is wired to have these kinds of experiences. You don't have to be a saint or a master meditator; you don't have to be born lucky, or suffer from an unusual mental glitch. Perhaps because we're extremely social animals, the ability to feel a deep sense of oneness with existence, which seems so therapeutic, is latent in us. "The results suggest that almost everyone is capable," he told me.

It also makes hallucinogens easier to study, and easier to administer as therapy. That's not to say that everyone who takes hallucinogens will feel at one with the universe, or see their version of God. The lead-up to the sessions is, Griffiths believes, important to the outcome. He and his colleagues put a lot of thought

PSILOCYBIN
C₁₂H₁₇N₂O₄P
HALLUCINOGEN



into creating a setting that they think increases the odds of a positive session. Kreitman began preparing for about two months before his psilocybin sessions. He learned to meditate, talked with a psychologist regularly, and developed a mantra—"For myself and my family, I quit for life"—meant to crystallize his intent to stop smoking.

On the day of his first session, after crushing and throwing away his last pack of cigarettes, he lay back on a comfortable couch in a warmly lit room decorated with Buddha statues, pulled a blinder over his eyes, and listened to pleasant, occasionally Indian-sounding music on earphones. Doctors monitored him, periodically asking how he was doing and taking his blood pressure. "It was comforting to know they were watching me," Kreitman said.

Post-psilocybin, Kreitman describes himself as the same, but also "deeper." And this newfound depth occasionally manifests in the strangest way: a tendency to spontaneously weep, not with sadness, but with joy. "It's great," he told me. "But my kids think I'm losing it."

WHEN YOU IMBIBE PSILOCYBIN, your body metabolizes it into psilocin, the active compound in the hallucinogen. Psilocin and LSD both stimulate serotonin receptors on neurons, exciting those cells and prompting a cascade of secondary activity. Serotonin is often described as a mood regulator, important to one's happiness and sense of well-being. Many antidepressant drugs also boost serotonin levels in the brain. Yet this biochemical understanding doesn't quite explain the subjective experience of "the trip," or the effects that continue long after hallucinogens have left the body.

It's from neuroscience that the most alluring and potentially informative portrait of what happens to the brain on psychedelics has begun to emerge. Scientists at the University of Zurich have found that activity in the amygdala, the fear center of the brain, declines on psilocybin, making people less reactive to negative stimuli, which might explain how it could help with depression.

A series of studies by scientists at Imperial College London indicate that while people are on hallucinogens, connectivity within neural networks responsible for

Hallucinogen researchers are addressing the question of how people change.

weaving information into a coherent whole declines; but connectivity between networks usually specialized in different tasks increases. What that implies is both a kind of disorder—the kaleidoscopic colors and sensation of dreaming while awake—and a kind of freedom, which the researchers call “ego dissolution.”

“Under the influence of psilocybin, there’s more cross talk across networks. Brain activity is less tightly organized,” Michael Bogenschutz, a scientist at New York University who was conducting a study on alcoholics, told me. “It’s consistent with people’s subjective reports of synesthesia”—smelling colors, seeing flavors, and a general sensory confusion—“and perceiving connections between things that don’t ordinarily appear to be related.”

One of the networks where activity declines is the “default mode network.” It’s important for internally directed activity like rumination and daydreaming, and

includes neural hub areas like the parahippocampus (involved in spatial recognition), the posterior cingulate cortex and precuneus (imagining oneself in the future or the past), and the medial prefrontal cortex (autobiographical memories).

The default mode network usually operates in opposition to another network associated with externally oriented tasks, like playing soccer or hunting deer, called the “task positive network.” These two separate neuronal webs tend to operate like a seesaw: When one is activated, the other is muted, and vice versa.

But when volunteers took psilocybin, the Imperial College scientists found, both networks activated simultaneously—a pattern also observed in experienced meditators. Brain scans of people on hallucinogens, as with meditators, have revealed that the concurrent activation of these networks predicts a loss of one’s sense of separateness—the ego—and the



DO YOU BELIEVE IN MAGIC? There may be nothing magical about how the organic compound in psilocybin mushrooms, psilocin, stimulates brain activity. But people who have been cured of addictions from psilocybin therapy describe their recovery as nothing less than magical.

By loosening the inner tyrant, hallucinogens impart a lightness of being.

emergence of a feeling of profound interconnectedness.

LSD also causes the default mode network to fragment slightly, while boosting activity between other usually segregated areas. The parahippocampus and another region called the dorsomedial prefrontal cortex, important in that sense of “me-ness,” begin talking more, even as the posterior cingulate cortex and the parahippocampus—two hubs of the default mode network—talk less.

The Imperial College scientists interpret these findings as evidence that regions of the brain charged with executive control and top-down maintenance of order—the “rich club,” they call it—relax their grip. The usual separation of brain regions and their functions collapses, and a kind of neural cosmopolitanism emerges. It’s tempting to imagine that, with the proverbial parents out of town, the brain throws a wild, teenage party—that what happens during an LSD trip is a bottom-up explosion of usually repressed exuberance.

This explanation gets at one of the more fascinating models of brain function. Making sense of the world may require the brain to restrain itself—to limit how

and what it perceives. In a Darwinian sense, it’s obvious why that imposition of order might be necessary. If you constantly experienced the world as an acid trip, unable to distinguish your imagined dragons from that very real tiger waiting to pounce, you probably wouldn’t last long. But it’s also possible that the imposition of order can, when it becomes too iron-fisted, imprison us psychologically. So by taking those punctilious, literal-minded “hubs” offline, hallucinogens may free up other brain regions and their associated talents, enabling “a state of unconstrained cognition,” as the scientists put it, and ultimately liberating us from ourselves.

In the neuroscience literature, case reports on stroke, trauma, and even dementia victims suggest that damaging one part of the brain can indeed lead to dramatic enhancements in creativity and well-being, likely by freeing other regions of the brain and their creative energies. Hallucinogens may do something similar, not by destroying those parts of the brain, but by momentarily weakening their hold over other areas.

Still, that doesn’t explain how hallucinogens, which

are taken for just a few sessions, can induce lasting changes—like Kreitman’s three-year abstinence from cigarettes. Most psychotropic drugs, such as SSRIs, must be taken chronically to work. The medication needs to be in your system to have its effect. By contrast, the effect of hallucinogens seems to continue long after they’ve left your body.

Bogenschutz hypothesizes that hallucinogens open a window of enhanced neural plasticity, the brain’s inherent ability to change. Networks of neurons, connected by branch-like filaments, underlie everything you think and feel. Rather like heat makes metal malleable, hallucinogens might enable and accelerate the formation of new connections between neurons, allowing you to alter the prison of your bad habits, fears, and compulsions. And if the mystical experience is important in this plasticity—Bogenschutz says “more work will be necessary to determine if that is indeed the case”—the implication is that the drug alone isn’t what’s important, but rather the subjective experience while on the drug.

As evidence that such a thing is even possible—that intense experience can rewire connections in the brain—Bogenschutz points to post-traumatic stress disorder. There are measurable differences in brain and immune function in people suffering from the condition, changes prompted by trauma that’s not necessarily physical, but experiential.

“In PTSD, it’s the intense emotional response generated by what you perceive is happening” that induces these changes, Bogenschutz says. “It’s mediated not just by the experience itself, but by the meaning attached to that.” Why, then, couldn’t an extraordinary experience of great significance push you in a more positive direction—toward, say, an epiphany that helps you stop smoking?

For his part, Griffiths sees hallucinogens as a crash course in the nature of mind, “which may be relevant to what meditation and religious traditions have explored,” he said. Many forms of meditation exercise the ability to observe the mind without becoming trapped in what’s happening. With time, strengthening this skill may result in a lightness to one’s day-to-day activity, a non-attachment that practitioners often describe as liberating. Perhaps by loosening the grip of the inner tyrant, hallucinogens impart a similar

The usual separation of brain regions collapses, and a kind of neural cosmopolitanism emerges.

“lightness of being,” as Griffiths calls it. That kind of “efficacy”—the ability to avoid becoming entangled in your own fickle desires—is probably essential to abstinence, he says. Post-psilocybin, patients “are not so worried about their addiction or cravings,” Griffiths told me. “They know that it will pass.”

NEARLY A CENTURY AGO, an alcoholic named Bill Wilson was lying in bed, in a hospital, struggling mightily with his lifelong depression. At wits’ end, he reportedly cried out, “I’ll do anything! Anything at all! If there be a God, let Him show Himself!” at which moment, he saw a bright light—he’d later call it a “hot flash”—was overcome by a feeling of ecstasy, and a great sense of peace.

He never drank again.

Wilson went on to found Alcoholics Anonymous, the well known recovery and abstinence program. At some point, Wilson became interested in LSD as a way to help alcoholics quit drinking. He tried it himself, and, like Osmond, thought it might induce in others the experience that had helped him. What Wilson’s story makes clear, however, is that people can naturally and spontaneously have epiphanic experiences that help them quit drinking.

Will Miller, an emeritus psychologist at the University of New Mexico in Albuquerque, has dubbed these sudden psychic shifts “quantum changes.” He began studying them after his own troubled daughter had an epiphany, and transformed into a caring, responsible woman seemingly overnight. These stories present certain commonalities, he says: an intense sense of interconnectedness; the sudden awareness that one’s sense of isolation is an illusion; the realization that

others' shortcomings should be met with compassion, not judgment and punishment. People find sudden release from addictions and dependencies. They repair broken relationships. "I think of it as an evolution in consciousness," Miller told me. He added, "dramatic change is possible. We're not stuck in yesterday."

But these sudden transformations were completely unpredictable. Miller couldn't pinpoint any characteristics that foretold who might experience them, or when. The hallucinogen research needs replication precisely for this reason. If you could induce "quantum change" reliably, you can study it. And imagine the potential benefit not just for addicts, but for everyone.

Assuming that addiction research continues to show promise, Griffiths foresees hallucinogens used in clinical settings that, like his own studies, offer extensive pre- and post-treatment support. Griffiths doubts that hallucinogen therapy will spread anytime soon, however, not because it's a bad idea, but because we have a strong cultural bias against performance-enhancing drugs. "Right now, the idea of giving drugs to improve the betterment of all people would strike at least some people as repugnant," he told me.

But in 20 years, who knows? By then, we may have more precise approaches to induce the same shifts, such as transcranial magnetic stimulation or even precision brain surgery. For Griffiths, hallucinogens' primary contribution may be as a teaching tool, a way to learn how human transformation works so we can encourage it by other methods with fewer potential side effects. The lesson for now, he said, is simply that profound metamorphosis is possible. "We do appear to be biologically predisposed to have experiences that can be the pivot point for enduring radical behavioral change in personality, attitudes, and behavior." ☺

MOISES VELASQUEZ-MANOFF is a journalist and the author of *An Epidemic of Absence: A New Way of Understanding Allergies and Autoimmune Diseases*.



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How We'll Forget John Lennon

Our culture has two types of forgetting

BY KEVIN BERGER

A FEW YEARS AGO A STUDENT walked into the office of Cesar A. Hidalgo, director of the Collective Learning group at the MIT Media Lab. Hidalgo was listening to music and asked the student if she recognized the song. She wasn't sure. "Is it Coldplay?" she asked. It was "Imagine" by John Lennon. Hidalgo took it in stride that his student didn't recognize the song. As he explains in our interview, he realized the song wasn't from her generation. What struck Hidalgo, though, was the incident echoed a question that had long intrigued him, which was how music and movies and all the other things that once shone in popular culture faded like evening from public memory.

Hidalgo is among the premier data miners of the world's collective history. With his MIT colleagues, he developed Pantheon, a dataset that ranks historical figures by popularity from 4000 B.C. to 2010. Aristotle and Plato snag the top spots. Jesus is third. It's a highly addictive platform that allows you to search people, places, and occupations with a variety of parameters. Most famous tennis player of all time? That's right, Frenchman Rene Lacoste, born in 1904. (Roger

Federer places 20th.) Rankings are drawn from, essentially, Wikipedia biographies, notably ones in more than 25 different languages, and Wikipedia page views.

In December 2018 Hidalgo and colleagues published a *Nature* paper that put his crafty data-mining talents to work on another question: How do people and products drift out of the cultural picture? They traced the fade-out of songs, movies, sports stars, patents, and scientific publications. They drew on data from sources such as *Billboard*, Spotify, IMDB, Wikipedia, the U.S. Patent and Trademark Office, and the American Physical Society, which has gathered information on physics articles from 1896 to 2016. Hidalgo's team then designed mathematical models to calculate the rate of decline of the songs, people, and scientific papers.

The report, "The universal decay of collective memory and attention," concludes that people and things are kept alive through "oral communication" from about five to 30 years. They then pass into written and online records, where they experience a slower, longer decline. The paper argues that people and things that make the rounds at the water cooler have a higher

probability of settling into physical records. “Changes in communication technologies, such as the rise of the printing press, radio, and television,” it says, affect our degree of attention, and all of our cultural products, from songs to scientific papers, “follow a universal decay function.”

I recently caught up with Hidalgo to talk about his *Nature* paper. But I also wanted to push him to talk about what he saw between the mathematical lines, to wear the social scientist’s hat and reflect on the consequences of decay in collective memory.

How do you define “collective memory”?

The easiest definition would be those pieces of knowledge or information that are shared by a large number of people.

Why does collective memory decay matter?

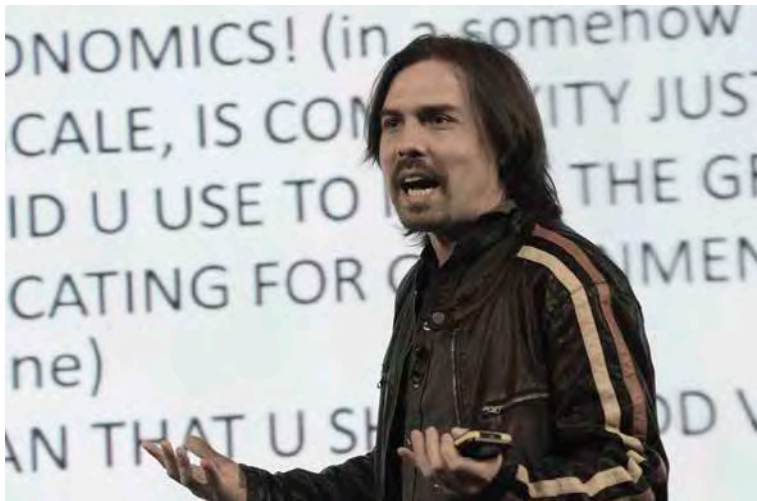
If you think about it, culture and memory are the only things we have. We treasure cultural memory because we use that knowledge to build and produce everything we have around us. That knowledge is going to help us build the future and solve the problems we have yet to solve. If aliens come here and wave a magic wand and make everyone forget everything—our cars, buildings, bridges, airplanes, our power systems, and so forth, we would collapse as a society immediately.

In your mind, what is a classic example of collective memory decay?

I thought everybody knew “Imagine” by John Lennon. I’m almost 40 and my student was probably 20. But I realized “Imagine” is not as popular in her generation as it was in mine, and it was probably less popular in my generation than in the generation before. People have a finite capacity to remember things. There’s great competition for the content out there, and the number of people who know or remember something decays over time. There’s another example, of Elvis Presley memorabilia. People had bought Elvis memorabilia for years and it was collecting huge prices. Then all of a sudden the prices started to collapse. What happened is the people who collected Elvis memorabilia started to die. Their families were stuck with all of this Elvis stuff and trying to sell it. But all of the people who were buyers were also dying.

You write collective memory also reflects changes in communication technologies, such as the rise of the printing press, radio, and TV. How so?

Take print. Changing the world from an oral tradition to a written tradition provided a much better medium for data. A lot of people have linked the revolution in the sciences and astronomy to the rise of printing because astronomical tables, for instance, could be



MEDIUM IS THE MESSAGE “As a new medium takes over, the type of information being produced changes dramatically,” says Cesar Hidalgo. “Printing was not good for actors but good for playwrights. TV was not good for playwrights but very good for sports.”

The relative power of scientists has diminished as we exited the printing era and went into this more performance-based era.

copied in a reliable way. Before printing, astronomical tables were hand-copied, which introduced errors that diminished the quality of the data. With printing, people had more reliable forms of data. We see very clearly from our data that with the rise of printing you get the rise of astronomers, mathematicians, and scientists. You also see a rise in composers because printing helps the transmission of sheet music. So when you look at people we remember most from the time when print first arose, you see ones from the arts and sciences.

What did the mediums that came next mean for science?

The new mediums of radio and TV were much more adaptive for entertainment than science, that's for sure. The people who belong to the sciences, as a fraction of the people who became famous, diminished enormously during the 20th century. The new mediums were not good for the nuances that science demands. For good reason, scientists need to qualify their statements narrowly and be careful when they talk about causality. They need to be specific about the methods they use and the data they collect. All of those extensive nuances are hard to communicate in mediums that are good for entertainment and good for performance. So the relative power of scientists, or their position in society, have diminished as we exited the printing era and went into this more performance-based era.

At the same time, scientists and the general scientific community have not been great at adapting their ideas to new mediums. Scientists are the first ones to bring down another scientist who tries to popularize content in a way that would not be traditional. So scientists are their own worst enemies in this battle. They have lagged behind in their ability to learn how to use

these mediums. Sometimes they focus too much on the content without paying attention on how to adapt it to the medium that will best help it get out.

What does your analysis tell us we didn't know before about the decay of collective memory?

We began by looking at how popular something is today based on how long ago it became popular in the first place. The expectation is collective memory decays over time in a smooth pattern, that the more time goes by, the more things become forgotten. But what we found when we looked at cultural products—movies, songs, sports figures, patents, and science papers—was that decay is not smooth, but has two defined regimes. There's the first regime in which the attention starts very high and the decay is really fast. Then there's the second regime in which it has a much longer tail, when the decay is smoother, and the attention is less.

When we started to think about decay, we realized we could take two concepts from anthropology—"communicative memory" and "cultural memory." Communicative memory arises from talking about things. Donald Trump is very much in our communicative memory now. You walk down the street and find people talking about Trump—Trump and tariffs, Trump and the trade war. But there's going to be a point, 20 years in the future, in which he's not going to be talked about every day. He's going to exit from communicative memory and be part of cultural memory. And that's the memory we sustain through records. Although the average amount of years that something remains in communicative memory varies—athletes last longer than songs, movies, and science papers, sometimes for a couple decades—we found this same overall decay pattern in multiple cultural domains.

In your paper, “How the medium shapes the message,” you refer to the late cultural critic Neil Postman who argued that the popular rise of TV led to a new reign of entertainment, which dumbed us down, because entertainment was best suited for TV. Is that what you found?

We found evidence in that favor, yes. Because the fraction of people who belong to the sciences, as a fraction of all of the people that become famous, diminishes enormously during the 20th century. It would completely agree with that observation.

Do you agree with Postman that we’re all “amusing ourselves to death?”

I don’t think we’re amusing ourselves to death. I’m not that much of a pessimist. I do think life is also about enjoying the ride, not just about doing important things. And new mediums like TikTok, a kind of Twitter for videos, are great for creative expression. People are doing amazing little performance skits on TikTok. The entertainment and artistic components of every new medium are not bad per se, but every medium can be hijacked by extreme people who know how to craft entertaining messages, especially when they want to advance a certain agenda.

What type of information is best suited for the Internet?

It’s hard to think of the Internet as a medium. It’s more of a platform in which Facebook, Twitter, email, and TikTok are different mediums. They each send their own type of message. A picture that does well on Instagram doesn’t necessarily shine on Twitter, where people are expecting something else. The behavior and the engagements are different. Twitter, for example, is about being controversial. You know, one way to get chewed up on Twitter is to try to be in the center! I use Twitter a little, but not that much. I find that it’s a little bit hostile. I’m a family type of guy, so I use Facebook. In Facebook, at least in my circle, you put more detail into comments and are a little bit more thoughtful.

Is collective memory decaying more rapidly because communication technologies are so much faster?

I would love to know that but I can’t. Some people would say collective memory decays based not on

calendar time but the speed at which new content is being produced. We forget Elvis because the Beatles came up and we forget the Beatles because Led Zeppelin came up and we forget Led Zeppelin because Metallica came up, and so forth. But things become very dear to a generation and people will not forget about them just because new content came in. So decay would be something characteristic of humans, not the volume of content. To separate those two things, we would need to look at content from very different time frames. At the moment, we don’t have the richness of data that we would need to answer that question.

Still, don’t you think the speed at which online information is tearing through our brains must be leaving some path of destruction in collective memory?

I don’t know. I grew up in Chile, which of course is small compared to the United States. I came to the U.S. for the first time in 1996. And one of the things that still surprises me is how monothematic American culture can be. In 1996 it was all about O.J. Simpson. Everybody talked about O.J. Simpson. He was everywhere on TV. Just like Trump today, he consumed the entire bandwidth. I’m surprised how a country with so many people, doing so many different things, can nevertheless become so monothematic on such a vast scale. Today we have so much more content than in 1996 because of the rise of the Internet and the ability of people to create content. But look at the percentage of all conversations and online communications that are consumed by Trump. So in that context, I don’t think content is being replaced so easily. I don’t see that much of a rise in diversity.

One of the common criticisms of the current information glut is we have no shared cultural center. Everybody has their own narrow interest and we have no shared cultural bond, no John Lennon.

Is that a collective memory phenomena or is it because nowadays the guys in the middle of the culture are different guys? Different people come into the center of culture because of the type of mediums that are available. There have been musicians for thousands of years, and for most of that history, musicians have not been wealthy. It was only when there was a medium that allowed them to sell their music—vinyl, magnetic

I'm surprised how the U.S., a country with people doing so many things, can become so monothematic on such a vast scale.

tapes, and discs—that they were able to make money. I think that generated a golden era of pop music in the '60s, '70s, and '80s. And that's associative to a communication technology that was dominant at that time. Radio and discs were a way to distribute those popular idols' musical performances. When that technology was replaced by simple forms of copying, like the ability to copy files on the Internet, all that went away. Now people like Elon Musk are in the center of culture. He's not John Lennon. It's a very different type of leadership, a different type of model for young people. But Musk's first job was an online payment start-up. And I think a lot of young people now look up to entrepreneurs the way we used to look up to musicians.

Did you come away from your study with insights into what may or may not cause something to stick in collective memory?

I read a very good book recently called *The Formula* by Albert-Laszlo Barabás. He says you can equate quality and popularity in situations in which performance is clearly measurable. But in cases in which performance is not clearly measurable, you cannot equate popularity with quality. If you look at tennis players, you find tennis players who win tournaments and difficult games are more popular. So quality and fame are closely correlated in a field in which performance is measured as tightly as professional tennis players. As you move to things that are less quantifiable in terms of performance, like modern art, your networks are going to be more important in determining popularity.

How should we think about quality in media content?

Well, I would say that collective memory decay is an important way to measure and think about quality. If you publish some clickbait that is popular in the

beginning, that gets a lot of views in the first couple of days, but a year later, nobody looks at it, you have a good metric. The same is true if you publish a more thoughtful piece that might not be as popular in the beginning because it didn't work as clickbait—it required more engagement from the readers—but keeps on building readers over time. So the differences in longevity are important metrics for quality.

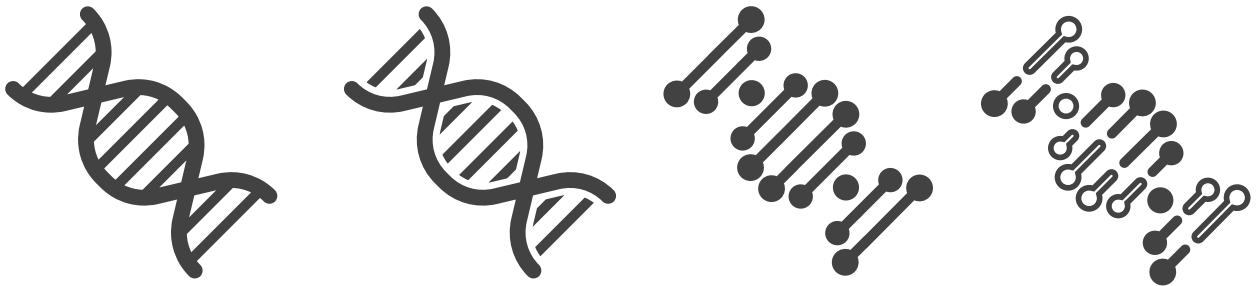
That goes back to a paper I did when I was an undergrad about the decay functions of attendance of movies. There were some movies that had a lot of box office revenue in the first week but then decayed really fast. And there were other movies that decayed more slowly. We created a model in which people would talk to each other and communicate information of the quality of the movie. And that model only had one parameter, which was how good was the movie. So the quality of the movie would increase or decrease the probability that people would go watch it. We could then look at the curves and infer how good the movie was, based not on the total area it was shown, or on the total revenue, but on the shape of the curve. That was interesting because there were movies that were really bad like *Tomb Raider*, which at first was a box office success. But if you put it in our model, you would see that it was just hype, people watched it, hated the movie, and the curve decayed really fast. ☺

KEVIN BERGER is the editor of *Nautilus*.

It's the End of the Gene As We Know It

We are not nearly as determined by our genes as once thought

BY KEN RICHARDSON



WE'VE ALL SEEN THE stark headlines: "Being Rich and Successful Is in Your DNA" (*Guardian*, July 12, 2018); "A New Genetic Test Could Help Determine Children's Success" (*Newsweek*, July 10, 2018); "Our Fortunetelling Genes" make us (*Wall Street Journal*, Nov. 16, 2018); and so on.

The problem is, many of these headlines are not discussing real genes at all, but a crude statistical model of them, involving dozens of unlikely assumptions. Now, slowly but surely, that whole conceptual model of the gene is being challenged.

We have reached peak gene, and passed it.

IT IS, OF COURSE, an impressive story. Today, most people know about Gregor Mendel's breeding experiments with pea plants in the 1850s. He concentrated on simple traits with well-defined, easy to count variations: purple or white flowers; long or short stems; smooth or wrinkled seeds; and so on. After cross-fertilization the patterns of variation in offspring suggested correlations with variation in single "hereditary units."

Mendel's inherited factors—hitherto imputed, but unidentified—are what came to be called the genes. In the early 1900s, it was tempting to equate them with the information and instructions for the comprehensive development of the whole offspring, mental and physical.

In a famous paper in 1911, Wilhelm Johannsen warned against doing that. We do not know, he said, how those inferred, but invisible, factors can possibly carry such complex information. But Johannsen was ignored, for reasons, as it turned out, more to do with ideology than biology.

The preferred dogma started to appear in different versions in the 1920s. It was aptly summarized by renowned physicist Erwin Schrödinger in a famous lecture in Dublin in 1943. He told his audience that chromosomes "contain, in some kind of code-script, the entire pattern of the individual's future development and of its functioning in the mature state."

Around that image of the code a whole world order of rank and privilege soon became reinforced. These

genes, we were told, come in different "strengths," different permutations forming ranks that determine the worth of different "races" and of different classes in a class-structured society. A whole intelligence testing movement was built around that preconception, with the tests constructed accordingly.

The image fostered the eugenics and Nazi movements of the 1930s, with tragic consequences. Governments followed a famous 1938 United Kingdom education commission in decreeing that, "The facts of genetic inequality are something that we cannot escape," and that, "different children ... require types of education varying in certain important respects."

Post-war research sensibly focused more on the biochemistry, but with similar preconceptions. The existence of a powerful code-script seemed to be confirmed with the discovery of the structure of DNA by Watson and Crick in 1953. They revealed how the sequences of components (called nucleotides) in DNA could serve as a template—a code—for a protein, much as a typewriter sequences letters to form words. So the accepted "central dogma" could be conceived as the one-way flow of information from the code in the gene:

DNA template > proteins > developing characteristics;

as if production of the words alone is tantamount to writing the whole "book" of a complex being.

Then came the brilliant technology for sequencing genes (the components or "letters" in the DNA) in the whole genome. Its application, at enormous cost, in the Human Genome Project would, we were told, reveal "what it is to be human." Extravagant promises were made that genes would soon be found that control human intelligence, social behavior, and complex diseases.

Now, in low-cost, highly mechanized procedures, the search has become even easier. The DNA components—the letters in the words—that can vary from person to person are called single nucleotide polymorphisms, or SNPs. The genetic search for our human definition boiled down to looking for statistical associations between such variations and differences in IQ,

education, disease, or whatever.

For years, disappointment followed: Only a few extremely weak associations between SNPs and observable human characteristics could be found. Then another stroke of imagination. Why not just add the strongest weak associations together until a statistically significant association with individual differences is obtained? It is such “polygenic scores,” combining hundreds or thousands of SNPs, varying from person to person, and correlating (albeit weakly) with trait scores such as IQ or educational scores, that form the grounds for the vaulting claims we now witness.

Today, 1930s-style policy implications are being drawn once again. Proposals include gene-testing at birth for educational intervention, embryo selection for desired traits, identifying which classes or “races” are fitter than others, and so on. And clever marketizing now sees millions of people scampering to learn their genetic horoscopes in DNA self-testing kits.

So the hype now pouring out of the mass media is popularizing what has been lurking in the science all along: a gene-god as an entity with almost supernatural powers. Today it’s the gene that, in the words of the Anglican hymn, “makes us high and lowly and orders our estate.”

In her 1985 book, *The Ontogeny of Information*, the philosopher of science Susan Oyama warned, “Just as traditional thought placed biological forms in the mind of God, so modern thought finds ways of endowing the genes with ultimate formative power.”

In scientific, as well as popular descriptions today, genes “act,” “behave,” “direct,” “control,” “design,”

“influence,” have “effects,” are “responsible for,” are “selfish,” and so on, as if minds of their own with designs and intentions.

But at the same time, a counter-narrative is building, not from the media but from inside science itself.

THE LONG-SUPPRESSED LOGIC OF Johansenn that has stalked the gene-god for decades has come home to roost. Scientists now understand that the information in the DNA code can *only* serve as a template for a protein. It cannot possibly serve as instructions for the more complex task of putting the proteins together into a fully functioning being, no more than the characters on a typewriter can produce a story.

This can seem confusing to those of us indoctrinated in the idea that there must be a set of genetic instructions prior to development: If not in the DNA code, then where? By the 1980s, research findings started to turn that notion on its head.

First, laboratory experiments have shown how living forms probably flourished as “molecular soups” long before genes existed. They self-organized, synthesized polymers (like RNA and DNA), adapted, and reproduced through interactions among hundreds of components. That means they followed “instructions” arising from relations between components, according to current conditions, with no overall controller: *compositional information*, as the geneticist Doron Lancet calls it.

In this perspective, the genes evolved later, as products of prior systems, not as the original designers and controllers of them. More likely as templates for components as and when needed: a kind of facility for “just in time” supply of parts needed on a recurring basis.

Then it was slowly appreciated that we inherit just such dynamical systems from our parents, not only our genes. Eggs and sperm contain a vast variety of factors: enzymes and other proteins; amino acids; vitamins, minerals; fats; RNAs (nucleic acids other than DNA); hundreds of cell signalling factors; and other products of the parents’ genes, other than genes themselves.

Molecular biologists have been describing how those factors form networks of complex interactions. Together, they self-organize according to changing conditions around them. Being sensitive to statistical patterns in the changes, they anticipate future states, often creating novel, emergent properties to meet them.

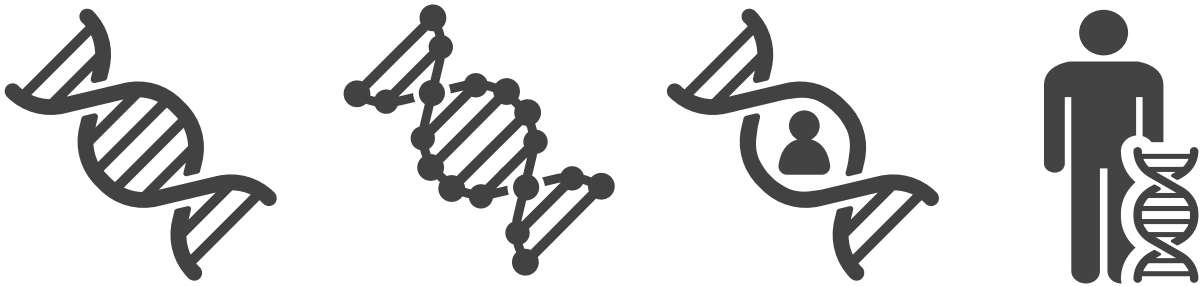
There is no correlation between the complexity of living things and the number of genes they have.

Accordingly, even single cells change their metabolic pathways, and the way they use their genes to suit those patterns. That is, they “learn,” and create instructions on the hoof. Genes are used as templates for making vital resources, of course. But directions and outcomes of the system are not controlled by genes. Like colonies of ants or bees, there are deeper dynamical laws at work in the development of forms and variations.

Some have likened the process to an orchestra without a conductor. Physiologist Denis Noble has described it as *Dancing to the Tune of Life* (the title of his recent book). It is most stunningly displayed in early development. Within hours, the fertilized egg

Molecular Life Sciences.³ On the other hand the assumed developmental “program” coded in a genotype has never been described.

It is such discoveries that are turning our ideas of genetic causation inside out. We have traditionally thought of cell contents as servants to the DNA instructions. But, as the British biologist Denis Noble insists in an interview with the writer Suzan Mazur, “The modern synthesis has got causality in biology wrong ... DNA on its own does absolutely nothing until activated by the rest of the system ... DNA is not a cause in an active sense. I think it is better described as a passive data base which is used by the organism to enable it to make the proteins that it requires.”



becomes a ball of identical cells—all with the same genome, of course. But the cells are already talking to each other with storms of chemical signals. Through the statistical patterns within the storms, instructions are, again, created *de novo*. The cells, all with the same genes, multiply into hundreds of starkly different types, moving in a glorious ballet to find just the right places at the right times. That could not have been specified in the fixed linear strings of DNA.

So it has been dawning on us is that there is no prior plan or blueprint for development: Instructions are created on the hoof, far more intelligently than is possible from dumb DNA. That is why today’s molecular biologists are reporting “cognitive resources” in cells; “bio-information intelligence”; “cell intelligence”; “metabolic memory”; and “cell knowledge”—all terms appearing in recent literature.^{1,2} “Do cells think?” is the title of a 2007 paper in the journal *Cellular and*

Of course, it’s easy to see how the impression of direct genetic instructions arose. Parents “pass on” their physical characteristics up to a point: hair and eye color, height, facial features, and so on; things that “run in the family.” And there are hundreds of diseases statistically associated with mutations to single genes. Known for decades, these surely reflect inherited codes pre-determining development and individual differences?

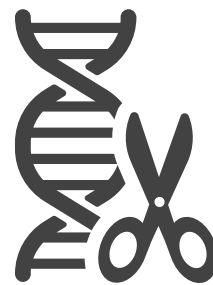
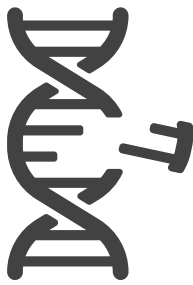
But it’s not so simple. Consider Mendel’s sweet peas. Some flowers were either purple or white, and patterns of inheritance seemed to reflect variation in a single “hereditary unit,” as mentioned above. It is not dependent on a single gene, however. The statistical relation obscures several streams of chemical synthesis of the dye (anthocyanin), controlled and regulated by the cell as a whole, including the products of many genes. A tiny alteration in one component (a

“transcription factor”) disrupts this orchestration. In its absence the flower is white.

This is a good illustration of what Noble calls “passive causation.” A similar perspective applies to many “genetic diseases,” as well as what runs in families. But more evolved functions—and associated diseases—depend upon the vast regulatory networks mentioned above, and thousands of genes. Far from acting as single-minded executives, genes are typically flanked, on the DNA sequence, by a dozen or more “regulatory” sequences used by wider cell signals and their dynamics to control genetic transcription.

This explains why humans seem to have only a few more genes than flies or mice (around 20,000), while a carrot has 45,000! There is no correlation between the

Another wrench in the works has been the discovery that a gene product typically undergoes rearrangements before being put to use.



complexity of living things and the number of genes they have. But there is a correlation with the evolving complexity of regulatory networks. Counting genes to understand the whole is like judging a body of literature by counting letters. It can't be done.

ALL OF THIS PROVIDES a fraught background for modern gene association studies. What's more, the statistical analyses that power these studies are, themselves, full of pitfalls. First, the methods for computing polygenic scores, in which millions of variables are analyzed by statistical manipulation, provides huge opportunities for false positives. Very large databases—even randomly generated ones—can contain large numbers of meaningless correlations; and statistical significance values can be inflated by invalid assumptions.

In polygenic score estimations, for example, it is assumed that SNP associations can be simply added

together, as if beans in a bag, with no effects on each other, or from the environment. Then, as the National Institutes of Health website reminds us, the majority of SNPs are functionally irrelevant anyway.⁴

More importantly, all modern societies have resulted from waves of migration by people whose genetic backgrounds are different in ways that are functionally irrelevant. Different waves have tended to enter the class structure at randomly different levels, creating what is called genetic population stratification. But different social classes also experience differences in learning opportunities, and much about the design of IQ tests, education, and so on, reflects those differences, irrespective of differences in learning ability as such. So some spurious correlations are, again, inevitable.

As Jeremy J. Berg and colleagues warned in 2018 in the online journal *Biorxiv*, polygenic scores “suffer dramatically from stratification bias, as even small

differences in ancestry will be inadvertently translated into large differences in predicted phenotype.”⁵

Another wrench in the works has been the discovery that a gene product typically undergoes rearrangements before being put to use. It means that different proteins, with potentially widely different functions, can be produced from the same gene: not one for one, as the central dogma has told us. Again, the instructions for such rearrangements are not in the genes themselves.

More startling has been the realization that less than 5 percent of the genome is used to make proteins at all. Most produce a vast range of different factors (RNAs) regulating, through the network, how the other genes are used.

Increasingly, we are finding that, in complex evolved traits—like human minds—there is little prediction from DNA variation through development to individual differences. The genes are crucial, of course, but nearly all genetic variations are dealt with in the way you can vary your journey from A to B: by constructing alternative routes. “Multiple alternative pathways ... are the rule rather than the exception,” reported a paper in the journal *BioSystems* in 2007.⁶

Conversely, it is now well known that a group of genetically identical individuals, reared in identical environments—as in pure-bred laboratory animals—do not become identical adults. Rather, they develop to exhibit the full range of bodily and functional variations found in normal, genetically-variable, groups. In a report in *Science* in 2013, Julia Freund and colleagues observed this effect in differences in developing brain structures.

In the same vein, we can now understand why the same genetic resources can be used in many different ways in different organs and tissues. Genes now utilized in the development of our arms and legs, first appeared in organisms that have neither. Genes used in fruit flies for gonad development are now used in the development of human brains. And most genes are used in several different tissues for different purposes at the same time.

IN A PAPER IN *Physics of Life Reviews* in 2013, James Shapiro describes how cells and organisms are capable of “natural genetic engineering.” That is, they

frequently alter their own DNA sequences, rewriting their own genomes throughout life. The startling implication is that the gene as popularly conceived—a blueprint on a strand of DNA, determining development and its variations—*does not really exist*.

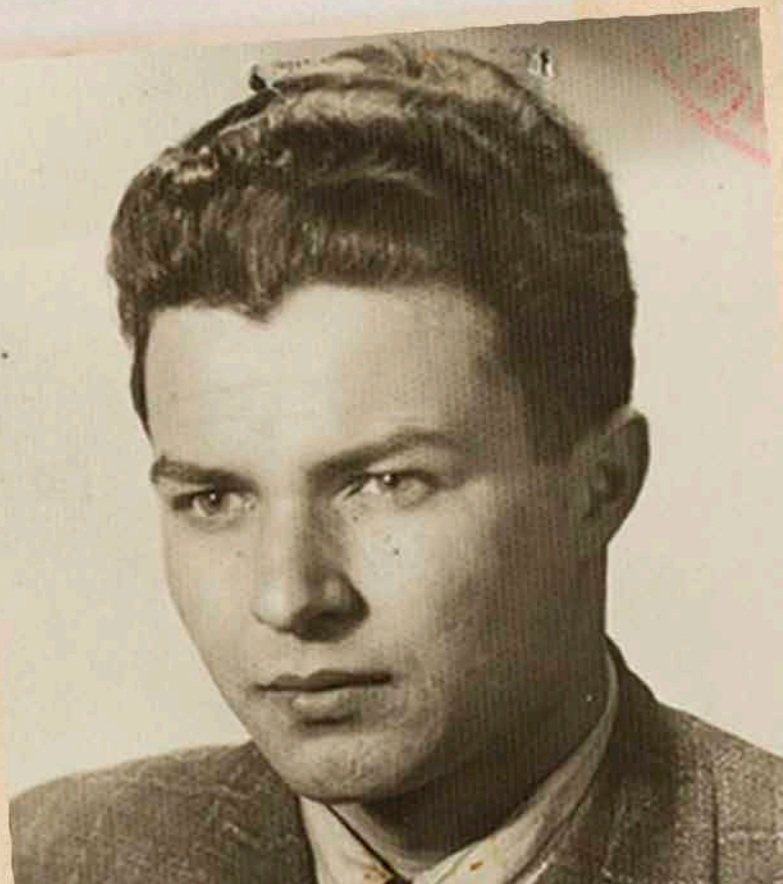
So it is, in a review in the journal *Genetics* in 2017, that the geneticists Petter Portin and Adam Wilkins question “the utility of the concept of a basic ‘unit of inheritance’ and the long implicit belief that genes are autonomous agents.” They show that “the classic molecular definition [is] obsolete.”

These radical revisions of the gene concept need to reach the general public soon—before past social policy mistakes are repeated. ☺

KEN RICHARDSON was formerly Senior Lecturer in Human Development at the Open University (U.K.). He is the author of *Genes, Brains and Human Potential: The Science and Ideology of Intelligence*.

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How Black Holes Nearly Ruined Time

Quantum mechanics rescued our understanding of past and future from the black hole

BY ANDREW TURNER & ALEX TINGUELY

B LACK HOLES ARE MYSTIFYING OBJECTS that have captivated our imaginations since their existence was first proposed. The most striking feature of a black hole is its event horizon—a boundary from within which nothing can escape. Objects can cross the event horizon from outside to inside, but once they do, they can never cross back, nor can any information about them; anything that crosses the event horizon of a black hole is cut off entirely from the outside universe.

For many years, the existence of black holes seemed to threaten a fundamental tenet of modern physics called the second law of thermodynamics. This law helps us to distinguish the past from the future, thus defining an “arrow of time.” To understand why black holes posed this threat, we need to discuss time reversal and entropy.

Entropy and the Arrow of Time

Based on our observations, the laws of physics are

(mostly) invariant under time reversal. What does this mean? Imagine a friend shows you the following video: A pendulum swings across the screen from left to right. Is this video being played normally or in reverse? Well, you have certainly seen a pendulum swing the other way before. If the laws of physics do not change under time reversal, then there is actually no way to tell: Physics looks the same with time playing forward or backward.

However, this doesn’t seem to jibe with our daily experience. Consider another video in which a bunch of ceramic shards fly up off the floor and assemble themselves into a coffee mug before coming to rest on a table. Is this video being played forward or backward? Most people would reasonably guess that the video was being played in reverse. If the laws of physics are truly invariant under time reversal, why does this intuition seem so obvious to us? The reason is that, although the laws of physics *technically* allow for this bizarre process to occur as shown in the video, the fact that the broken

mug is made up of many, many particles means that it is essentially impossible for it to spontaneously reassemble itself.

This concept is formalized by the second law of thermodynamics, which tells us that a certain quantity, the entropy S , of any isolated system cannot decrease over time (but can increase). In other words, the change in entropy cannot be negative:

$$\Delta S \geq 0.$$

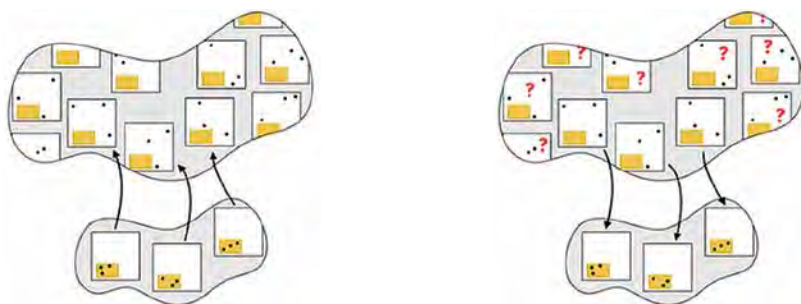
The entropy S is a statistically defined notion measuring our lack of knowledge about the underlying state of a system when we only know “macroscopic” (large-scale) information about it. By “state” here, we mean the exact configuration of each particle making up the entire system. For example, consider a box filled with gas. While we can easily measure the temperature and pressure of the gas, it is practically impossible for us to know the position and velocity of each gas particle within the box. In fact, there are many configurations of particle positions and velocities, i.e., states,

that would give rise to the same temperature and pressure. The entropy encodes our ignorance of which specific state the system is actually in.

The greater the number of states that are consistent with the same temperature and pressure, the greater the entropy.

The fact that the entropy cannot decrease over time—but *can* increase—follows from invariance under time reversal combined with an additional property called causality. Together, these tell us that any single state of a system corresponds to exactly one state at any point in the past or in the future—no more, and no fewer. For example, one state cannot become two states at some point in the future, and two states cannot become one state.

Now consider what happens when we open our box of gas into a large room. If the gas starts in the box and then flows out to fill the room, as in Figure 1a, then we can easily satisfy the rule that each initial state in the box evolves to a unique final state in



a) States with particles initially confined in the box evolving to states with particles filling the room. There are plenty of available states of the gas filling the room for initial states to evolve to.

b) States with particles initially filling the room evolving to states with particles confined in the box. There are not enough available states of the gas in the box for the initial states to evolve to, so this cannot occur.

FIGURE 1 The sets of possible states of the gas when confined to the box (lower set) and when filling the room (upper set). Each square shows one possible state of the gas particles. The upper set is much larger because there are many more possible states in which the gas fills the room.

Without the second law of thermodynamics, why shouldn't we see coffee mugs reassembling themselves in our day-to-day lives?

the room. If we were paying close attention to every particle in the room during this process, the entropy couldn't increase because each initial state evolves to a single final state, but we can't keep track of so many variables; all we are able to do is measure the temperature and pressure after opening the box, and we will find that there are many, many more possible states of the gas in the whole room that are consistent with the new temperature and pressure. During this process, we lose information about the exact configuration of the particles, and thus the entropy increases. If instead the gas starts in the room and then flows into the box, as in Figure 1b, then the vast majority of the initial states in the room have nowhere to go—there simply aren't enough states in the box. Thus, the entropy cannot decrease!

The second law of thermodynamics now gives us some sense of an “arrow of time.” Despite the fact that the laws of physics are time-reversible, the statistical notion of entropy allows us to define a forward direction for time: Time flows forward in the direction that entropy increases! This is why we feel that a video of a spontaneously reassembling coffee mug must be playing in reverse.

Black Holes and Entropy

Now, what does this all have to do with black holes? Classical black holes—the kind that would exist in a world without quantum physics—have no entropy. Physicist Jacob Bekenstein once said that these

classical black holes “have no hair,” a cute phrase meaning that a classical black hole only has a few measurable properties: mass (how big it is), angular momentum (how fast it is spinning), and electric charge (like built up static electricity). When an object falls into a black hole, it contributes to these three quantities, but other than that, any information about it is lost forever.

This is a big problem for the second law of thermodynamics! If black holes truly had no entropy, then any time an object fell into a black hole, its entropy would effectively be deleted, reducing the entropy of the universe and violating the second law of thermodynamics. Without the second law of thermodynamics, why shouldn't we see coffee mugs reassembling themselves in our day-to-day lives?

The resolution to this problem is to add quantum physics into the mix. In 1974, the late Stephen Hawking showed that in addition to the three properties above, black holes also have a temperature, now known as the Hawking temperature. The thermodynamic definition of temperature relates changes in energy to changes in entropy, so this revelation allowed Hawking to show that black holes actually *do* have entropy, consistent with the second law of thermodynamics. In fact, because the energy of a black hole increases when the surface area of its event horizon increases, it turns out that the entropy of a black hole is proportional to its surface area, a fact originally conjectured by Bekenstein.

Hawking's discovery of the exact value of the Hawking temperature allowed him to compute the constant of proportionality, resulting in what is now known as the Bekenstein–Hawking (conveniently, the same letters as “Black Hole”) formula:

$$S_{\text{BH}} = \frac{k_{\text{B}} A}{4l_{\text{P}}^2}$$

where S_{BH} is the black hole's entropy, A is its surface area, and k_{B} and l_{P} are constants known as the Boltzmann constant and the Planck length, respectively. This formula was later verified in a particular theory of black holes by the calculations of physicists Andy Strominger and Cumrun Vafa, as well as others.

The punchline is that black holes *do* have entropy, exactly as we had hoped, and we can tell exactly how much they have just by looking at how big they are. Once we know that black holes have entropy, we have a new form of the second law of thermodynamics that includes not only the universe outside the black hole, but also the universe within the event horizon: The total entropy, $S_{\text{total}} = S_{\text{outside}} + S_{\text{BH}}$, must never decrease. Whenever something is thrown into the black hole, the entropy S_{outside} of the universe outside the black hole decreases, but amazingly the surface area of the black hole, and therefore S_{BH} , increases enough to ensure that S_{total} does not get smaller. Thus, the second law of thermodynamics and the arrow of time are saved! ☺

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This essay is one of the five winners in the 2019 writing competition held by the Black Hole Initiative at Harvard University.

You can read all five winning essays at nautil.us/issue/71/flow.



"IS LIFE SPECIAL JUST BECAUSE IT'S RARE?"

ILLUSTRATION BY **GIZEM VURAL**



Gustav Klimt in the Brain Lab

What is neuroscience doing to art?

BY KEVIN BERGER

THE NEUROSCIENTIST WAS in the art gallery and there were many things to learn. So Eric Kandel excitedly guided me through the bright lobby of the Neue Galerie New York, a museum of *fin de siècle* Austrian and German art, located in a Beaux-Art mansion, across from Central Park. The Nobel laureate was dressed in a dark blue suit with white pinstripes and red bowtie. I was dressed, well, less elegantly.

Since winning a Nobel Prize in Physiology or Medicine in 2000 for uncovering the electrochemical mechanisms of memory, Kandel had been thinking about art. In 2012 and 2016, respectively, he published *The Age of Insight* and *Reductionism in Art and Brain Science*, both of which could be called *This Is Your Brain on Art*. *The Age of Insight* detailed the rise of neuroscience out of the medical culture that surrounded Sigmund Freud, and focused on Gustav Klimt and his artistic disciples Oskar Kokoschka and Egon Schiele, whose paintings mirrored the age's brazen ideas about primal desires smoldering beneath conscious control.

I'd invited Kandel to meet me at the Neue Galerie because it was the premier American home of original works by Klimt, Kokoschka, and Schiele. It was 2014 when we met and I had long been reading about neuroaesthetics, a newish school in neuroscience, and a foundation of *The Age of Insight*, where brain computation was enlisted to explain why and what in art turned us on. I was anxious to hear Kandel expound on how neuroscience could enrich art, as he had written, though I also came with a handful of doubts.

Kandel and I made our way up a spiral marble staircase and into a dark wood and white marble parlor on the second floor. *Woman in Gold*, Klimt's portrait of maverick Vienna socialite Adele Bloch-Bauer—its official title is *Adele Bloch-Bauer I*—commanded the grand room like a film star, a cynosure of odd beauty. We took a seat on a bench and stared.

There she was in her lavish gold gown, filigreed with ovoid shapes—eyes, eggs, fish—blended into a golden background of circles, spirals, and squares.

"The gown is extremely unusual because it's decorated in all kinds of symbols," Kandel said. "And do you

know what they mean?"

"I think they're sexual," I said.

"And where did you get that from?"

"I got it from your book."

"That's right," Kandel said, smiling. "Klimt was fascinated with science. He began to look in a microscope and became fascinated with cells, with sperm and eggs, and incorporated them into his paintings."

But the painting's fertility symbols were only foreplay. "We're attracted to the painting because of the symbols, the gold, but it's Adele's face that really draws us into it," Kandel said.

Indeed, Adele's cabaret white face, with pink cheeks and big oval eyes, hovered above the golden tapestry with a sly supplication.

"Our visual senses are tremendously specialized for faces," Kandel said. "This is the point Darwin made: The face is the most important visual image we ever encounter. We recognize other people, we recognize ourselves, by faces."

Kandel spoke like a 19th-century intellectual who loved to explain, a Freud for the neuroscience age, though with more charm than pedantry.

He continued. The inferior temporal cortex, the brain's assembly room of perception, has six subsystems specialized for faces, each one with a distinct task. Some processed the geometric shape of a face while others determined its orientation; notably, whether it was upright. Because the entire brain was interconnected, activity in facial neurons put neurons responsible for emotions on alert. As a result, Kandel said, Adele's face had us asking, "What is her expression? She's sitting on that golden throne and talking directly to us. What's she saying? She presents us with the same ambiguity as the *Mona Lisa*." An ambiguity that our brains had to resolve.

The neurochemical charge of Adele's face could be as powerful as love, Kandel said. It could even help explain how the famous painting got to New York. Ronald Lauder, 74, the cosmetic heir and cofounder of the Neue Galerie, fell in love with *Woman in Gold* when he was a teenager and bought it for \$135 million in 2006—at the time, the most ever paid for a painting.

GUSTAV KLIMT (1862–1918) *ADELE BLOCH-BAUER I*, 1907, OIL, SILVER, AND GOLD ON CANVAS / NEUE GALERIE NEW YORK. ACQUIRED THROUGH THE GENEROSITY OF RONALD S. LAUDER, THE HEIRS OF THE ESTATES OF FERDINAND AND ADELE BLOCH-BAUER, AND THE ESTÉE LAUDER FUND

When you look at Adele's face, Lauder has said, "you see a sensuous woman looking at you, feeling, reacting to you, you feel her emotion, you feel her sexuality."

When Lauder gazed at Adele, Kandel said, his "ventral tegmental area," where the neurotransmitter dopamine, a key chemical in stimulating pleasure, is manufactured, sprang to action. "The dopamine system gets activated by primary rewards like food and sex, by addiction, by romantic love, and by the love of art," Kandel said. "If you show somebody a picture of their loved one, it gets the dopamine system going. If you're rejected in a love relationship, it drives the system even more. So Ronald Lauder falls in love with the painting, goes to see it every year, but can't get the thing. This is driving him crazy, his dopamine system is going off the charts. It was so active he would have paid \$140 million for the painting!"

Kandel smiled. He said he didn't know exactly what was going on with the tycoon when he looked at Adele. He's never scanned his brain. But if Lauder can fall prey to the siren call of *Woman in Gold*, so could we. "Because the painting may have had this effect on Lauder, and we all have the same anatomy, the implication is there must be something special in the art to set off the physiological triggers of attraction and love," Kandel explained. "And so we say, 'What a great painting.'"

I TOLD KANDEL THE PAINTING didn't trigger such love in me. Surprisingly, he felt the same way. He preferred Klimt's painting *Judith I*, which depicts the

biblical Jewish heroine, mostly naked, holding the severed head of Holofernes, leader of the enemy Babylon-Assyrian forces, whom she seduced and decapitated. "This is usually depicted as a painful act for Judith, which she did out of altruism," Kandel said. "With Klimt it's pure hedonic sexuality." In fact, Kandel said, because *Judith I* sparked "a fascinating swirl of emotions," it was influential in setting him off to explore "what we know biologically about the perception of art, the empathy of art, and the emotional response to it."

We stood up and walked along the dark wooden walls and came to rest in a corner of gloom. Before us was a painting by the mercurial Kokoschka. Like Klimt, Kokoschka was obsessed with medical renderings of the human body. With slashing brushstrokes of dark green and brown, Kokoschka, in a portrait of Austrian architect Adolf Loos, plumbed viewers into melancholy.

"This is not a pretty portrait," Kandel said. "The guy doesn't look particularly handsome. The eyes are not symmetrical. The hand position is extremely awkward." The distorted features, Kandel explained, captured "a new internal reality—the psychic conflicts of the sitter and the tortured self-inquiry of the artist."

At the turn of the 20th century, Kandel said, art that captured people's internal realities mirrored what scientists were seeing in the lab. Neurologists were learning the brain was a factory of many floors, each with its own function. This one processed language, this one limb movements, this one emotions. While evolution fashioned each neural system to carry out the same function using the same electrochemistry, the interaction of them produced individual thoughts and responses. Myriad environments, after all, presented manifold challenges.

Take the visual system, Kandel said. Everybody's works the same. The lens of the eye projects a two-dimensional image onto the retina, a sheet of cells on the back of the eye. Retinal cells transmit the image information (essentially lines and contours), converted into neural circuits, along an optic nerve to the thalamus, a region of cells in the mid-brain. The thalamus relays the circuits to the primary visual cortex, which acts like a post office and distributes the circuits to destinations that include the amygdala (center of emotion), the hippocampus (key to memory formation),

The purpose of a scientific approach to art is not to take the mystery out of the art. It's to give you new insight into why you think it's so wonderful and mysterious.



INTERIORS Oskar Kokoschka painted emotional states more than people, Eric Kandel says. “He painted them with an idea of getting inside their heads.”

and the cerebral cortex, which regulates circuits from throughout the brain. This “bottom-up process,” Kandel said, was universal. But it explains only half of what’s going on when we look at art.

Kandel and I came to a halt in front of another Kokoschka painting, *Martha Hirsch (Dreaming Woman)*, a pale introvert, painted in wan yellows, lounging in a Viennese café or a mental asylum. It wasn’t hard to imagine either.

This is where the other half of brain function, the “top-down process,” was apparent, Kandel said. We filled out the painting with the story that resonated with us individually.

“Go back to the bottom-up process for a moment,” he said. Along every step of the way, neural circuits are being rewired, constructing visual images. Seeing, Kandel stressed, isn’t a matter of our brain working like a camera, freezing images in our head. It’s an act of

assembly with numerous brain areas contributing their part. But the bottom-up process alone can’t resolve the anarchy of information that vision sends pouring into our brains. So a top-down process, directed by “executive powers” in the prefrontal cortex, synthesizes neural circuits and restores order. On the brain’s assembly line, memories serve as guides to visual resolution.

Kandel held his eyes on Kokoschka’s dreaming woman. “Top-down processing accounts for the fact that you and I can look at this painting and have a different response,” he said. “That’s because we’re reconstructing the whole thing. We all have different experiences, interact with different people, and have different lifestyles. So we all have a slightly different brain.”

In *The Age of Insight*, he wrote, “This distinctive modification of brain architecture, along with our distinctive genetic makeup, constitutes the biological basis

for the expression of individuality. It also accounts for differences in how we respond to art.”

KANDEL AND I CONTINUED to stroll along the gallery’s dark oak floors. I asked him about his past. Did his own life color his appreciation of art. “Of course,” he said. He got into neuroscience, and later neuroaesthetics, because he wanted to make sense of his past.

Kandel was born in a Jewish family in Vienna in 1929. When he was 9, Nazi Germany, under Hitler’s command, annexed Austria. Amid their murder and exile of Jewish citizens, Nazi soldiers ransacked the homes of Jewish families. They invaded Kandel’s apartment and stole everything of value: jewelry, silverware, and his favorite toy, a battery-powered car. His father, who owned a toy store, was incarcerated by Nazis for months and won his release because he was able to prove he had fought for Germany during World War I. Kandel’s parents sent him and his brother to live in

Seeing isn’t a matter of our brain working like a camera, freezing images in our head. It’s an act of assembly.

New York with grandparents in 1939, joining them six months later.

“Although my family and I lived under the Nazi regime for only a year, the bewilderment, poverty, humiliation, and fear I experienced that last year in Vienna made it a defining period of my life,” Kandel wrote in his autobiography, *In Search of Memory*.

The same year Nazis raided Kandel’s home, they stole *Woman in Gold* from the Vienna mansion of Adele’s widow, Ferdinand, a sugar-industry magnate, who had fled to Switzerland. (Adele died in 1925, at age 43, from meningitis.) In her 2012 book, *The Lady in Gold*, journalist Anne-Marie O’Connor breathed new life into Adele’s family members and close friends who were imprisoned, raped, or marched to death camps. Under Hitler’s reign, O’Connor revealed, Nazi officers twisted the *Woman in Gold* into an instrument of Nazi propaganda. When the Nazi governor of Vienna exhibited the portrait in 1943 at a downtown art show, he stripped Adele of her Jewish provenance and renamed the painting *Portrait of a Lady with Gold Background*. “Adele symbolized one of the most brilliant moments in time, but also one of the world’s greatest thefts: of all that was lost when one woman and an entire people were stripped of their identity, their dignity, and their lives,” O’Connor wrote.

Kandel and I stopped in front of a Kokoschka portrait of Austrian merchant Emil Lowenbach, a sad aristocrat with cavernous eyes. “I got interested in what happened in Vienna in the early 1900s because I wanted to understand how people could listen to Haydn,



WHO ARE YOU? Our brains fill in the stories of paintings. Eric Kandel likes to quote the late neuropsychologist Richard Gregory: “Our brains create much of what we see by adding what ought to be there.”

OSKAR KOKOSCHKA (1886-1980), *MARTHA HIRSCH (DREAMING WOMAN)*, 1909. OIL ON CANVAS



HUNGER ARTIST “Egon Schiele is the Kafka of painting,” Eric Kandel says. “He thought he could communicate emotions most effectively using his own naked body.”

Mozart, and Beethoven one day and beat me up, beat up the Jews, the next,” Kandel said. “Getting kicked out of Vienna was like post-traumatic stress disorder. You want to come to grips with it. And one way to do it is to master it.”

Kandel majored in modern European history and literature at Harvard, determined to understand the contradictory passions of people. His girlfriend at the time, Anna Kris, was another émigré from Vienna. Her father, Ernst Kris, a psychoanalyst in Freud’s circle, convinced Kandel to change course. “He told me, if you think intellectual history is going to lead you this way, you’re completely wrong,” Kandel said. “The only way you can do it is through the mind. So I dropped everything and went to medical school to become an analyst. In addition to getting psychiatric training, I also took neurobiology.”

Kandel said he was greatly influenced by Kris’ writings about art. “He said no painting is complete unless you have somebody paint it and somebody respond to it,” Kandel said. “He pointed out the ‘beholder’ is undergoing a creative experience that recapitulates what the artist is doing. Obviously it’s a much greater creative experience to create it in the first place than to respond to it. But nonetheless looking at a work of art is a creative experience—and the creative experience is pleasurable in itself. And each of us brings our own creative process. Our top-down processes are different.”

It was fascinating, I said to Kandel, to reflect on how the architecture of our brains, constructed from our individual genes, experiences, and memories, shaped our view of art. Beauty was in the brain of the beholder. But I still wasn’t quite clear on how neuroscience enhanced our appreciation of art itself. If art was an external stimulus, indistinguishable from any other, what was special about it? In fact, by reducing our experience of art solely to brain chemistry, weren’t we creating a new kind of night school in art depreciation?

Kandel laughed. “This is what many humanists are concerned with,” he said. “They think these heathen scientists are going to come along and provide a little bit of visual, biological insight into art, and this is going to replace the aesthetic response. That’s not my feeling at all. The purpose of a scientific approach to art is not to take the mystery out of the art. It’s to give you new insight into why you think it’s so wonderful and mysterious. If we had a detailed understanding of sexual activity, knew exactly which regions of the brain were involved when each of us had an orgasm, would it reduce the pleasure of having sex? No. It would give you additional insights that might give you additional approaches. But it wouldn’t alter the basic experience. This is the same thing. This is an aid to greater understanding.”

Art, too, engaged us in the world and lives of others like nothing else, Kandel said. Semir Zeki, a British neurobiologist and vision expert, the pioneer of neuroaesthetics, had written that the main function of the brain was to acquire knowledge about the world. Art was a special form of knowledge because it engaged the brain’s full orchestra of neural systems. “Since art arouses emotion, and emotion elicits both cognitive and physiological responses in the observer, art is

capable of producing a whole-body response,” Kandel explained.

We stopped in front of a painting by another Austrian in Klimt’s circle, Egon Schiele. It was a self-portrait by the saturnine artist, who died from Spanish flu at age 28. Schiele was standing naked in profile, his right arm twisted around his head. With charcoal lines and elemental watercolors in brown hues, Schiele pictured himself as gaunt and angular, bones stretching his skin, a look of recrimination frozen on his face.

“I think this is a damn interesting painting,” Kandel said. “The guy looks like he’s on the verge of a breakdown. This is the existential anxiety of modern man. Austria is about to go to war. This is a terrible burden. But you see no overt reference to war. It’s in the body and face.”

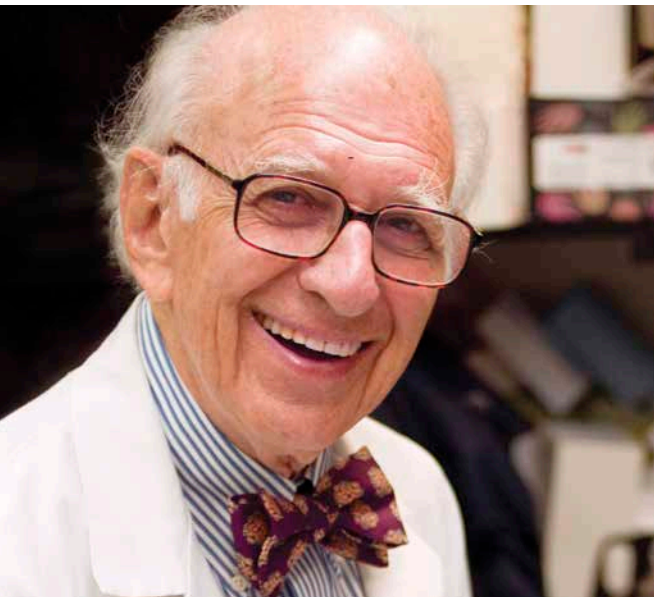
At base, Kandel said, the Schiele painting was a story, and stories inspired us, as they did our earliest ancestors, to envision another way of life. “Art allows us to see aspects of the world we’ve never seen or experienced, feel emotions we’ve never felt, see beauty we’ve never seen, love women who would never love us. It

creates a fantasy life for us,” he said, smiling. “And we all live by fantasy.”

KANDEL AND I MADE OUR WAY back to *Woman in Gold* and took a seat. We discussed it with a renewed perspective. “I’ve seen this painting dozens of times, but each time I’m more aware of the decoration in one corner or elements I’ve either ignored or forgotten,” Kandel said. It’s a biological verity of perception, he added, that you can focus on only one thing at a time. “As a result, you’re filling in the painting by looking. This is wonderful. This shows how your imagination, your creativity, works.”

As we recreated the *Woman in Gold* in our minds, Kandel said, there was another element at work. In the process of seeking visual and emotional resolution, our brains engaged our knowledge of the world and art. During his lifelong research into memory, Kandel had written extensively about the neurochemistry of learning, how learning “can significantly increase the number of synaptic contacts between the nerve cells,” potentially expanding our capacities to think and feel. “Our experience of a painting is not determined simply by the image that we see in front of us, but also by the history of the image and everything we know about it,” he said.

It was now my turn to share what moved me most about *Woman in Gold*—which indeed stemmed from everything I knew about the painting and Klimt. Adele, unlike her Victorian sister, Therese, fled the parlors of high society for Vienna’s demimonde of artists and intellectuals. At the time, Klimt’s talents were in full bloom, but he was working in a vale of resignation. A swaggering bear of a man, Klimt lived to upend Austria’s ruling class. His works spirited away mythical Greek goddesses to assail conventional morality and expose desire gone wild. In 1894 he was commissioned by Austria’s Ministry of Culture to create three ceiling paintings at the University of Vienna on the theme, “The triumph of light over darkness.” Klimt’s paintings, *Philosophy*, *Medicine*, and *Jurisprudence*, were phantasmagorias of naked bodies, a giant octopus, skeletons, and priestesses, floating in a cosmic firmament. Austrian authorities expected the murals to spread the light of human reason over the darkness of chaotic nature. When they saw the opposite, they



THE TWO CULTURES Eric Kandel says, “I don’t think art and science are that far apart because both are playing all the time to make sure they’ve got it right.”

CHRIS WILLCOX

refused to exhibit them.

Klimt was disgusted. “Enough of censorship,” he sniped to his friend Berta Zuckerkandl, a writer who hosted Vienna’s avant-garde literary salon. “I want to get out.” Klimt’s remarks were noted by Carl Schorske in *Fin-De-Siecle Vienna*, a definitive history of the period. Schorske, director of European Cultural Studies at Princeton University for many years, who died in 2015, wrote the depth of Klimt’s dejection was expressed in his art. Klimt underwent a “reshuffling of the self,” Schorske wrote. In his previous public works, Klimt raged against repression. “Now he shrank back to the private sphere to become painter and decorator for Vienna’s refined *haut monde*.”

The narrative of a political artist whose public defeat caused him to withdraw into a private utopia struck a deep emotional chord in me. I don’t know why exactly. The heroic drive of the rebel in search of naked truths has always been an emotional rush for me—in art and science. And so the rebel’s invariable failure fills me with pathos. I didn’t grow up during the horrors of World War II, as Kandel did, but at the end of the postwar baby boom in suburban California, stifling in its own right, at least to me. Still, I shared with Kandel the transcendent power of Klimt’s work, even though we each saw it in the studios of our own minds.

Before I met Kandel at the Neue Galerie, I tended to side with critics, from both the sciences and arts, who had written neuroaesthetics portrayed the experience of art as little more than a “programmed response of brain circuitry,” as one critic said of Kandel’s *The Age of Insight*, and ignored the social and cultural factors that influenced our appreciation and understanding of art. My afternoon in the gallery with Kandel had shown me quite the opposite.

As much or more than any painting in history, *Woman in Gold* symbolized how art was affected by social and cultural factors that forever shaped our brains, emotions, and perspectives. Knowledge was such a powerful elixir when looking at *Woman in Gold*. The 2015 release of *Woman in Gold*, a film about the restitution of the painting to Adele’s niece, Maria Altmann, of Los Angeles, introduced the painting to a new mainstream audience. Knowledge of the emotional story helped the 2015 exhibition, “Gustav Klimt and Adele Bloch-Bauer: The Woman in Gold,” to be among the

Neue Galerie’s most popular ever.

I had felt, too, neuroscience was anesthetizing art like a specimen upon a lab table. But looking at the paintings with Kandel drew me closer to them. The importance of art, he told me, was its power to reflect who we were and what we cared about. It showed us we evolved to learn, connect with others, and change.

As we got up to leave, Kandel made a suggestion. “Walk back and forth in front of Adele. Her eyes follow you. That’s the magic here.” Kandel was referring to our visual systems converting Klimt’s two-dimensional image into a three-dimensional portrait in our minds. But I felt he was talking about much more. Adele was looking into us from Klimt’s private studio, her eyes evoking an endless sorrow. It was a deeply personal experience that felt like a universal one. Art, the scientist showed me, was our portal into the world. ☺

KEVIN BERGER is the editor of *Nautilus*.



Why We Stink at Tackling Climate Change

Global threats result from human culture outrunning human biology

BY DAVID P. BARASH

WHAT'S WRONG WITH US? Not us Democrats, Republicans, or Americans. Rather, what's wrong with our species, *Homo sapiens*? If human beings are as Hamlet suggested, "noble in reason, infinite in faculty," then why are we facing so many problems?

In many ways, people are better off than ever before: reduced infant mortality, longer lifespans, less poverty, fewer epidemic diseases, even fewer deaths per capita due to violence. And yet global threats abound and by nearly all measures they are getting worse: environmental destruction and wildlife extinction, ethnic and religious hatred, the specter of nuclear war, and above all, the disaster of global climate change.

For some religious believers, the primary culprit is original sin. For ideologues of left, right, and otherwise, it's ill-functioning political structures. From my biological perspective, it's the deep-seated disconnect between our slow-moving, inexorable biological evolution and its fast-moving cultural

counterpart—and the troublesome fact we are subject to both, simultaneously.

Biological evolution is an organic process that can never proceed more rapidly than one generation at a time, and many generations are nearly always required for any appreciable change to occur. By contrast, cultural evolution is extraordinary in its speed. Biological evolution is Darwinian, moving by the gradual substitution and accumulation of genes. Cultural evolution is Lamarckian, powered by the nongenetic "inheritance" of acquired characteristics. During a single generation, people have selectively picked up, discarded, manipulated, and transmitted cultural, social, and technological innovations that have become largely independent of any biological moorings.

In their early stages, these two processes would likely have been mutually reinforcing. Our capacity for culture is itself our most potent biological adaptation, enabling a population of weak-bodied Pleistocene primates to gain ascendancy over most of the world. At

the same time, as cultural evolution proceeded and we endowed ourselves with language, impressive cognition, complex social organization, and increasingly potent technology, the ability to employ these skills to master our immediate environment almost certainly outran our biological evolution.

It seems inevitable that as these cultural skills developed and provided leverage over the material and natural world—not to mention over other human beings, less adroit at these things—natural selection favored those individuals most able to take advantage of such traits. Up to a point, our biological and cultural evolution would have been mutually reinforcing. We are now past that point.

THERE IS NO REASON for our biological and cultural evolution to proceed in lockstep, and many reasons for them to have become disconnected. Biological evolution is chained to genetic change; indeed, that's what biological evolution is. Cultural evolution is entirely different. Although it depends on a biological infrastructure (it takes brains to make a fire, a computer, a functioning language, a hydrogen bomb), cultural “mutations” can arise and be adopted, modified, and passed along within days, without waiting for the passing of even a single biological generation. I wrote this on a computer, having purchased my first word processor in the 1980s. Before that, I wrote on an IBM Selectric typewriter, and before that, on a Smith Corona manual. All within just one lifetime.

If my use of a computer depended on biological evolution, and if I had invented the computer in the 1980s, then at most one or two of my daughters (and their toddler offspring, my grandchildren) would currently be using computers. Instead, literally billions of people are doing so; not only that, but they are using technology that is updated every few years. During that time, of course, there has been effectively no change in the biological nature of *Homo sapiens*.

Imagine this thought experiment. An infant born on the Pleistocene savannah is switched at birth with another born in 21st-century America. Each would undoubtedly grow up to be a functional member of her society: hunting mastodons or gathering roots and berries in one case, and perhaps running a hedge fund or piloting jet aircraft in the other. Now, delay a few

Imagine this. An infant born on the Pleistocene savannah is switched at birth with another born in 21st-century America.

decades and switch these two individuals as adults; the results would be disastrous for both. The biological nature of these individuals will be comparable whereas cultural evolution will have produced qualitatively different circumstances in the two cases, such that individuals carrying only their shared biology into each situation would find themselves woefully unable to function in the other's cultural milieu.

This discrepancy italicizes the gulf between our biological and our cultural selves. Moreover, the rate of these changes and the dimensions of our biology-culture discrepancy has itself been accelerating. Recalling Kenneth Grahame's 1908 classic *The Wind in the Willows*, our species has been on Mr. Toad's Wild Ride. Exciting, yes. But also dangerous. In Aesop's classic race, the tortoise wins because the hare is overconfident and downright foolish. In human reality, though, both are part of ourselves. The problem is our hare-y alter ego outpaced our inner tortoise, which has not evolved to deal effectively with the risks presented by our speedy culture.

Let's think about our species-wide sweet tooth. Primates all, we evolved in trees with a special predilection for ripe fruit. Ripeness indicates maximum nutritional value—a lure to get arboreal creatures to consume them, after which the seeds are pooped out elsewhere, surrounded by nutrition-rich fertilizer. So far, so biological. Not surprisingly, ripe fruits and fruity flavors still exert a biological attraction for modern *Homo sapiens*. Also, to no one's surprise, people have seized on this fondness via cultural practices that generate “sweets” that are nothing but sweet—that is,



YOU DESERVE A BREAK

We evolved a taste for wild game that was fat in calories. But our primate ancestors had to work for it. Our culture now sates us with fat and we only have to lift a finger.

devoid of nutritional value. They are, however, deeply satisfying, not to mention remunerative to chocolatiers, bakers, processors of sugar and high fructose corn syrup, and dentists.

A similar dietary situation pertains to fats. Wild game is notoriously lean, and yet fat is calorically dense as well as relatively rare during 99 percent of our evolutionary past. When available, a fatty meal would have been highly valued. Today, not only can we pander to our fondness for “empty calories” in the form of highly sugared drinks and desserts, but we have the luxury of treating ourselves to highly marbled steaks, courtesy of feed lots and industrial agriculture, along with the gustatorially appealing fat present in bacon, burgers, butter, cream, and fried foods of all sorts. The beneficiaries, in addition to the denizens of corporate animal husbandry, include cardiologists, coronary bypass surgeons, diet consultants, and undertakers.

Let’s look now at another related example: exercise. There are, of course, people who enjoy exercise, who go out of their way to get it, often paying large fees to join athletic clubs, gyms, and hire fitness gurus. But it’s also notable how many gym memberships go unused, how many home exercising devices end up collecting dust in the basement, and how serious is the

increasingly worldwide obesity epidemic, despite the unambiguous medical assessment that aerobic activity is beneficial for maintaining cardiovascular health, appropriate body weight, and protecting against a range of degenerative and inflammatory diseases.

Why don’t people get more exercise? Much of the blame resides, once again, in the disconnect between the imprint of our biological past and our present-day predilections made available by our cultural interventions. There is debate among paleo-anthropologists over precisely how much exercise our savannah-dwelling ancestors normally experienced, but it is unlikely that they took elevators or escalators, commuted by bus or automobile, spent their weekdays at a desk and their weekends on a couch watching golf. For most of our evolutionary past, it was probably difficult to avoid getting heavy doses of exercise, and a good idea to minimize it when possible.

OUR BIOLOGY-CULTURE DISCONNECT is not limited to matters of nutrition, exercise, and health. Its imprint can be seen in nearly every big-picture problem we currently face. Enter global heating (a better word than “warming,” which carries misleading connotations of comfy and toasty). Insofar as the combustion

of fossil fuels generates millions of tons of carbon dioxide, which, via the greenhouse effect, absorbs heat from the sun while preventing much of it from being radiated back into space, our technological hare has set the pace. This phenomenon is largely due to the industrial revolution, barely more than two centuries old, during which time our biological evolution has essentially remained unchanged. Rapid cultural evolution has bequeathed us 50 percent of the problem: the physical and chemical half. At the same time, slow moving biological evolution has left us both reluctant to acknowledge the problem and—even when that psychological roadblock is surmounted—often disinclined to do very much about it. Why?

Go back to our weak-bodied, savannah-dwelling ancestors. Although some regular environmental variations were doubtless recognized and anticipated—such as daily and seasonal cycles—excepting certain rare events such as asteroid impacts or earthquakes, changes would have been so gradual as to be almost imperceptible. I don't know if anyone has actually tested the cliché that a frog dropped in boiling water will immediately jump out, whereas the same amphibian placed in cold water that is imperceptibly heated will not notice the gradual change, and die of heatstroke. But the metaphor is compelling. It has similarly been observed that if the air pollution that now afflicts so many great cities had arrived overnight, the inhabitants would have run screaming into the hills; as it is, residents by and large accept the deterioration of their immediate environment and wonder about the strange blue sky that blows in every now and then.

Our biologically evolved selves are quite good at perceiving events that are prompt and threatening; those that are slow-moving, although equally threatening, not so much. A fire in a building and people run outside. A slow moving fire in the Earth's thermal budget and people hardly notice. For nearly all of our evolutionary past, it was not adaptive to detect such slow-motion changes, and so our ability to do so is limited.

Quick events, not surprisingly, evoke quick responses. In the past, a sabre-tooth about to leap; in the present, a car approaching too fast. Similarly, we are exquisitely sensitive to the immediate past, which made us good at responding to a location, where we might have found food, or narrowly missed becoming food. It is a

Up to a point, our biological and cultural evolution would have been mutually reinforcing. We are now past that point.

selective sensibility that now readily misleads us. We are inclined to interpret the latest cold snap as evidence against global heating, or, on the other hand, a heat wave as confirming it. Long term trends leave us confused and psychologically indifferent, just as we are largely insensitive to statistical compilations—highly significant though they are—such as a long-term, 2-degree-Fahrenheit temperature rise.

In addition to being dangerously indifferent to slow-moving changes, it seems likely that our ancestors were predisposed to refrain from struggling with problems that were on a global, continental, or ecosystem scale. Recent evidence suggests that in the prehistoric past, early humans were responsible for the extinction of some of the Earth's large mammals, events that would have had ecological consequences. But for the most part, those relatively rare, weak-bodied primates limited to Stone Age technology weren't able to act as major geological and biological sculptors of the planetary environment. Our numbers were too small and capabilities too limited. Moreover, there was nothing our great-great-etc. grandparents could have done about whatever changes nature might have wrought.

And it would not have been in their adaptive interest to try. There is no payoff (emotional, psychological, social, or biological) to wrestling with a tornado or struggling to cap a volcano. Any who tried wouldn't have benefitted from the effort, and might well have

left few if any descendants compared to those who saved their energy for more manageable threats. An enemy with an upraised club was one thing; a raised ambient temperature—no matter what its cause—would have been quite another.

Very little in the realm of human behavior is caused by just one thing. Similarly, few of our problems result from simple, unimodal cause and effect. When it comes to global climate change, there is little doubt that politics, economics, and social factors are implicated, not only in causing the problem but interfering with our ability to perceive and deal with it effectively. But the strictures placed on our psychology by the conflict between our rapidly moving cultural and technological hare and our glacially slow Darwinian tortoise are also to blame.

As I've said, cultural evolution has provided us with huge benefits. Few people would choose to live without antibiotics, readily available food, shelter, and communication. At the same time, we cannot adjust our biological evolution to make it congruent with its cultural counterpart, at least not within any reasonable time scale.

OUR SITUATION IS NOT HOPELESS. We are not doomed to plod into an overheated future, prisoners of our slow-moving genomes and at the mercy of our hare-brained, rapid-moving, CO₂-spewing technology. The human species is capable of remarkable and adaptive adjustments—not of our biological evolution (that's ethically questionable and too slow in any event), but in our cultural actions. Indeed, it is because of our big, biologically evolved brains that we possess this capacity.

Consider, of all things, toilet-training. We are clearly more intelligent than dogs or cats, and yet it often takes three or more years for young *Homo*, ostensibly *sapiens*, to learn to pee and poop in a toilet, whereas our household pets learn the trick almost immediately. An evolutionary perspective suggests why. Arboreal creatures, as our ancestors were, have no reason for their DNA to be encumbered with a penchant for tidy potty habits. By contrast, dogs and cats evolved in a two-dimensional world where it was maladaptive for them to foul their dens. Hence it is easy for them to become house-broken.

I submit that everyone reading this article—primates all—have been toilet-trained. Thanks to our cultural evolution, we have cities, houses, and indoor plumbing. As a result, to the benefit of our health, we learned to use toilets. A primate with such behavioral flexibility, capable of going against millennia of natural selection, is nearly miraculous, yet an everyday event. Take heart. An originally arboreal primate species capable of being toilet-trained should also be capable of becoming planet-trained. In Aesop's tale, remember, the tortoise triumphs. Because the hare and the tortoise are both part of ourselves, they can only win or lose together, which makes it all the more important that we get our hare-brained selves under control. ☺

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Sparks of Science

Physicist Melissa Franklin and geneticist Pardis Sabeti on the scientists who inspired them

STORY AND ART BY DAY'S EDGE PRODUCTIONS

Melissa Franklin, Experimental Particle Physicist

“PHYSICS IS OFTEN BROKEN up into two types of people. The theorists. They sit in their office with pencil and paper or a computer. Experimentalists actually measure things. That’s why experimentalists are more like cowboys. Or what I think cowboys are like. I’m not sure. I don’t really know any cowboys. Experimentalists have to be able to say to the theorists: I don’t care about your stupid theory, I’m going to measure this. Ernest Rutherford was the experimentalist who figured out that an atom was made of a nucleus and electrons around it. He had all these women graduate students in his lab. I like that the guy who discovered something so fundamental was also ahead of his time in terms of supporting women as scientists.”





Pardis Sabeti, Computational Geneticist

“I USE COMPUTERS TO look at data from biology, from our genomes. I’ve always loved math. But I love nature. And computational genetics is an access point to use math to understand nature. I didn’t ever intend to be a scientist. But I was fortunate enough as an undergraduate to have Eric Lander as my undergraduate advisor. I saw throughout that time the way he was endlessly curious with an extraordinary mission to change the world through science. He really showed me that science could have an impact on the lives of many, not just through the results that science produces, but through the communities it creates. He really showed me what an amazing and fulfilling life the life of a scientist can be.”



The Math That Takes Newton Into the Quantum World

How a math professor learned to stop worrying and love algebraic geometry

BY JOHN BAEZ

IN MY 50S, TOO OLD to become a real expert, I have finally fallen in love with algebraic geometry. As the name suggests, this is the study of geometry using algebra. Around 1637, René Descartes laid the groundwork for this subject by taking a plane, mentally drawing a grid on it, as we now do with graph paper, and calling the coordinates x and y . We can write down an equation like $x^2 + y^2 = 1$, and there will be a curve consisting of points whose coordinates obey this equation. In this example, we get a circle!

It was a revolutionary idea at the time, because it let us systematically convert questions about geometry into questions about equations, which we can solve if we're good enough at algebra. Some mathematicians spend their whole lives on this majestic subject. But I never really liked it much until recently—now that I've connected it to my interest in quantum physics.

As a kid, I liked physics better than math. My uncle Albert Baez, father of the famous folk singer Joan Baez, worked for UNESCO, helping developing countries with physics education. My parents lived in Washington, D.C. Whenever my uncle came to town, he'd open

his suitcase, pull out things like magnets or holograms, and use them to explain physics to me. This was fascinating. When I was 8, he gave me a copy of the college physics textbook he wrote. While I couldn't understand it, I knew right away that I wanted to. I decided to become a physicist and my parents were a bit worried, because they knew physicists needed mathematics, and I didn't seem very good at that. I found long division insufferably boring and refused to do my math homework, with its endless repetitive drills. But later, when I realized that by fiddling around with equations I could learn about the universe, I was hooked. The mysterious symbols seemed like magic spells. And in a way, they are. Science is the magic that actually works.

In college I majored in math, and became curious about theoretical physicist Eugene Wigner's question about the "unreasonable effectiveness" of mathematics: Why should our universe be so readily governed by mathematical laws? As he put it, "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve." As

a youthful optimist, I felt these laws would give us a clue to the deeper puzzle: why the universe is governed by mathematical laws in the first place. I already knew that there was too much math to learn it all, so, in grad school, I tried to focus on what mattered to me. And one thing that did *not* matter to me was algebraic geometry.

How could any mathematician *not* fall in love with algebraic geometry? Here's why: In its classic form, this subject considers only *polynomial* equations—equations that describe not just curves, but also higher-dimensional shapes called “varieties.” So, $x^2 + y^2 = 1$ is fine, and so is $x^{43} - 2xy^2 = y^7$, but an equation with sines or cosines, or other functions, is out of bounds—unless we can figure out how to convert it into an equation with just polynomials. As a graduate student, this seemed like a terrible limitation. After all, physics problems involve plenty of functions that aren't polynomials.

Why does algebraic geometry restrict itself to polynomials? Mathematicians study all sorts of functions, but while they're very important, at some level their complications are only a distraction from the fundamental mysteries of the relation between geometry and algebra. By restricting the breadth of their investigations, algebraic geometers can dig deeper into these mysteries. They've been doing this for centuries, and by now their mastery of polynomials is truly staggering: Algebraic geometry has grown into a powerful tool in number theory, cryptography, and many other subjects. But for its true devotees, it is an end in itself.

I once met a grad student at Harvard, and I asked him what he was studying. He said one word, in a portentous tone: “Hartshorne.” He meant Robin Hartshorne's textbook *Algebraic Geometry*, published in 1977. Supposedly an introduction to the subject, it's actually a very hard-hitting tome. Consider Wikipedia's description:

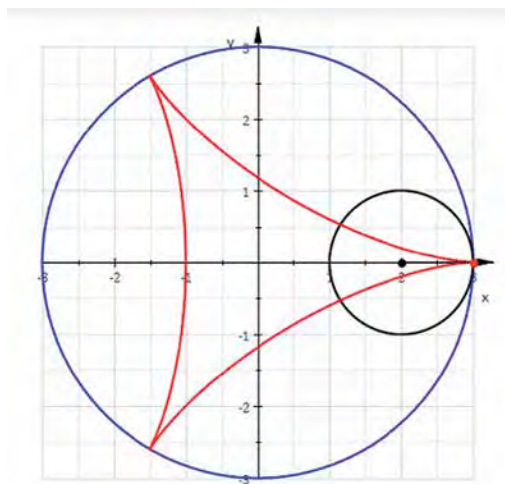
The first chapter, titled “Varieties,” deals with the classical algebraic geometry of varieties over algebraically closed fields. This chapter uses many classical results in commutative algebra, including Hilbert's Nullstellensatz, with the books by Atiyah–Macdonald, Matsumura, and Zariski–Samuel as usual references.

If you can't make heads or tails of this ... well, that's exactly my point. To penetrate even the first chapter

of Hartshorne, you need quite a bit of background. To read Hartshorne is to try to catch up with centuries of geniuses running as fast as they could.

One of these geniuses was Hartshorne's thesis advisor, Alexander Grothendieck. From about 1960 to 1970, Grothendieck revolutionized algebraic geometry as part of an epic quest to prove the Weil Conjectures, which relate varieties to solutions of certain problems in number theory. Grothendieck guessed that the Weil Conjectures could be settled by strengthening and deepening the link between geometry and algebra. He had a concrete idea for how this should turn out. But making this idea precise required a huge amount of work. To carry it out, he started a seminar. He gave talks almost every day, and enlisted the help of some of the best mathematicians in Paris.

Working non-stop for a decade, they produced tens



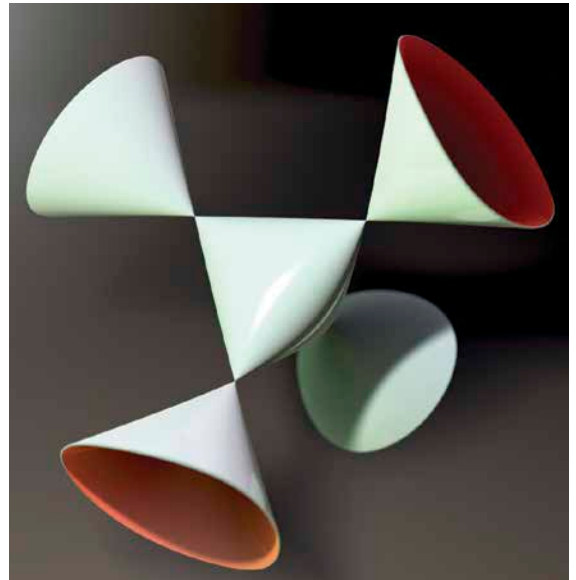
THERE'S A POLYNOMIAL FOR THAT We can describe many interesting curves with just polynomials. For example, roll a circle inside a circle three times as big. You get a curve with three sharp corners called a “deltoid,” shown in red above. It's not obvious that you can describe this using a polynomial equation, but you can. The great mathematician Leonhard Euler dreamt this up in 1745.

If we can figure out how to reduce topology to algebra, it might help us formulate a theory of quantum gravity.

of thousands of pages of new mathematics, packed with mind-blowing concepts. In the end, using these ideas, Grothendieck succeeded in proving all the Weil Conjectures except the final, most challenging one. A student of his polished that one off, much to Grothendieck's surprise.

During his most productive years, even though he dominated the French school of algebraic geometry, many mathematicians considered Grothendieck's ideas "too abstract." This sounds a bit strange, given how abstract *all* mathematics is. What's inarguably true is that it takes time and work to absorb his ideas. As a grad student I steered clear of them, since I was busy struggling to learn physics: There, too, centuries of geniuses have been working full-speed, and anyone wanting to reach the cutting edge has a lot of catching up to do. But, later in my career, my research led me to Grothendieck's work.

Had I taken a different path, I might have come to grips with his work through string theory. String theorists postulate that besides the visible dimensions of space and time—three of space and one of time—there are extra dimensions of space curled up too small to see. In some of their theories these extra dimensions



FAME, CUBED This is Cayley's nodal cubic surface. It's famous because it is the variety with the most nodes (those pointy things) that is described by a cubic equation. The equation is $(xy + yz + zx)(1 - x - y - z)xyz = 0$ and it's called "cubic" because we're multiplying at most three variables at once.

form a variety. So, string theorists easily get pulled into sophisticated questions about algebraic geometry. And this, in turn, pulls them toward Grothendieck.

Indeed, some of the best advertisements for string theory are not successful predictions of experimental results—it's made absolutely none of these—but rather, its ability to solve problems within pure mathematics, including algebraic geometry. For example, string theory is shockingly good at counting how many curves of different kinds you can draw on certain varieties. Thus, we now see string theorists talking with algebraic geometers, each able to surprise the other with their insights.

My own interest in Grothendieck's work had a different source. I've always had serious doubts about string theory, and counting curves on varieties is the last thing I'd ever try: Like rock climbing, it's exciting to watch but too scary to actually attempt it myself. It turns out that Grothendieck's ideas are so general and powerful that they spill out beyond algebraic geometry into many other subjects. In particular, his 600-page unpublished manuscript *Pursuing Stacks*, written in 1983, made a big impression on me. In it, he argued that topology—very loosely, the theory of what space can be shaped like, if we don't care about bending or stretching it, just what kind of holes it has—can be completely reduced to algebra!

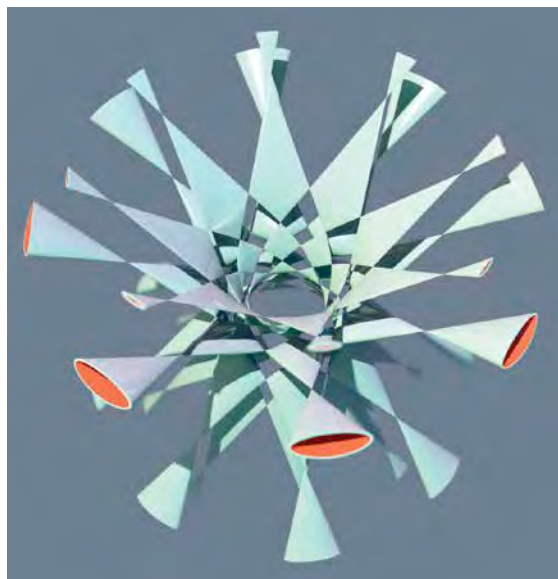
At first this idea may sound just like algebraic geometry, where we use algebra to describe geometrical shapes, like curves or higher-dimensional varieties. But “algebraic topology” winds up having a very different flavor, because in topology we don't restrict our shapes to be described by polynomial equations. Instead of dealing with beautiful gems, we're dealing with floppy, flexible blobs—so the kind of algebra we need is different.

Algebraic topology is a beautiful subject that has been around long before Grothendieck—but he was one of the first to seriously propose a method to reduce *all* topology to algebra. Thanks to my work on physics, his proposal was tremendously exciting when I came across it. Here's why: At the time I had taken up the challenge of trying to unify our two best theories of physics: quantum physics, which describes all the forces except gravity, and general relativity, which describes gravity. It seems that until we do this, our

understanding of the fundamental laws of physics is doomed to be incomplete. But it's devilishly difficult. One reason is that quantum physics is based on algebra, while general relativity involves a lot of topology. But that suggests an avenue of attack: If we can figure out how to reduce topology to algebra, it might help us formulate a theory of quantum gravity.

My physics colleagues will let out a howl here, and complain that I am oversimplifying. Yes, I'm oversimplifying: There is more to quantum physics than mere algebra, and more to general relativity than mere topology. Nonetheless, the possible benefits to physics of reducing topology to algebra are what got me so excited about Grothendieck's work.

So, starting in the 1990s, I tried to understand the powerful abstract concepts that Grothendieck had



VARIETY The Endrass octic is a beautiful, highly symmetrical example of a “variety”: a shape described by polynomial equations. Algebraic geometry began as the study of such shapes.

invented—and by now I have partially succeeded. Some mathematicians find these concepts to be the hard part of algebraic geometry. They now seem like the easy part to me. The hard part, for me, is not these abstract concepts but the nitty-gritty details. First, there is all the material in those texts that Hartshorne takes as prerequisites: “the books by Atiyah–Macdonald, Matsumura, and Zariski–Samuel”—in short, piles and piles of algebra. But there is also a lot more.

So, while I now have *some* of what it takes to read Hartshorne, until recently I was too intimidated to learn it. A student of physics once asked a famous expert how much mathematics a physicist needs to know. The expert replied: “More.” Indeed, the job of learning mathematics is never done, so I focus on the things that seem most important and/or fun. Until last

year, algebraic geometry never rose to the top of the list.

What changed? I realized that algebraic geometry is connected to the relation between classical and quantum physics. Classical physics is the physics of Newton, where we imagine that we can measure everything with complete precision, at least in principle. Quantum physics is the physics of Schrödinger and Heisenberg, governed by the uncertainty principle: If we measure some aspects of a physical system with complete precision, others must remain undetermined.

For example, any spinning object has an “angular momentum.” In classical mechanics we visualize this as an arrow pointing along the axis of rotation whose length is proportional to how fast the object is spinning. And in classical mechanics, we assume we can measure this arrow precisely. In quantum mechanics—a more



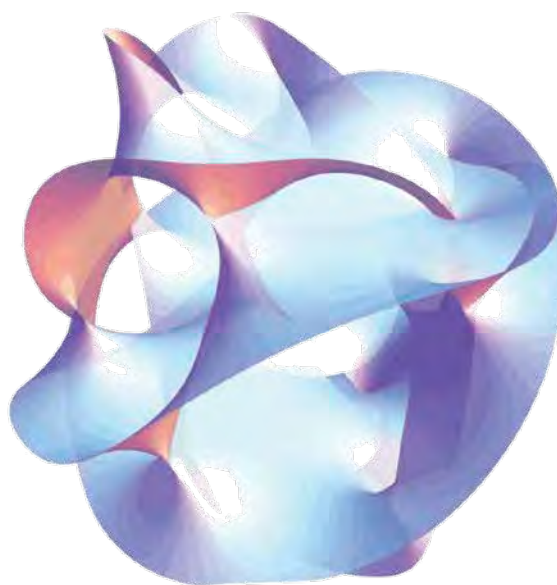
LET'S DO A MATH-A-THON Alexander Grothendieck in his seminar.

The mysterious symbols seemed like magic spells. And in a way, they are. Science is the magic that actually works.

accurate description of reality—this turns out not to be true. For example, if we know how far this arrow points in the x direction, we cannot know how far it points in the y direction. This uncertainty is too small to be noticeable for a spinning basketball, but for an electron it is important: Physicists had only a rough understanding of electrons until they considered this.

Physicists often want to “quantize” classical physics problems. That is, they start with the classical description of some physical system, and they want to figure out the quantum description. There is no fully general and completely systematic procedure for doing this. This should not be surprising: The two world views are so different. However, there *are* useful recipes for quantization. The most systematic ones apply to a very limited selection of physics problems.

For example, sometimes in classical physics we can describe a system by a point in a *variety*. This is not something one generally expects, but it happens in plenty of important cases. For example, consider a spinning object: If we fix how long its angular momentum arrow is, the arrow can still point in any direction, so its tip must lie on a sphere. Thus, we can describe a spinning object by a point on a sphere. And this sphere is actually a variety, the “Riemann sphere,” named after Bernhard Riemann, one of the greatest algebraic geometers of the 1800s.



I’M ALL CURLED UP A slice of one particular variety, called a “quintic threefold,” that can be used to describe the extra curled-up dimensions of space in string theory.

SAM DERBYSHIRE

When a classical physics problem is described by a variety, some magic happens. The process of quantization becomes completely systematic—and surprisingly simple. There is even kind of a reverse process, which one might call “classicization,” that lets you turn the quantum description back into a classical description. The classical and quantum approaches to physics become tightly linked, and one can take ideas from either approach and see what they say about the other one. For example, each point on the variety describes not only a state of the classical system (in our example, a definite direction for the angular momentum), but also a state of the corresponding quantum system—even though the latter is governed by Heisenberg’s uncertainty principle. The quantum state is the “best quantum approximation” to the classical state. Even better, in this situation, many of the basic theorems about algebraic geometry can be seen as facts about quantization. Since quantization is something I’ve been thinking about for a long time, this makes me very happy.

Richard Feynman once said that, for him to make progress on a tough physics problem, he needed to have some sort of special angle on it:

[...] I have to think that I have some kind of inside track on this problem. That is, I have some sort of talent that the other guys aren’t using, or some way of looking, and they are being foolish not to notice this wonderful way to look at it. I have to think I have a little better chance than the other guys, for some reason. I know in my heart that it is likely that the reason is false, and likely the particular attitude I’m taking with it was thought of by others. I don’t care; I fool myself into thinking I have an extra chance.

This may be what I’d been missing on algebraic geometry until now. Of course, algebraic geometry is not just a problem to be solved, it’s a body of knowledge—but it’s such a large, intimidating body of knowledge that I didn’t dare tackle it until I got an inside track. Now I can read Hartshorne, translate some of the results into facts about physics, and feel I have a chance at understanding this stuff. And it’s a great feeling. ☺

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A Magician Explains Why We See What's Not There

Our brain is constantly picturing what the future should be

BY GUSTAV KUHN

NORMAN TRIPLETT WAS A PIONEER in the psychology of magic, and back in 1900, he published a wonderful scientific paper on magic that, among many other things, discusses an experiment on an intriguing magical illusion. A magician sat at a table in front of a group of schoolchildren and threw a ball up in the air a few times. Before the final throw, his hand secretly went under the table, letting the ball fall onto his lap, after which he proceeded to throw an imaginary ball up in the air.

Described like this, it does not sound like an amazing trick, but what was truly surprising is that more than half of the children claimed to have seen an illusory ball—what Triplett referred to as a “ghost ball”—leave the magician’s hand and disappear somewhere midway between the magician and the ceiling. This was clearly an illusion because on the final throw, no ball had left his hand; the children had perceived an event that never took place.

Triplett carried out several studies using this illusion,

and he came to some rather interesting, though not necessarily correct, conclusions. He thought that the illusion resulted from retinal *afterimages*, or in his own words, “What the audience sees is an image of repetition, which is undoubtedly partly the effect of a residual stimulation in the eye, partly a central excitation.”

At the time, this seemed to be a reasonable suggestion. I came across Triplett’s paper in my early days of researching scientific studies on magic, and I was intrigued by this illusion. Triplett’s Vanishing Ball Illusion relies on a principle that I often used to vanish objects, so I had some ideas as to why the illusion worked. I was skeptical about Triplett’s explanation, and I knew from experience that the illusion relies on misdirecting the audience’s expectations so that they anticipate you throwing the ball for real. A person’s eye gaze provides one of the most powerful tools to misdirect expectations, and so I embarked on one of my first scientific projects to study the role that social cues play in driving this illusion.



I recorded two different versions of the Vanishing Ball Illusion. In the normal version, I threw the ball up in the air twice, before secretly palming it in my hand and simply pretending to throw it up in the air (as shown in the image on page 79). Importantly my gaze followed the ball, and in the pretend throw, my gaze followed the imaginary trajectory of the ball. In a different version of the trick, I carried out exactly the same actions, but this time, my gaze did not follow the imaginary ball. Instead, I stared at the hand that was palming the ball. Triplett's account of retinal afterimages predicts that both versions of the trick should be equally effective, because both groups of participants observed exactly the same sequence of events and thus had the same sensory stimulation.

ball at the top or that it had stuck to the ceiling. The illusion does not work for me because I know how it is done; indeed, once you know the secret, it will not work for you either. However, most of the participants in the experiment were fully convinced that they had seen the ball move up and were truly astonished when they watched the video again.

My intuition about the role of my gaze was correct, for the illusion was far less effective when I looked at my hand that was concealing the ball. These findings reveal some interesting insights into the illusion. They illustrate that the illusion is mostly driven by expectations, rather than perceptual afterimages. More recently, we have shown that even when you simply pretend to throw a ball up in the air without ever having thrown

No ball had left his hand; the children had perceived an event that never took place.

Doing science in the 21st century gave me the advantage of new scientific instruments. I could measure participants' eye movements while they watched video clips of the trick, in order to gain insights into why they experienced the illusion. The findings from this study were surprising: In the normal version of the trick, nearly two-thirds of our adult participants experienced the illusion and claimed that they had seen the magician throw the ball up in the air and that it had left the screen at the top. When I asked them how they thought the trick had been created, these participants typically claimed that someone must have caught the

the ball for real, more than a third of people still experience the illusion. In some ways, we are behaving like dogs who run after the stick their owner simply pretends to throw.

The eye-tracking data revealed some very interesting insights into why the illusion works. After participants watched the video, we asked them about where they were looking, and most of them claimed that they were simply looking at the ball. This, however, was not the case: Although they looked at the ball once it had been thrown in the air, they spent a lot of time looking at my face, particularly before the ball reached the top

of the screen. What this shows is that participants used my face to predict where I would throw the ball, which turns out to be a very clever strategy.

We live in a dynamic world where things change rapidly, and we often need to react very quickly. For example, when driving, it is important to anticipate what others are doing so that you can react quickly. One of the main differences between novice drivers and experts lies in their ability to predict what others will do in the future, and eye-tracking studies have shown that as you become more proficient, you start to look farther ahead. I was one of the first people in the world to learn to drive wearing an eye tracker, and this data revealed that the first time I sat behind the wheel, my eyes were pretty much stuck to the hood of the car. However, with experience, I managed to look farther

where I would throw the ball.

The eye movement data revealed another interesting finding: Although most of our participants experienced an illusory event, the eyes were not tricked. When the ball was thrown for real, most of the participants managed to look at it when it reached the top of the screen. During the fake throw, participants claimed to have seen the illusory ball at the top of the screen, but they did not move their eyes there, which suggests that our eyes are resilient to the illusion. This result took us by surprise, but it dovetails with several other findings and highlights another truly amazing feature of visual illusions.

We typically think about vision simply in terms of seeing things, but most of the time, we use our vision without consciously realizing that we do so. For



DO YOU BELIEVE IN MAGIC? Why do normal people maintain magical beliefs? They reflect the biases and quirks found in our everyday cognition, says psychologist and magician Gustav Kuhn.

ahead and to use cues in the environment to anticipate future events.

Watching me toss a ball in the air is far less complex than driving, but perceiving a fast-moving ball is much more difficult than one would expect. Seeing a small ball requires us to look at it, but our eyes are bad at tracking fast-moving objects. Seeing the ball requires your eyes to be looking at the right place at the right time, and you have a very short time window to plan an eye movement to the correct location. Looking at the ball is only possible if you can predict where it will be in the future, and this is exactly what our participants did. In other words, they were using my gaze to predict

example, as you reach for your cup of coffee, you use visual information to guide your arm movement and adjust your grip so that you can successfully pick up the cup. Back in 1995, David Milner and Melvyn Goodale proposed an influential theory of perception that suggests that the visual processes we require for perceiving objects are driven by separate visual pathways than those involved in visually guided actions, such as picking up an object. Some of the most compelling evidence for this theory comes from a neurological patient who goes by the name “D.F.” D.F. sustained severe damage to the ventral part of her brain, the pathway that is responsible for object perception. She

now suffers from a special condition known as agnosia, which means that even though her vision is intact, she fails to recognize objects and simple shapes and can't even distinguish between horizontal and vertical lines.

One would imagine that not being able to recognize even the simplest of shapes would severely limit her day-to-day capabilities, yet when I met D.F. for the first time, I was astonished by how normal her behavior seemed. She was perfectly capable of navigating a cluttered room, and during lunch, she managed to pick up her knife and fork without problems. How is this possible? D.F.'s lesion has impaired parts of the brain that are responsible for object perception, while the

perceptual system is often fooled by illusions, I rarely misjudge where to reach. The reason why I don't make these mistakes is that the part of the visual system responsible for orchestrating these actions is not fooled by visual illusions. For example, Richard Gregory and colleagues have shown that if participants are presented with a hollow mask and are asked to point to the nose, they point to a location outside the mask. This is because they consciously perceive the face as being solid. However, if you ask them to quickly flick the nose, their hand moves inside the mask and touches the correct location. This is because flicking is a visually guided action that is driven by the dorsal

The neural delay means we perceive things at least a tenth of a second after they have occurred.

neural systems that are responsible for visually guiding her actions are still intact. As these two systems are anatomically and functionally independent, D.F. is perfectly able to use her vision to guide her actions, while being consciously unaware of the objects around her. For example, even though she is incapable of consciously distinguishing between different line orientations, she is perfectly capable of picking up a letter and putting it in a mailbox.

Picking up objects and interacting with our physical world requires accurate representations of the objects around us, and our perceptual errors imply that we should constantly misjudge our actions. Although my

stream, the visual system that requires reliable spatial information, and thus is not fooled by the illusion. Our eyes are also driven by the dorsal stream, so even though your conscious perception has been fooled by the illusion, your eyes have not.

Our visual system has evolved so that we can interact with the world around us, but why are we so easily tricked into seeing an illusory ball? The answer to this question lies in one of the most surprising and possibly unsettling features of our perceptual systems.

My morning commute takes me through some of London's busiest transportation hubs, yet I am perfectly capable of navigating my way through the crowds

and rarely collide with fellow commuters. One of my other truly astonishing skills involves throwing a ball one meter into the air and catching it. “So what?” you might ask. “Most people can do these things with ease, so why should I be amazed?” These tasks are truly incredible, but a full appreciation requires us to look at the challenges in perceiving our dynamic world.

We see things because objects reflect light that is projected onto our retina, and once our photoreceptors register the light, they send a neural signal down the optic nerve. As we have learned earlier on, perception does not take place in the eyes, and lots of complex neural computations are required before we can experience the world. Neural signals are initiated in the retina and then pass via different neural centers to the visual cortex and higher cortical areas, which eventually build a mental representation of the outside world. Neural processing is not instantaneous because neural signals are passed along neurons at a finite speed. It takes about a tenth of a second for the light registered by the retina to become a visual perception in the brain. This means that our perception lags about a tenth of a second behind what is happening in the world. I will give you a few moments for this thought to settle, and just in case you are still struggling to come to terms with it, let me help you with an analogy: During a thunderstorm, vast amounts of electrical energy are discharged, which results in a flash and a loud bang. As you watch the storm from a distance, you see the lightning before you hear the thunder. This is, of course, because sound travels much slower than light, and so we hear the thunder several seconds after the electrical discharge has occurred. It is the same for perception. The neural delay means that we perceive things at least a tenth of a second after they have occurred.

You might think that a tenth-of-a-second delay makes very little difference to your morning commute, but believe me, this is a substantial delay. Let me put it in context: If you are walking at a modest speed of about one meter per second, a tenth-of-a-second delay will result in you perceiving the world as lagging 10 centimeters behind you. This is quite hard to believe because you simply do not experience the world as lagging, and such a perceptual error should certainly result in many early-morning collisions. Likewise, this

perceptual delay should make it impossible for you to catch a ball, especially because this perceptual delay does not account for the substantially longer amount of time your brain requires to plan and initiate a motor response capable of catching the ball.

It is only once you start thinking about some of the huge day-to-day challenges our visual system constantly faces that the true wonders of the brain start to emerge. Our brain uses a really clever and almost science-fictional trick that prevents us from living in the past: We look into the future. Our visual system is continuously predicting the future, and the world that you are now perceiving is the world that your visual system has predicted to be the present in the past. This idea takes a bit of time to get used to, and the first time I heard it, I thought it must be crazy. However, unless we predict the future, we will always experience the past. ☺

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The Dam Problem in the West

*On a raft trip down the Green River, a writer faces
her environmental preconceptions*

BY HEATHER HANSMAN

I AM PADDLING THROUGH THE SILT of the Green River, the largest, most remote, and least developed tributary of the Colorado River, which brings water to nearly 40 million people across the western United States. It's crucial, it's overused, and it's at risk.

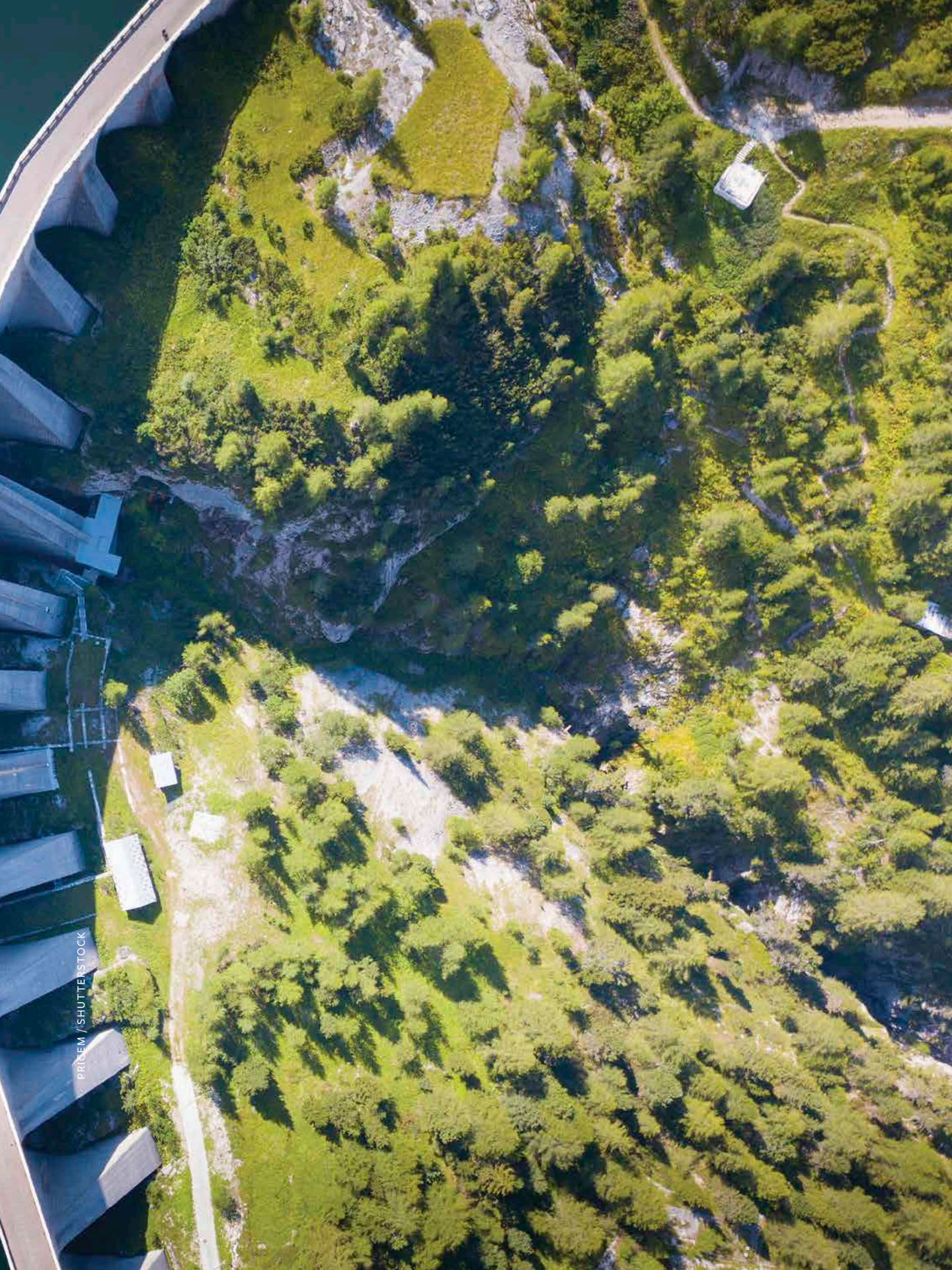
The Green starts in the glaciated high alpine of Wyoming's Wind River Range, then winds through hundreds of miles of sagebrush flats, scrubby plains, tight gorges, and empty gas lands to the red rock desert of Utah's Canyonlands National Park, where it meets up with the main stem of the Colorado. All signs of western development—from coal to cattle to cities—surround the river. As population swells in cities like Denver and Salt Lake, and as climate change shrinks stream flow, the question of how the water in this river is used and how far it can be stretched is becoming more urgent.

Like nearly all water sources in the western U.S., it's been dammed up, spread thin, and abused. Drought has wracked most of the western half of the U.S. since the beginning of the 21st century, draining reservoirs and depleting aquifers. Water is mired in the future of the climate, it's tied to the physical, political, and economic divide between urban areas and rural ones, and

it's crucial to the debate about future energy sources. And more than anything, it's indispensable. More than oil. More than food.

I'm paddling downstream into the pooled up water of Fontenelle Reservoir, formed by the first dam on the river, one of two major storage sites on the Green. My pack raft is about as long as I am tall. I paddle it with an old, chipped kayak paddle, bought in the days before I realized I was too nervous to be any good at whitewater kayaking. The little raft feels slightly more stable than a kayak and is easier to wrangle than a canoe or a full-sized raft, but it's easily deflected by wind, and it feels flimsy sometimes when I'm alone.

I'm particularly curious about Fontenelle because I want to know more about how dams changed the dynamic of the river. Coming into the trip, I knew enough about reservoirs, dams, and storage to think about them as a necessary evil: manmade breaks in the ecosystem to be worked around and reckoned with. I had the view that dams were, for the most part, bad, environmentally destructive, and stupid, and that they should be removed wherever possible. But I've been on the river for two weeks now, and the more I talk to people who touch the water every day, the more I realize how naïve and unsubtle my thinking has been.



How the West Was Won

In the morning, I cold-call Kirk Jensen, who runs the Fontenelle Dam and Power Plant, to ask if I can see the inside of the dam. “Is now good?” he says. “We’ll open the gates for you.”

Fontenelle is a utilitarian dam. It has square corners and lacks any kind of architectural grace. When Jensen walks me inside, I get the feeling that a random visitor is a rare occurrence. He leads me into the narrow, humming control room, which is lined on both sides with analog dials and switches. It feels like we’re inside a submarine, monitoring water pressure below the surface.

I follow him down a set of skinny stairs to look at the guts of the power plant. Fontenelle has a single Francis-style turbine, a kind he says is often used on rivers with large flows and dams with steep drops. The turbine creates a small amount of power—10,000 kilowatts—but Fontenelle mainly operates to store and supply water and to keep its reservoir, and Flaming Gorge Reservoir downstream, at certain levels. The amount of water pushed through the dam is based on river flow and demand downstream.

The Seedskaadee Project, the official name of the Fontenelle Dam construction project, was authorized under the Bureau of Reclamation’s Colorado River Storage Project Act of 1956. The bureau, an agency in the U.S. Department of the Interior, provided jobs in the wake of the Great Depression, and it did what it set out to do: It provided a large-scale plumbing system for expanding agriculture and growing cities. The bureau has long defended its dams and reservoirs because they provide agricultural, household, and industrial water to about one-third of the population of the American West, and that’s true. We’ve staked life in desert cities on their ability to deliver water steadily. Water storage is a big part of the reason people can live in areas where it doesn’t rain.

The Colorado River Storage Project Act initiated construction of a number of large dams, including Glen Canyon and Flaming Gorge as well as Fontenelle, with the intent to manage and mitigate risk in the upper Colorado River and to control flows between the Upper and Lower basins. By the time Fontenelle was built in 1963, it had already become clear that there was less water in the river than was allocated in the Colorado River Compact.

An idealized version of what the river looked like before the dam isn’t an accurate or useful goal.

There’s a constant thrumming fear around the lack of storage in the Upper Basin, and because of that anxiety, Fontenelle is at an interesting crossroads. It was initially built to supply water for irrigation, but that never happened. The area around it is too dry, gravelly, and cold to grow crops. A test farm run by the bureau after dam construction started quickly proved that, so these days, Fontenelle is a storage reservoir, which helps guarantee that Wyoming can get its designated 14 percent of the Upper Basin’s water.

When Jensen and I walk out onto the deck above the turbine, a tempest of whitewater flows into the river below us. With the laconic practicality of a government engineer, he explains what the course of his year looks like. Spring, which comes with a rush of snowmelt that needs regulating, is when things are busiest, because he’s trying to balance runoff with downstream water



RIVER RAFTER Environmental journalist Heather Hansman paddled a one-person inflatable pack raft down the length of the Green River to get a firsthand look at the challenges it faces. Fights over the river's water are longstanding, intractable, and only getting worse as the West gets hotter and drier and more people depend on the river with each passing year.

needs and with filling the reservoir for the upcoming summer and fall. He says the reservoir is usually at its highest around July 4, and he thinks they'll fill it up this year. After an unusually dry winter, the spring has been wet and cold, and it's been raining more than normal. He says they're pushing 1,550 cubic feet per second out of the turbine right now. If the reservoir gets too high and they need to dump water, they can let out as much as 6,500 cubic feet per second through bypasses that flow around the turbine. If they release more than that, they start to flood out the fields around Green River. "We have to control it slowly," he says.

The city of Green River, with a population near 13,000, is highly dependent on Fontenelle, both to prevent it from flooding with spring snowmelt and to keep its supply of water steady through the year. Because the water treatment plant currently can't store much more than a few days' supply, it relies on the dam to release the water it processes so residents have something to drink. The river makes the city livable, but the dam makes it possible to live there year-round. "The general public doesn't know what the dams do. They'd

be at the mercy of the rivers without them." We watch water pound out into the eddy below the dam. "People don't realize how much we need this," Jensen says.

No Turning Back

There are an estimated 90,000 dams in the U.S., ranging in size from inches high to the Hoover Dam's 726 feet. Dams of any size irrevocably change complex river ecosystems. As soon as water backs up behind a dam or diversion, it moves through its former channel differently. Stagnation alters both physical and chemical characteristics. When dams artificially slacken water that used to move, they alter its temperature, its dissolved oxygen content, and the ability of native plants and animals to live in it. Reservoirs, which emit methane, contribute to greenhouse gas emissions. The sweeping canyons of Flaming Gorge are beautiful, but the reservoir is a constructed, changed ecosystem, and, as I'm learning every day, beauty and nature aren't necessarily the same thing.

The 2000s brought a wave of backlash against existing dams and an effort by environmental groups to

remove structures deemed unnecessary, environmentally destructive, or dangerous. That dam removal movement has worked really well in some places. After the Elwha and Glines Canyon dams, on Washington's Olympic Peninsula, were removed, in 2012 and 2014 respectively, native salmon populations rebounded almost immediately, and the river's delta stabilized, thanks to increased sediment loads, creating habitat for elk and other animals. In Maine, when the Veazie Dam came down on the Penobscot River in 2013, fisheries came back, boosting the economy in the area. But a lot of the successful dam removals have been on rivers where water storage isn't important, or where power-generating infrastructure is no longer relevant. The cause and effect isn't always as straightforward as those projects have been.

The reservoirs of the Colorado River system, from Fontenelle down to the Morelos Dam on the U.S. border with Mexico, are the largest in relation to the river's stream flow in any watershed in North America. The river is stopped up, slaked off, and used up to the point that it dries up a hundred miles inland from its

delta. But if Fontenelle Dam were to disappear tomorrow, Rock Springs, just off the main stem of the river, would be dry by midsummer. In a human-constructed and constrained system, the positives and negatives aren't in balance. You can't look backward and think about ripping out dams without taking the present into account. People are important. An idealized version of what the river looked like before the dam isn't an accurate or useful goal.

A lot of the anti-dam arguments put forth by environmental groups and scientists are based in hydrology and biology. Dams will stress a watershed almost beyond repair, and they fundamentally change the river's function. Jack Schmidt, a fluvial geomorphologist and professor of watershed sciences at Utah State University, who has spent much of the past four decades working on the Colorado River system, says he thinks it's impossible to fully restore pre-dam conditions. Despite that, he's constantly trying to recreate the past, and to help manage rivers in as natural a state as possible, to maintain ecosystem integrity. The hard part is figuring out what counts as natural and how to



CONTROLLING THE FLOW

The Flaming Gorge Dam, as it releases 8,000 cubic feet per second. Even with all that water, the yearly flooding is less than it used to be, which is having an untold impact on the surrounding ecosystem.

The general public doesn't know what the dams do. They'd be at the mercy of the rivers without them.

preserve multiple aspects of the river at once: to manage for native fish and the fly-fishing economy that's sprung up below the dam at the same time, or for both power generation and stable base flows.

Schmidt, who is a paddler and a river junkie in addition to being a sediment nerd, has been looking at the Green since 1992, when the superintendent of Dinosaur National Monument asked him to evaluate the impact of the Flaming Gorge Dam on the rest of the river. That's his specialty. Fluvial geomorphology is the study of how a river changes itself physically: how the channels narrow and vary, and how flood patterns—man-made or otherwise—affect the landforms and sandbars along its course.

Those changes are both consistent and mysterious. Allegedly, when Albert Einstein's son Hans declared that he wanted to study fluid dynamics, Einstein asked him why he'd ever want to look at something so hard. Geology adjusts on a granular scale. As rivers flow downstream, they're constantly moving sediment loads downstream, too, in the slow rolling force of geologic history. Like race cars, rivers move faster around

the outsides of corners, building up sediment on the insides as they lose centripetal force. Migrating sandbars switch side to side as they move downstream, and they vary over time, alternating cut banks and point bars, eroding from one side of the river and loading the other bank.

Spring floods set the sediment in motion as they flush more powerfully erosive flows downstream. On the Green River, below Fontenelle and Flaming Gorge, those floods don't happen like they used to because of the dams—if you have smaller floods, you have less pushing. Even with the dam-created spring peak flows for the fish, the river can never run higher than the 8,600 cubic feet per second that Flaming Gorge will release with all the floodgates open. Sediment accumulates in reservoirs, and dams change the way alluvial fans build up: They can stagnate and grow over, or they can wash downstream. That's what Schmidt is trying to understand.

In Browns Park, downstream from here, the river is between 10 and 25 percent narrower than it was at the beginning of the 20th century. Schmidt thinks that's because of the lack of early-season floods and the resulting ecological changes. Non-native vegetation, like tamarisk, which thrives in the alkaline soil here and has long, many-tentacled root balls that hold riverbanks together, has changed the channel size. Those physical forces then trigger biological outcomes—they break down habitats and change what kinds of species can live where. “Scientifically, we have to worry about the flow regime, how the timing and the magnitude of the flow regime triggers natural ecosystem processes,” Schmidt says.

Those impacts carry far downstream, and they're exacerbated by drought, climate change—which comes with variable runoff and increasing temperatures—and those non-native fish and plants that have spread across the river's system. Schmidt says that, all things considered, the Green has the healthiest river ecosystem of any part of the Colorado River Basin, in part because the untouched Yampa River, which flows in just south of here, adds so much to its flow, but it's still highly changed. Nothing is untouched anymore. When a river's flow is reduced or altered, which is happening across the West, it's less dynamic, degraded, simplified. And that means it's less naturally resilient.

What the Bugs Say

Out here alone, where I have space to focus on the river, the interconnectedness feels vivid and impossible not to think about—the way the water slowly changes from clear to murky below the dam, or the intakes pump water up to wells in surprising places. It changes the way I think about the river as a whole, because I’m realizing how much I was wrong, or narrow-minded, about.

Sometimes, to show the big picture, it’s helpful to focus on something small. To gauge how dam operations impact everything below the power plants, scientists have been looking at one of the bases of the food chain, the insects. Because the bugs are close to the bottom of the riparian food web, they’re bioindicators for the whole system, indicative of the health of the river.

On the Green River, USGS research scientist Anya Metcalfe has been looking at insect diversity in the river, and she’s started a citizen science campaign to collect data. She sends boaters like me out with a bug-trapping kit. I carry a rectangular metal ammo can painted sky blue and filled with bottles of ethanol, a light, and a paperback book-sized tray. At night, after I make dinner, I set the tray on the riverbank, pour one of the ethanol bottles out into it, and leave the light shining on it for an hour. When I come back, it’s often filled with the carapaces of dinosaur-like bugs, a sample of what’s living in the section of river I’m on. “It’s a proxy to look at the river,” Metcalfe says. “It’s a really powerful tool to understand the availability, what bugs are there, and how many are there.”

Metcalfe is trying to get a sense, over time and space, of how many bugs are in the river because that can show how many fish can survive there. The goal of the project is twofold. She’s gathering a vast map of data, but she’s also hoping that the boaters who capture the bugs start thinking about what it means, and why they might not find any insects in one place, but a lot somewhere else. She thinks it’s a line in to caring about the river, and a way to give people a stake.

Metcalfe is spearheading bug tracking on the Green, but she and other researchers in her lab at the Grand Canyon Monitoring and Research Center have been tracking insects in the Grand Canyon, below Glen Canyon Dam, since 2012, and they’ve found that the impacts of the dam are significant. “Something that became immediately obvious is that there’s not a lot of

I had the view that dams were destructive and stupid, and should be removed wherever possible.

diversity. Midges, blackflies, micro caddis flies—that’s all we’ve been finding,” she says. “With classical ecology in the river continuum you’re supposed to get more diversity as you go downstream, but the recovery rate is really slow. One-hundred-fifty miles from Glen Canyon we still have low diversity.”

They’re not seeing many types of bugs even though algae, the insects’ main food source, is healthy. They’re trying to figure out why, because without bugs, the fish are hungry and struggling. They think that peaking the dam’s releases based on hydropower-needs might be washing bug larvae downstream, and that temperature might play a role, too, so they’re trying to figure out what dam operators can do to create better conditions for bugs and fish, how they can use man-made tools to mimic natural cycles, or mess up the river less. The water coming out of Glen Canyon Dam, which comes from the bottom of the reservoir, is incredibly cold, and the researchers think that’s rough on the native flora, which was historically used to warm river temperatures. At Flaming Gorge Dam they’ve installed what’s called a selective withdrawal system, which lets them pull water from whichever layer of the reservoir they

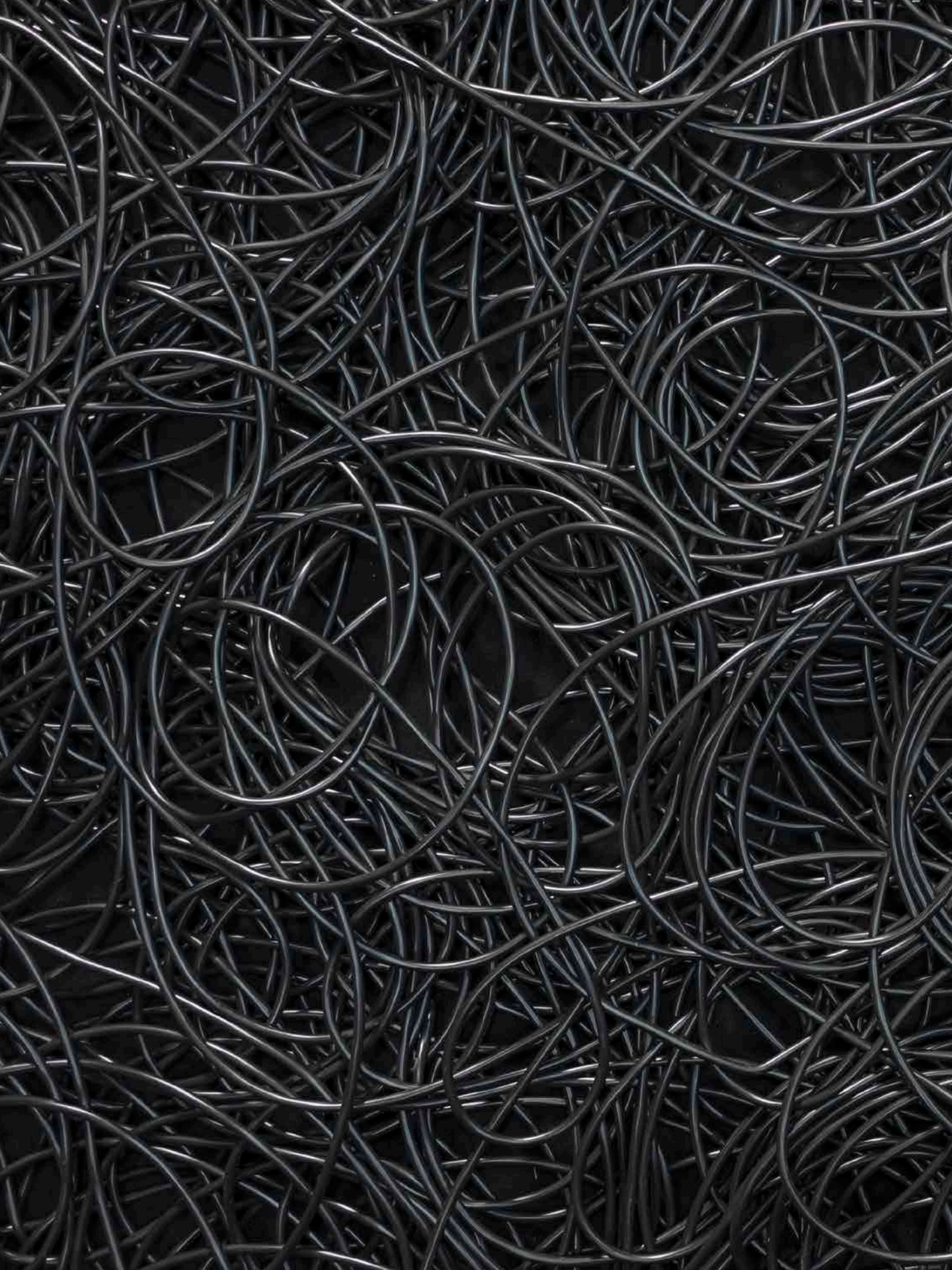
want, adjusting the temperature of what's released downstream. They think that helps bug viability downstream. "Immediately below Flaming Gorge looks a lot like the Grand Canyon, but 15 to 20 miles downstream you start to get the foodstuff bugs, like stone flies and caddis flies," Metcalfe says. "They're classic indicators of healthy, happy ecosystems."

Metcalfe says she's excited by the idea that dam managers are thinking about bugs and are working within the framework of the system to try to manage for them. "We can't restore the river because it would require taking out the dam, but we can understand how the dam impacts ecosystems, then try to understand how to best manage it," she says. "You can't always manage for restoration, but you can try to manage for a healthy ecosystem."

Healthy is a tricky, subjective word, couched in expectation and endgame. It means something different to people who live in Rock Springs than it does to the fish biologists, and none of them are wrong. And the longer I spend on the river, balancing those expectations, and giving them all weight, feels like the hardest, most important part. ☺

HEATHER HANSMAN is the author of *Downriver: Into the Future of Water in the West*. She is a former raft guide and a current environmental journalist.

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Why the Brain Is So Noisy

*The surprising importance of spontaneous order
and noise to how we think*

BY MICHAEL SEGAL



ONE OF THE CORE CHALLENGES of modern AI can be demonstrated with a rotating yellow school bus. When viewed head-on on a country road, a deep-learning neural network confidently and correctly identifies the bus. When it is laid on its side across the road, though, the algorithm believes—again, with high confidence—that it’s a snowplow. Seen from underneath and at an angle, it is definitely a garbage truck.

The problem is one of context. When a new image is sufficiently different from the set of training images, deep learning visual recognition stumbles, even if the difference comes down to a simple rotation or obstruction. And context generation, in turn, seems to depend on a rather remarkable set of wiring and signal generation features—at least, it does in the human brain.

Matthias Kaschube studies that wiring by building models that describe experimentally observed brain activity. Kaschube and his colleagues at the Frankfurt Institute for Advanced Studies, the Max Planck

Florida Institute for Neuroscience, the University of Minnesota, and elsewhere have found a host of features that stand in stark contrast to the circuits that engineers build: spontaneous activity and correlation, dynamic context generation, unreliable transmission, and straight-up noise. These seem to be fundamental features of what some call the universe’s most complex object—the brain.

What’s the biggest difference between a computer circuit and a brain circuit?

Our computers are digital devices. They operate with binary units that can be on or off, while neurons are analog devices. Their output is binary—a neuron fires in a given moment or not—but their input can be graded, and their activity depends on many factors. Also, the computing systems that we build, like computers, are deterministic. You provide a certain input and you get a certain output. When you provide the same input again and again, you get the same output.

This is very different in the brain. In the brain, even if you choose the exact same stimulus, the response varies from trial to trial.

Where does this variable response in the brain come from?

There are various hypotheses. There is, for example, unreliable synaptic transmission. This is something that an engineer would not normally build into a system. When one neuron is active, and a signal runs down the axon, that signal is not guaranteed to actually reach the next neuron. It makes it across the synapse with a probability like one half, or even less. This introduces a lot of noise into the system.

Another factor is ongoing activity in other parts of the brain. For instance, the visual cortex will be activated by a visual scene, but it also receives a lot of information from other brain areas. Since there's a lot of crosswiring, these other parts of the brain can affect activity patterns in the visual cortex at any given time. This can modulate incoming signals quite significantly. Part of this modulation might be useful in generating context and encoding expectation. You hear a barking dog, and you turn around, and you are looking for a dog. We understand more and more that part of the brain's response variability is actually meaningful and contains important background information or context.

What role does spontaneous activity play?

Even if you don't have any visual input, the visual cortex is not silent. It shows widespread and strong patterns of activity, which sometimes are as strong as activity evoked with real visual stimuli, and can be similar to it in structure. Given this similarity, spontaneous activity may represent something like visual imagination. You see something but, at the same time, you visually think about what you saw yesterday. Spontaneous activity could contribute to trial-by-trial variability in the brain.

Do we understand the nature of noise in the brain?

There's debate about whether the fluctuations that we see in experiments are really meaningful and contain information that we don't understand yet, or whether they're just noise arising from the stochasticity of biochemical processes and are something that the brain

needs to ignore or average out. To arrive at a better model of ongoing fluctuations we have to understand its sources. We can, for instance, do this by looking at animal behavior. Neural activity in animals that are processing a visual stimulus depends on whether they are moving, and whether they are alert. It helps if you can record from many neurons, so that you can understand the contribution to the variability in one part of the cortex by the activity of other parts. We will only be able to understand this variability once we're able to record from a large part of the brain simultaneously.

Can real noise be useful?

It might be useful that the brain is not completely deterministic, that every time we look at the same thing we process it slightly differently. Having slightly different responses to the same stimulus can help us detect different aspects of the scene. However, there are a whole lot of details out there in the world that are irrelevant to us. A visual scene can have hundreds and thousands of features, a lot of which don't matter. Making the response a little bit noisy may help us to ignore some of the less relevant features. Think about evolution, where random mutations are followed by selection of the fittest. Taking this as an analogy, it could be that the brain adds noise in order to sample different representations of what's out there. And by exploring the space of potential representations, the brain may try to find the one that is most suited given the current context. Noise could facilitate this search.

What is missing is a notion of context. As context changes, AI must interpret incoming signals in a different way.



MIND THE GAP The brain operates differently from a deep neural network, says Matthias Kaschube. There remains a considerable gap between artificial and human intelligence.

When does spontaneous activity arise in the developing brain?

Interestingly, patterns of spontaneous neuronal activity are already highly structured early in development, before there is any structured sensory input. In the visual cortex, for example, such activity appears before the eyes open. After the eyes open, some of these spontaneous patterns become associated with actual visual stimuli. Once this assignment is established, it appears to be stable and may be maintained for life.

Do these early patterns speak to the nature vs. nurture debate?

Such spontaneous activity patterns are present early on, but we haven't been able to understand what gives rise to their structure. It could be that this structure is hardwired in circuitry and genetically predetermined, but it appears more plausible that it's the result of a self-organization process. There are concepts from dynamical systems theory that describe how a self-organizing system can form complex patterns. The starting point would be just a few basic rules of how neurons form circuits and how circuit activity in turn reshapes connectivity, in a feedback loop. Really, it's less about nature vs. nurture, and more a question of

how much nature you actually need to set up the system. You could say the whole brain is in our genes, but this is not possible because the genetic information in our DNA is way too small to determine all of our synaptic connections. What could be genetically encoded are just a few simple rules that set up dynamics that can evolve and generate structure. Largely autonomous at very early stages in development, while more influenced by sensory input at later stages.

How can you probe the genetic component of early spontaneous activity?

One interesting possibility is to look at identical twins. We actually did something along these lines several years ago. We had a study where we looked at littermates in a colony of cats, and we found the spacing between active domains in the visual cortex was more related in littermates than in animals from a different litter. This suggests that there is a genetic component in determining this basic property. The other possibility is to look at an earlier stage in development when these structures are first emerging, and to try to manipulate them.

Is this early spontaneous activity entirely short-range?

We have found through experiment and modeling that, despite the fact that early synaptic connections are purely local, interesting long-range correlated activity can emerge. This would not be surprising in the mature cortex because there you have actual long-range anatomical connections. But even early on, when you don't have long-range connections yet, you get long-range correlations. Long-range correlations are interesting because they connect different modules that carry out different kinds of processing. For example, when your visual cortex processes different parts of a scene, long-range correlations are likely involved in integrating information across visual space.

Does the brain use error-correcting codes?

It's very plausible. For instance, there's this old concept of attractor networks. The idea is that a network converges to one of a finite set of activity states. When you provide some input, you reach one of these attractors, and when you provide a nearby input, you reach the same attractor. This makes the network robust

against small amounts of input variation and noise. This has been discussed for years, but it's still hard to get good empirical evidence for or against it in the brain. It would be helpful to get recordings from sufficient numbers of cells under sufficiently stable conditions combined with methods that allow us to directly perturb neural activity.

How does modern AI compare to the brain?

Deep neural networks, which are currently the best performing AI in a wide range of tasks, are obviously inspired by brain circuits. Deep networks have neurons, a sort of hierarchy, and plasticity of connections. They may or may not provide a good analogy to what's actually happening in the first processing stages inside the brain and there is currently an intense debate on this in the field. But one problem with current AI is that it's highly context-specific. You train your deep network on a data set, and it works for that particular data set, but it doesn't adjust when you have different data sets. What is missing is a notion of context. As context changes, AI must interpret incoming signals in a different way. This kind of flexibility is a great challenge to current artificial intelligence. Obviously, the brain is able to do that.

How might we solve the context problem?

We need to draw more inspiration from the brain. For instance, one interpretation of spontaneous activity in the brain is that it encodes context. That could be useful in AI. Also, the trial-by-trial response variability in the brain could be a hint of what we need to do in artificial intelligence. The same with unreliable synaptic transmission, which is present in the brain—something analogous is sometimes used in machine learning to avoid over-fitting. This is an interesting direction, and I think there's a lot more to study here.

Is the spontaneous long-range order that you observed a clue about how context can be generated dynamically?

Potentially, yes. What emerges in the brain early in development could be interpreted as the neural basis of visual representations that involve relationships among different objects and their parts distributed across visual space. A lot of what we need for visual scene processing is to form the right relationship between the object and the parts of the object that we see, and this might be associated with these long-range correlations. This is speculative because understanding the functional implication of these correlations is difficult. But long-range spontaneous order is

Making the response
a little bit noisy may
help us to ignore some
of the less relevant
features.

suggestive, and it intuitively makes sense that correlations between different functional modules in the brain could play a role in scene processing.

Are deep-learning networks wired like the brain?

One aspect of deep neural networks that has been criticized a lot is that their connections are typically feed-forward, meaning activity propagates from the input layer through a sequence of intermediate layers until it reaches the final output layer. There are no loops in feed-forward networks. Recurrent connections, i.e., connections between neurons within a given layer, are either absent or modeled in a crude way. Convolutional neural networks do have a convolutional kernel, which acts a little bit like recurrent connections, but there's relatively little use of more realistic and long-range connections. Also, there aren't typically any top-down connections that send information back in the direction toward the input layer. Part of the reason why recurrent and top-down connections are avoided is that they make the training of networks more difficult. But in the cortex, top-down connections are abundant and recurrent connections the majority. A feed-forward network is really a crude oversimplification and very distinct from the highly interconnected networks in the brain.

Do deep-learning networks react to stimuli in the same way as the brain?

Even at the first cortical processing stage of visual information, in the visual cortex, connections carrying input from the eyes are by far the minority of total connections, and this is even more drastic deeper inside the brain. A large part of neuronal activity is ongoing cross talk among different brain areas, and sensory input sometimes appears to only play a modulatory role in this internal activity. That's a very different perspective than the one that you usually have in deep neural networks, in which neurons only get activated when they are provided with input. So, both anatomically and in terms of functional properties, the brain seems to operate very differently from a deep neural network. There's still a considerable gap between real intelligence and so-called artificial intelligence. ☹️

MICHAEL SEGAL is the editor at large at *Nautilus*.

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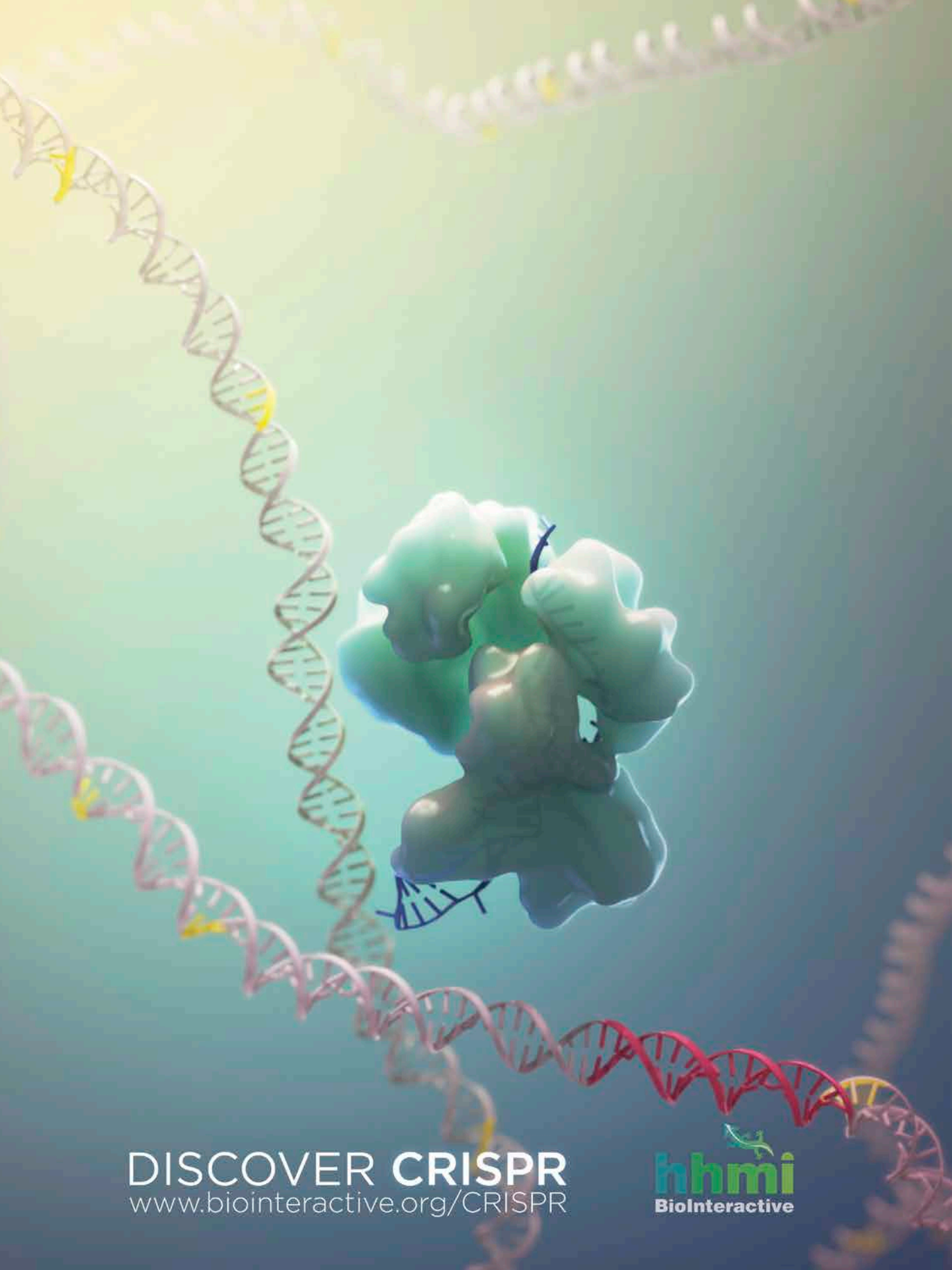


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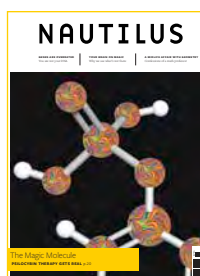
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Anne Sverdrup-Thygeson

The conservation biologist reflects on the beauty and peril of insects

INTERVIEW BY KEVIN DUPZYK

THE BIG PICTURE

Evolution is not run by love or being nice. It's a rough system out there. If you just live in a city and never see nature up close, you get a strange view on these things. I studied history before I went into biology. History is not so different from ecology. It's about seeing the system, the connections between the details, the single events in history, like species in an ecosystem. It's about the big picture, the web of life, and how history develops across continents and time.

THE MANY MEANINGS OF BEAUTY

Insects are incredibly beautiful. If you look at the scales on the wing of a butterfly, it's just incredible. You have these tiny beetles or wasps that are metallic, colorful, like little jewels, and these things fly around you. There's a lot of beauty in the way insects are built and the way they live their lives. A strange beauty. That a fly can live for several days without its head is a sort of brutal beauty, but it's fascinating they have tiny brains in several parts of their body, so several functions can work if they are beheaded. They have so many weird and wonderful ways to live: Ears on their legs, like the bush crickets; some butterflies and moths have ears in their mouths to detect bats. Once you get close up to see all these strange adaptations, you see a lot of beauty.

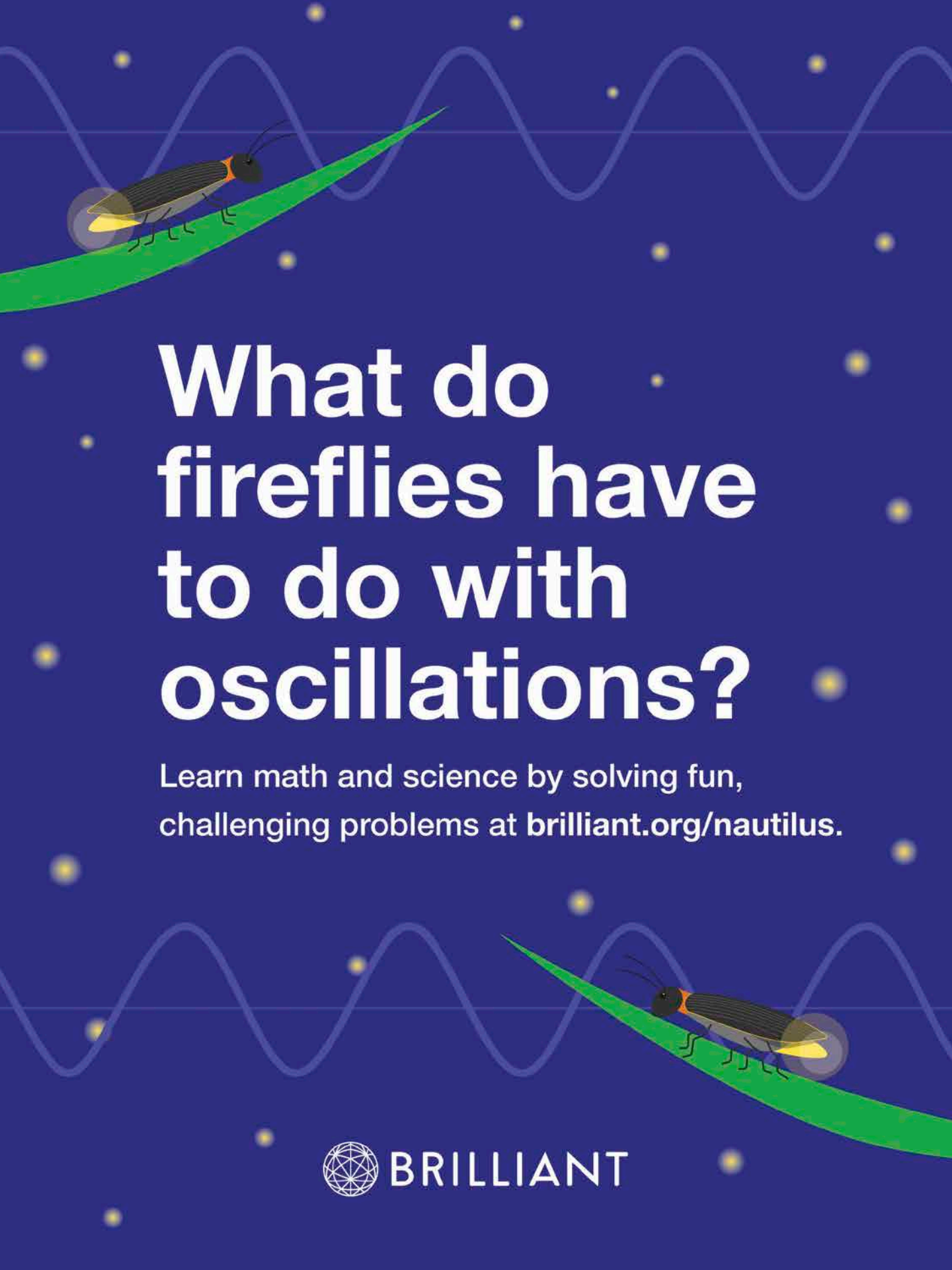


THE UNKNOWN WORLD

We've learned that honeybees can recognize human faces, even though their brains are the size of a sesame seed. Neurobiologists thought that was impossible with so few cells and few synapses between the cells. There are many mysteries. We don't even understand how metamorphosis works. A larvae turns into this pupa or chrysalis, and then everything is just rebuilt inside there? It's like if kids were playing with LEGO bricks, took those LEGO bricks and put them into the box, shook it, and then a completely new figure was inside when you opened it up.

THE END OF INSECTS

Insects have survived five mass extinctions already. They will be here long after we're gone. But it's pretty sure they're declining. When species go extinct, there are two arguments for why that's a problem. One is that all species should have a right to live out their life potentials, even if they don't have soft hair or big brown eyes or look familiar to us. It's about ethics and morals, something each person has to decide for him or herself. Even if you don't care about that, I think it's strange that there aren't more people who care about insects because they are such an important part of ecological processes. If a lot of them disappear, that will have knock-on effects on larger species, including us. 🌀

The background is a dark blue field with a light blue sine wave pattern and small yellow dots. A green leaf curves from the top left to the bottom right. A firefly with a black body, orange thorax, and glowing yellow abdomen is on the leaf. The title text is centered in the upper half.

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