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TINY KILLERS

How plantlike predators rule the seas

PLUS

MECHANICAL BRAINS
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Mystery signals from the far cosmos
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THE SHAPE OF SEASHELLS
How mollusks get their spirals
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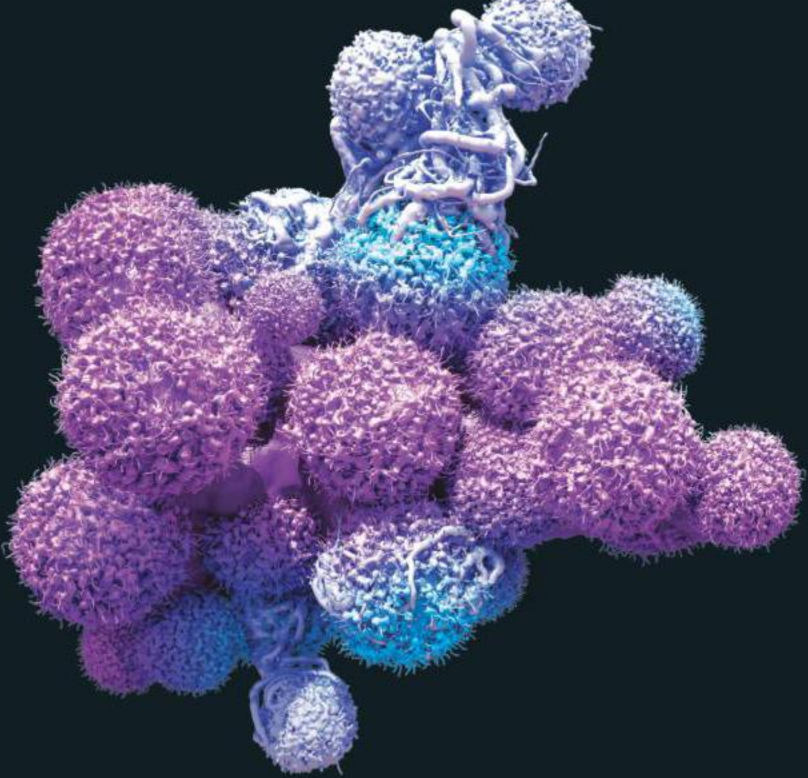

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SCIENTIFIC AMERICAN

MIMI DITCHIE *Getty Images*

ON THE COVERS

Previously thought to be a rarity, microscopic plankton called mixotrophs are turning out to be rulers of the ocean food web. These hybrid beasts hunt like animals and photosynthesize like plants. Here a mixotroph called *Dinophysis* (*right*) sucks the innards from another, *Mesodinium*.
Illustration by Mark Ross Studios (*left*)

The Arctic is melting and warming faster than anyone thought possible. As a result, billions of people may face longer heat waves, deeper freezes and heavier rains.
Illustration by Maciej Frolow (*right*)

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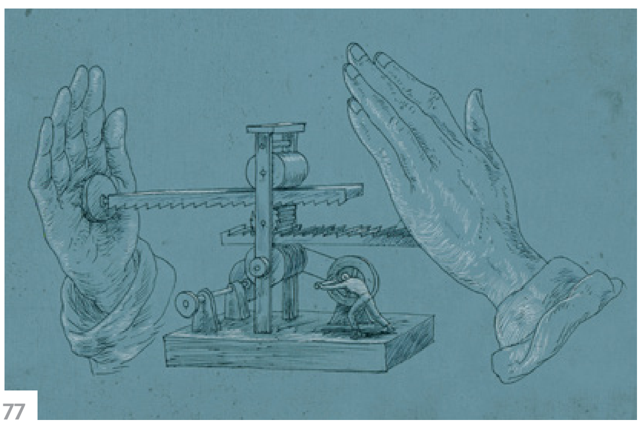

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ON THE WEB

"Planet Nine" Revisited
Scientific American examines the still frenzied search for the elusive Planet Nine, more than two years after astrophysicists revealed the strongest evidence yet of its existence.
Go to www.ScientificAmerican.com/apr2018/planet-9

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

Big Blue Marble

Viewers of a certain age (including my own) may remember the children's TV show *Big Blue Marble*—reminiscent of the photograph of our water world taken by *Apollo 17* astronauts in 1972 (*right*). I found myself reflecting on that image of a blue oasis in an inky cosmos as we put together this issue. Although we at *Scientific American* didn't set out to plan a special report on life and our ocean planet, you'll see a liquid line running through this edition's feature "well" (as we editors call the section of main articles).

For starters, here's a headline: "Meltdown," by Jennifer A. Francis, who studies marine and coastal sciences, starting on page 48. Francis describes how the Arctic climate is shattering record after record—at least a dozen in the past three years—altering weather worldwide. Sea ice is vanishing, air temperatures are rising, permafrost is thawing and glaciers are shrinking.

Meanwhile our traditional view of the ocean food web most likely is all wrong, writes Aditee Mitra, a zooplankton researcher, in her feature, "The Perfect Beast." Meet mixotrophs: tiny ocean creatures that grow like plants but hunt like animal predators. They sound unusual, but they are not. The majority of the seas' single-celled plankton are neither pure plants nor pure eaters of plants. And they collectively have an outsize ecosystem impact: their activities may control everything from the health of fish to the amount of carbon that leads to global warming. Dive in on page 26.

At the risk of being chided by our stalwart copyediting team, may I call the gorgeous images in "How Seashells Take Shape" (wait for it) *splashy?* Researchers Derek E. Moulton, Alain Goriely and Régis Chirat apply mathematical modeling to help understand the forces that govern the elegantly complex forms of mollusk spines, spirals and ribs. Using differential geometry, they have identified a few simple rules that mollusks employ to build fantastic shapes. You can see the wonders within and without beginning on page 68.

Stepping out of the seas, science and society intertwine in other articles in the issue: research advances bring new hope for saving lives in an important yet often overlooked area ("Preventing Suicide," page 54); mechanical pulses may be driving communication among nerve cells ("The Brain, Reimagined," page 60); a powerful new approach to therapy could come from the recognition that genetic changes enabling tumor cells to develop arise surprisingly early ("The Cancer Tree," page 34); and strange bursts of radio light in the distant cosmos offer enticing puzzles for curious minds ("Flashes in the Night," page 42). An ocean of discovery awaits. SA

NASA

Illustration by Nick Higgins

December 2017

“To avoid war, it would be far more intelligent and compassionate to alleviate the issues that motivate governments to resort to violence.”

WILL OGILVIE *VIA E-MAIL*

MEET THE BEETLES

“Beetle Resurrection,” by Hannah Nordhaus, discusses the American burying beetle, which eats and breeds on the carcasses of small animals. This fascinating article reminded me of an event some years ago: I live in a wooded area with a large population of sexton, or burying, beetles. And mice. One of the latter found its way under the floorboards of my library, where it died. Oh, the stink!

I removed the cover of an unused heating element in the floor, hoping to fish about and find the corpse. No luck. I sat there, wondering what to do, when a huge black-and-orange beetle buzzed past my ear and landed next to the opening, then zipped inside and vanished. It was lunchtime, and I departed. Some time later my wife exclaimed, “You found the mouse!” I certainly did *not* find the mouse, but there it was, the stinky cadaver, right in the middle of the room. The beetle had evidently found it and, unable to bury it in place, had dragged it up and out of the opening, then across the floor, where it must have eventually given up. I wanted to thank the beetle, but it had departed. To this day, I don’t know how it entered, or left, my house.

Don Dilworth
East Boothbay, Me.

Nordhaus refers to researchers carrying guns for protection against rattlesnakes and feral pigs. I’m horrified. These people are such puffed-up wimps. Here in Australia, families with kids regularly camp in the bush where there are feral pigs, dingoes and several species of snakes more venomous than a rattlesnake. If one were seen carrying a sidearm, he or she would be laughed at, ostracized and probably arrested.

Bob Trlin
via e-mail

LEGAL BATTLE

Michael Shermer’s editorial in support of “Outlawing War” is well said as far as it goes, but how would he advocate enforcing such a law? Legislators usually do not want to pass laws that cannot be enforced. Should whoever passes a law against war have a compliance division that uses force against someone who breaks the law? We have laws against violent crime, but that has not done away with murder or the need for police.

Shermer discusses “outcasting” techniques such as economic sanctions. But would Hideki Tojo or Adolf Hitler have responded to widespread sanctions? As Shermer notes, the dictators in North Korea have not so far. To avoid war, it would be far more intelligent and compassionate, though difficult, to alleviate the issues that motivate governments to resort to violence—such as poverty, unemployment, lack of education, and so on.

Will Ogilvie
via e-mail

SHERMER REPLIES: Of the many reasons nations go to war, poverty, unemployment and lack of education do not figure into anyone’s causal formula. In fact, the opposite is true, as evidenced in the examples of Imperial Japan and Nazi Germany, both of which enjoyed apparently high prosperity and education. Outlawing war and outcasting violators of international law do not always work, but they have helped attenuate the frequency and deadliness of war since the end of World War II. That’s something, and these approaches are almost always a better response than armed conflict, which is expensive, removes people from the labor market and racks up body counts.

As for North Korea, whereas sanctions have not worked to curtail its drive to become a viable nuclear power, it is my opinion that Kim Jong-un’s motive is deterrence and that as long as he is left alone, he will not use his nukes.

COOL MACHINE

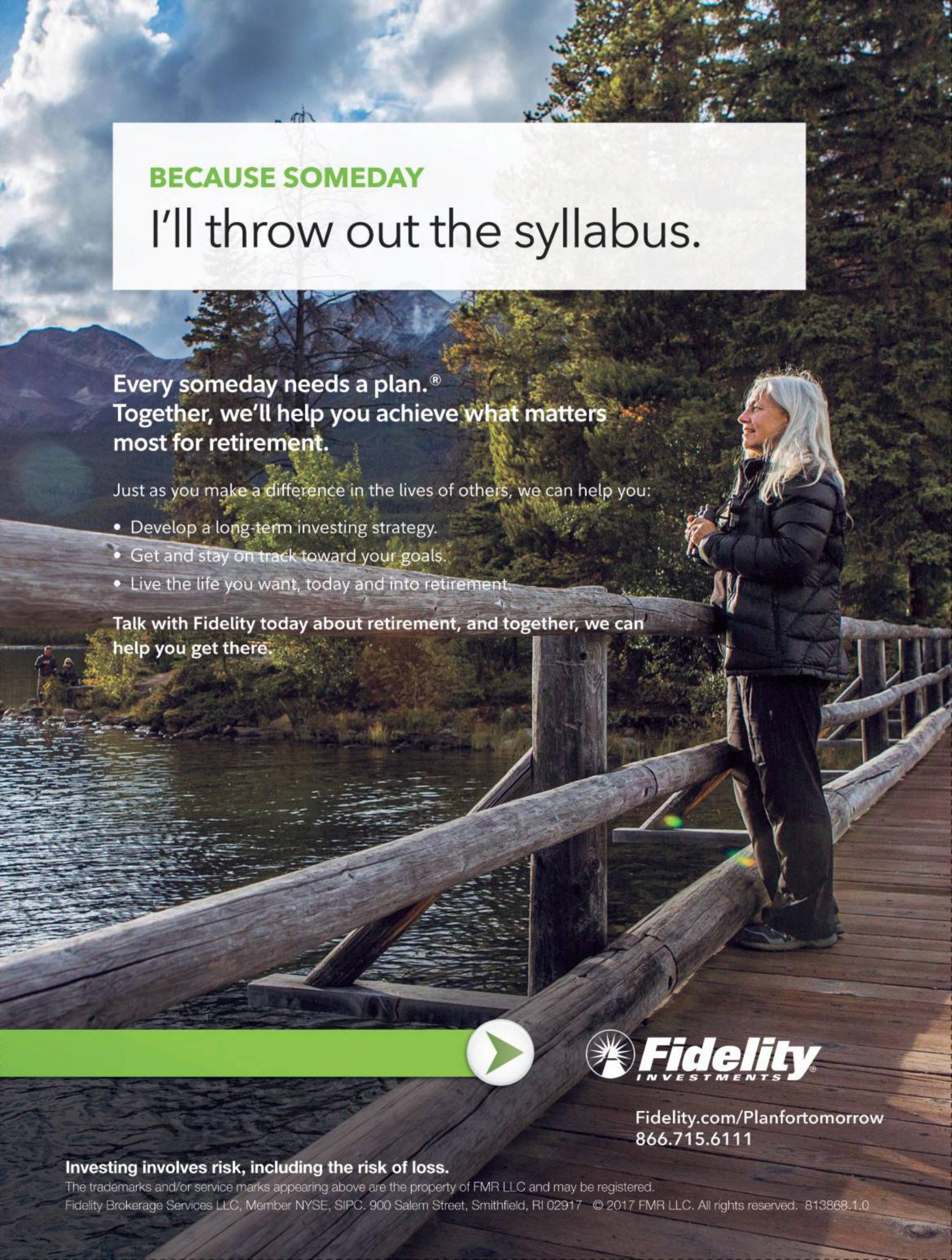
In “Quantum Computing” [“Top 10 Emerging Technologies of 2017”], Dario Gil reports that quantum computers are difficult to build, noting that “a popular design requires superconducting materials that must be kept 100 times colder than outer space.”

What does that actually mean? I am not a scientist, so I find the concept of having something be a given number of times colder than something else not immediately clear.

William Crosby
Kingston, Ontario

THE EDITORS REPLY: The standard temperature scale used by physicists is kelvins, where zero kelvin is “absolute zero,” the lowest temperature theoretically possible, at which point atoms would cease to move. (Although scientists have created a quantum gas with a value below zero kelvin in the laboratory.) The temperature of interstellar space is typically given as that of the cosmic microwave background radiation that permeates the universe: about 2.7 kelvins. Meanwhile the processor in the D-Wave 2000Q quantum computer, for example, is kept at 0.015 kelvin. So on the kelvin scale, the processor is 180 times colder than the temperature of space.

But such comparisons break down when temperatures are converted to the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scales that are more familiar in our daily life in the U.S.: in Fahrenheit, the temperatures of space and the processor would be given as −454.81 and −459.643 degrees F, respectively.

HEALTH DISPARITY

In "End the Assault on Women's Health" [Science Agenda; September 2017], the editors discuss Republicans' failed plan to repeal and replace the Affordable Care Act and argue that it would disproportionately harm women, particularly in the area of reproductive health.

We should consider the focus on curtailing reproductive health by such political forces as discrimination propaganda on a scale so massive that no one wants to see it. To test this, try substituting the word "blacks" for "women" and "whites" for "men" in reporting on the subject of this article. Cast that way, bloody battles would erupt in the streets.

It's not about reproduction; it's about one group of people controlling the lives and bodies of another. And it's up to us females to change this, not *Scientific American*'s editorial board.

Prudie Orr
via e-mail

ORIGIN OF SCOPOPHOBIA

In "Your Security Cam Is Watching You" [TechnoFiles; October 2017], David Pogue writes about that uncomfortable feeling people have when they are being observed by video cameras. His wife described it as "creepy," and he calls it "irrational" and "primal." Is it possible this uncomfortable feeling is not so irrational, albeit primal? Could it be our modern-day manifestation of a time when getting a creepy feeling while being watched by a hidden sabertooth tiger had an evolutionary advantage?

Lou Eisenberg
Buffalo Grove, Ill.

CLARIFICATION

"Sustainable Communities," by Daniel M. Kammen ["Top 10 Emerging Technologies of 2017"], describes the Oakland EcoBlock project as involving retrofitting homes in a neighborhood near the Golden Gate Bridge in California. The nearest bridge is the San Francisco–Oakland Bay Bridge.

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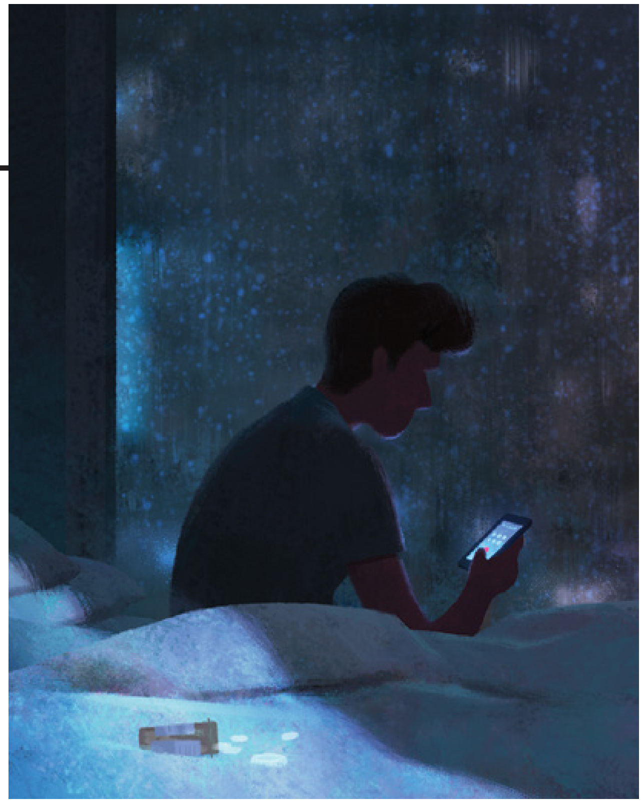
How to Stop the Epidemic of Suicides

Health workers are not trained to address patients' self-destructive impulses—but they should be

By the Editors



Every 11.7 minutes in the U.S., a person takes his or her own life. That figure, the latest available, makes suicide the 10th leading cause of death in this country. Rates have been rising every year for the past dozen years. It's nothing short of an epidemic.

Yet those most well placed to stop this public health crisis are not equipped to do so: few doctors and less than half of U.S. mental health professionals are trained in suicide prevention. According to a recent report from the American Association of Suicidology (AAS), only 50 percent of psychology training programs, fewer than a quarter of social work programs, 6 percent of marriage and family therapy programs, and 2 percent of counselor education programs teach their students how to spot individuals at risk for suicide and how to stop them from going through with it.

To get people through such a crisis, experts now have several methods available that have proved effective ["see "Preventing Suicide," on page 54]. Treatments focus on teaching patients how to identify and regulate their emotions and to learn to bear the feeling of distress. It's critical for those at risk to have a plan in place and to practice skills for calming themselves when suicidal thoughts return. Although most therapies involve weeks or months of sessions, even short interventions can work at a moment of crisis. One study, for instance, found that even a single session with a therapist trained in "crisis response planning," which helps patients identify their own warning signs and come up with coping strategies, reduced suicide attempts in soldiers by 76 percent compared with other treatment methods. "A lot of people hold fast to the old adage: if someone wants to kill themselves, they'll find a way. But it's not true," says psychologist William Schmitz, Jr., lead author of the report and a past president of the AAS. "We know if we get people through a suicidal crisis, most of them will never end up dying by suicide."

Yet these interventions can only work when they actually reach the people who need them. One obvious way to make that connection is through mental health professionals—such as therapists, psychologists and social workers. About a third of those who commit suicide had come into contact with mental health services in the year before they died—and about a fifth had done so during the past month. Yet there are no national standards requiring these workers to know how to identify patients at serious risk of suicide or what techniques help them survive. If there were, perhaps some of those deaths could have been avoided.

Primary care doctors are in an even better position to help but are similarly lacking the tools to do so. They prescribe more than half of all psychotropic drugs, and 77 percent of people who die by suicide had contact with their primary care provider in their last year of life—45 percent in just the past month. Yet most physicians do not learn how to identify those at risk of suicide or what to do to help them.

These arguments have fallen on deaf ears at the guilds overseeing these professions, who often argue that their training programs are burdened by too many requirements already. But suicide prevention should be among those requirements. For some patients, it is the most significant and only service that really matters.

Things tend to change, however, when state governments take on the issue themselves. In September 2017 California became the most recent state to pass a law requiring suicide prevention training. To get a California license, a psychologist must complete six hours of education in suicide risk assessment and intervention. Nine other states have similar laws, and another four encourage this training but do not require it, according to the American Foundation for Suicide Prevention. Washington State is the only one, however, that extends the education requirement beyond mental health providers to all health workers, including doctors, nurses, and even dentists and naturopaths.

More states should follow in Washington's footsteps. Suicidal thoughts do not have to be a death sentence. Research has found treatments that work, and it's time to make sure people receive them. SA

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Illustration by Ileana Soon

Martin Elvis is a senior astrophysicist at the Harvard-Smithsonian Center for Astrophysics. The opinions expressed here are purely his own.

Has Astronomy Peaked?

A focus on costly space telescopes is hurting the field

By Martin Elvis

Starting around 50 years ago, astronomy began a winning streak of amazing discoveries. We found the cosmic microwave radiation left over from the big bang back in the 1960s, for instance, and in recent years we have identified thousands of planets orbiting distant stars. But the good times may be about to stop rolling. There is reason to fear that astronomy is ending its long run of lifting the veil on cosmic wonders.

Our early successes came from looking through new windows across a vast range of wavelengths invisible to the naked eye. The first radio, x-ray, ultraviolet and infrared telescopes were small, but everything we saw through them was new and mysterious. The next generation of telescopes leaped forward in capabilities, leading to the discoveries of neutron stars, black holes, dark matter, dark energy—the list goes on.

But this greater power came at a cost. Each new generation of telescopes carried a price tag several times higher than that of the one before. Today a single telescope can now take almost a full decade's worth of NASA's budget for "big astronomy." A case in point is the James Webb Space Telescope, now scheduled for launch next year. Webb's price tag ballooned from what was originally supposed to be just about $1 billion to nearly $9 billion, crowding out nearly everything else. Without other major missions to fall back on, the only response to technical problems with Webb was to keep throwing more money at them.

The glory of our golden age has been that we can access the entire electromagnetic spectrum at a single point in time, from various instruments. The discovery of gravitational waves from the merger of two neutron stars is a perfect example: ground-based detectors spotted these ripples in spacetime, but follow-up observations with gamma-ray, x-ray and visible-light telescopes gave us a far better understanding of how the event unfolded. Ideally we need several comparably sensitive "flagship" telescopes, on a par with Webb—and they need to be flying at the same time.

Yet such flagships are designed to last only about five years (although that can often be stretched to 10). When the infrared-sensitive Webb flies, it will be 10 to 100 times more powerful than its predecessors, the Hubble and Spitzer space telescopes. But if new flagships cost as much as Webb, it will be a decade before even one of them can be launched. By then, Webb itself will likely be on its last legs. Every discovery it makes will take more than 10 years to follow up. At that point, we will have forgotten what it was that we wanted to know in the first place.

But it does not have to be this way. Once a decade astronomers set priorities about what new space telescopes to build, and the next time we do so, in the "Astro2020" survey, we should require multiple new missions. There are at least half a dozen ideas for much cheaper telescopes—not as powerful as Webb-scale flagship telescopes but dramatically better than their predecessors. These range from gamma-ray telescopes that can detect merging neutron stars to x-ray and ultraviolet telescopes for probing intergalactic space and more to a far-infrared telescope we can use to understand how stars and planets form. And unlike Webb, they are not just affordable; all of them can be completed within 10 years.

The downside of this approach is that highly desirable but extremely expensive flagship telescopes along the lines of Webb must be postponed until the commercial space industry comes fully of age. SpaceX, for example, already launches satellites at one third of the traditional cost, and soon, maybe, that will drop to as little as one fifth. That is a sizable saving by itself.

Cheaper launch services also take the pressure off engineers to relentlessly shave mass from the telescopes themselves by using the lightest and most expensive possible components. Without such a restriction, costs could plausibly be cut by two thirds. Shrinking costs makes a doubling of flagship launch rates feasible. As this commercial revolution continues, an even higher rate of flagship missions could come about.

If we embrace such a strategy, the good times needn't stop rolling, and the golden age of astronomy doesn't have to end. SA

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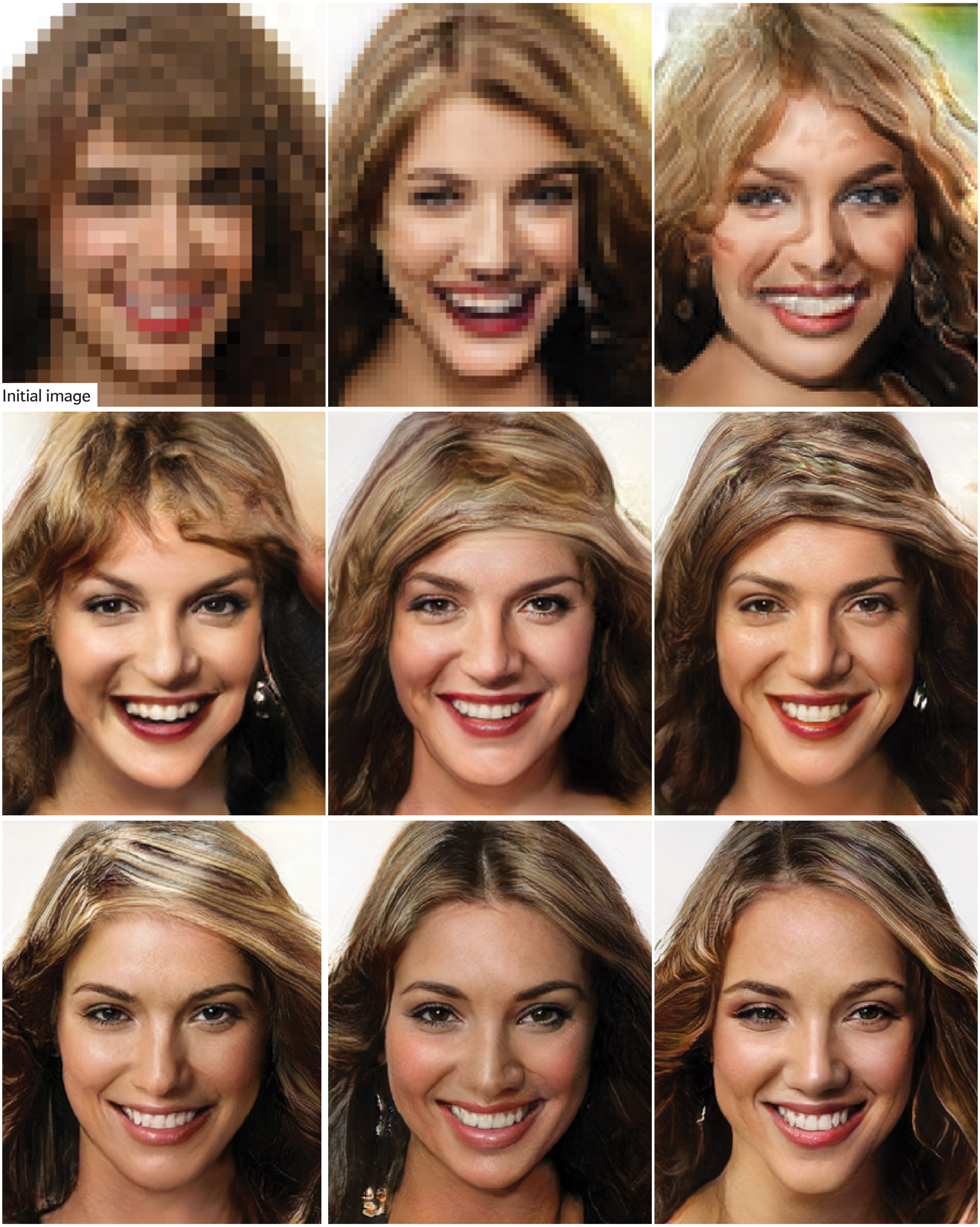
Illustration by Matthew Harrison Clough

ADVANCES



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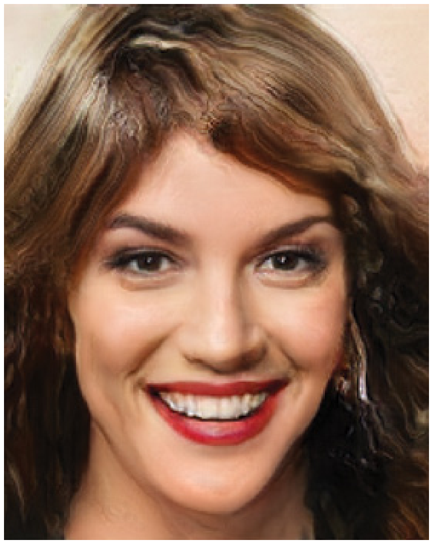
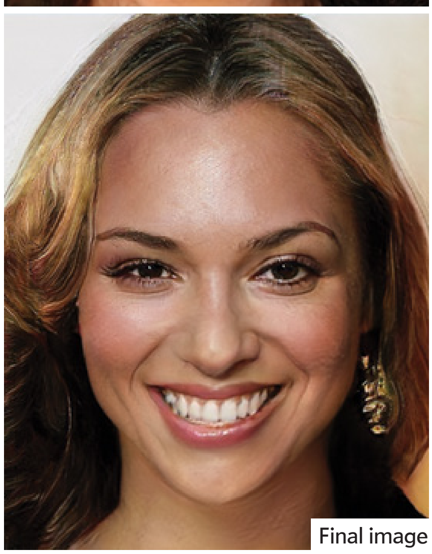


Using "adversarial" neural networks, artificial intelligence can create convincing images of computer-generated people. Here a team of researchers from Nvidia used such a network to create progressively lifelike images based on hundreds of thousands of photographs of actual celebrities. The resulting picture is nearly indistinguishable from that of a real person.



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Don't Believe Your Eyes

Artificial intelligence can produce deceptively realistic-looking photographs

Fraudulent images have been around for as long as photography itself. Take the famous hoax photos of the Cottingley fairies or the Loch Ness monster. Photoshop ushered image doctoring into the digital age. Now artificial intelligence is poised to lend photographic fakery a new level of sophistication, thanks to artificial neural networks whose algorithms can analyze millions of pictures of real people and places—and use them to create convincing fictional ones.

These networks consist of interconnected computers arranged in a system loosely based on the human brain's structure. Google, Facebook and others have been using such arrays for years to help their software identify people in images. A newer approach involves so-called generative adversarial networks, or GANs, which consist of a "generator" network that creates images and a "discriminator" network that evaluates their authenticity.

"Neural networks are hungry for millions of example images to learn from. GANs are a [relatively] new way to automatically generate such examples," says Oren Etzioni, chief executive officer of the Seattle-based Allen Institute for Artificial Intelligence.

Yet GANs can also enable AI to quickly

produce realistic fake images. The generator network uses machine learning to study massive numbers of pictures, which essentially teach it how to make deceptively lifelike ones of its own. It sends these to the discriminator network, which has been trained to determine what an image of a real person looks like. The discriminator rates each of the generator's images based on how realistic it is. Over time the generator gets better at producing fake images, and the discriminator gets better at detecting them—hence the term "adversarial."

GANs have been hailed as an AI breakthrough because after their initial training, they continue to learn without human supervision. Ian Goodfellow, a research scientist now at Google Brain (the company's AI project), was the lead author of a 2014 study that introduced this approach. Dozens of researchers worldwide have since experimented with GANs for a variety of uses, such as robot control and language translation.

Developing these unsupervised systems is a challenge. GANs sometimes fail to improve over time; if the generator is unable to produce increasingly realistic images, that keeps the discriminator from getting better as well.

Chipmaker Nvidia has developed a way of training adversarial networks that helps to avoid such arrested development. The key is training both the generator and discriminator progressively—feeding in low-resolution images and then adding new layers of pixels that introduce higher-resolution details as the training progresses. This progressive machine-learning tactic also cuts training time in half, according to a paper the Nvidia researchers plan to present at an international AI conference this spring. The team demonstrated its method by using a database of more than 200,000 celebrity images to train its GANs, which then produced realistic, high-resolution faces of people who do not exist.

A machine does not inherently know whether an image it creates is lifelike. "We chose faces as our prime example because it is very easy for us humans to judge the success of the generative AI model—we all have built-in neural machinery, additionally trained throughout our lives, for recognizing and interpreting faces," says Jaakko Lehtinen, an Nvidia researcher involved in the project. The challenge is getting the GANs to mimic those human instincts.

Facebook sees adversarial networks as a way to help its social media platform better predict what users want to see based on their previous behavior and, ultimately, to create AI that exhibits common sense. The company's head of AI research Yann LeCun and research engineer Soumith Chintala have described their ideal system as being "capable of not only text and image recognition but also higher-order functions like reasoning, prediction and planning, rivaling the way humans think and behave." LeCun and Chintala tested their generator's predictive capabilities by feeding it four frames of video and having it generate the next two frames using AI. The result was a synthetic continuation of the action—whether it was a person simply walking or making head movements.

Highly realistic AI-generated images and video hold great promise for filmmakers and video-game creators needing relatively inexpensive content. But although GANs can produce images that are "realistic-looking at a glance," they still have a long way to go before achieving true photo-realism, says Alec Radford, a researcher now at AI research company OpenAI and lead author of a study (presented at the international AI conference in 2016) that Facebook's work is based on. High-quality AI-generated video is even further away, Radford adds.

It remains to be seen whether online mischief makers—already producing fake viral content—will use AI-generated images or videos for nefarious purposes. At a time when people increasingly question the veracity of what they see online, this technology could sow even greater uncertainty.

—*Lawrence Greenemeier*

ANIMAL BEHAVIOR

Bonobos Like Bullies

Our primate cousins prefer dominance over manners

Unlike their human cousins, bonobos favor others that throw their weight around.

GETTY IMAGES

Given a choice, most humans would probably rather spend time with nice people than with jerks. But the opposite seems to be true of bonobos, a recent study suggests.

"Of our two closest relatives, chimps and bonobos, [bonobos] are the ones known to show less extreme aggression," says the study's lead author Christopher Krupenye, an evolutionary anthropologist now at the University of St. Andrews in Scotland. "So we thought, if either of them are likely to share with humans this motivation to prefer helpers, it may be bonobos."

Krupenye and Duke University anthropologist Brian Hare tested a group of 43 bonobos living in a sanctuary in the Democratic Republic of the Congo. In one experiment, 24 bonobos watched a series of cartoons depicting an anthropomorphic circle trying to ascend a hill. The circle was either helped by a triangle or hindered by a square. The apes were then offered two identical pieces of fruit under a paper cutout of either the "helper" triangle or the "hinderer" square. Like human infants, bonobos could distinguish each shape on the basis of its social behaviors. But unlike humans, they preferred the square. The findings appeared in January in *Current Biology.*

Behaviors humans see as antisocial might, among bonobos, be more reflective of social dominance. And for apes living in a strict hierarchy, it pays to befriend those on top. Krupenye says his team's results support the notion that the preference to avoid individuals who mistreat others is one of the things that set humans apart from other apes. But University of Southern California developmental psychologist Henrike Moll, who was not involved in the study, argues it may not make sense to compare the two species this deeply on the basis of their reactions to these videos—especially if humans interpret them in terms of morality, whereas bonobos view them through the lens of social dominance.

—*Jason G. Goldman*


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Children of the Menominee Nation in Wisconsin in 2008.

STEVEN L. RAYMER *Getty Images*

How do young children understand the natural world? Most research into this question has focused on urban, white, middle-class American children living near large universities. Even when psychologists include kids from other communities, too often they use experimental procedures originally developed for urban children. Now researchers have developed a methodology for studying rural Native American kids' perspectives on nature and have compared their responses with those of their city-dwelling peers. The findings offer some rare cross-cultural insight into early childhood environmental education.

Sandra Waxman, a developmental psychologist at Northwestern University, and her colleagues have long collaborated with the Menominee, a Native American nation in Wisconsin. When the researchers presented plans for their study to tribe members who were trained research assistants, the assistants protested that the experiment—which involved watching children play with toy animals—was not culturally appropriate. It does not make sense to the Menominee to think of animals as divorced from their ecological contexts, Waxman says.

Instead one of the Menominee researchers constructed a diorama that in-

GEOLOGY

Hot Rocks

The U.S. Northeast may be more geologically active than thought

For the past 200 million years New England has been a place without intense geologic change. With few exceptions, there have been no rumbling volcanoes or major earthquakes. But it might be on the verge of awakening.

Findings published this January in *Geology* show a bubble of hot rock rising underneath the northern Appalachian Mountains. The feature was first detected in 2016 by EarthScope, a collection of thousands of seismic instruments sprinkled throughout the U.S. Vadim Levin, a geophysicist at Rutgers University, says this wealth of sensors lets earth scientists peer under the North American continent, just as the Hubble Space Telescope has enabled astronomers to gaze deep into the night sky. Should the broiling rock breach the surface—which could happen, though not until tens of millions of years from now—it would transform New England into a burbling volcanic landscape.

The finding has sparked many questions, given that New England is not located along an active plate margin (where one tectonic plate rubs against another) but sits squarely in the middle of the North American plate. The exact source of the hot rock bubble, for example, is unclear. Because the edge of the North American continent is colder than a plate near an active margin, Levin suspects this edge is cooling the mantle—the layer just below the crust that extends toward the earth's core. As cold chunks of mantle sink, they may displace hotter segments, which would rise toward the surface. Scientists believe they have now imaged such an ascending piece. Although it sounds simple, this scenario "is a story that at present does not have a place in a textbook," Levin says.

Or perhaps pieces of the North American continent are breaking off and sinking into the mantle (which would also push the warmer mantle upward), observes William Menke, a geophysicist at Columbia cluded realistic trees, grass and rocks, as well as the original toy animals. The researchers watched as three groups of four-year-olds played with the diorama: rural Menominee, as well as Native Americans and other Americans living in Chicago and its suburbs.

All three groups were more likely to enact realistic scenarios with the toy animals than imaginary scenarios. But both groups of Native American kids were more likely to imagine they *were* the animals rather than give the animals human attributes. And the rural Menominee were especially talkative during the experiment, contrary to previous research that characterized these children as less verbal than their non–Native American peers. The results were published last November in the *Journal of Cognition and Development.*

"The involvement of tribal communities in all aspects of the research—planning, design, execution, analysis and dissemination—has to be the minimum requirement of all research involving Native people," says Iowa State University STEM scholars program director Corey Welch, who is a member of the Northern Cheyenne.

—*Jason G. Goldman*

University, who was not part of the study.

Scientists do not yet know which model is correct or if an entirely different one may be involved. Levin and his colleagues are eager to collect more data to bring this unusual hotspot into sharper focus and, in doing so, flesh out the theory of plate tectonics. "We know little about the interior of our planet, and every time we look with a new light ... we find things we did not expect," Levin says. "When we do, we need to rethink our understanding of how the planet functions."

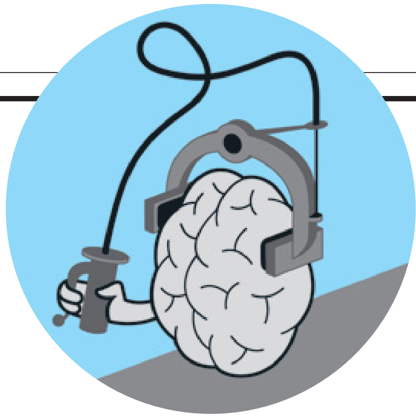
—*Shannon Hall*

Illustrations by Thomas Fuchs

NEUROSCIENCE

The Brain's Brakes

Scientists identify a chemical involved in suppressing thoughts



Everyone has unwelcome thoughts from time to time. But such intrusions can signal serious psychiatric conditions—from "flashbacks" in post-traumatic stress disorder (PTSD) to obsessive negative thinking in depression to hallucinations in schizophrenia. "These are some of the most debilitating symptoms," says neuroscientist Michael Anderson of the University of Cambridge.

New research led by Anderson and neuroscientist Taylor Schmitz, now at McGill University, suggests these symptoms may all stem from a faulty brain mechanism responsible for blocking thoughts. Researchers studying this faculty usually focus on the prefrontal cortex (PFC), a control center that directs the activity of other brain regions. But Anderson and his colleagues noticed that conditions featuring intrusive thoughts—such as schizophrenia—often involve increased activity in the hippocampus, an important memory region. The severity of symptoms such as hallucinations also increases with this elevated activity.

In the new study, Anderson and his team had healthy participants learn a series of word pairs. The subjects were presented with one word and had to either recall or suppress the associated one. When participants suppressed thoughts, brain scans detected increased activity in part of the PFC and reduced activity in the hippocampus. The findings, which were published last November in *Nature Communications,* are consistent with a brain circuit in which a "stop" command from the PFC suppresses hippocampus activity.

Using magnetic resonance spectroscopy, the team also found that levels of GABA—the main chemical that inhibits signals in the brain—in participants' hippocampi predicted their ability to suppress thoughts. "If you have more GABA to work with, you're better at controlling your thoughts," Anderson says. In other words, if the PFC contains the mental brake pedal, hippocampal GABA levels are the brake pads that determine how effectively the brain stops.

The study helps to bridge the gap between molecular neuroscience and human behavior—and how the process goes awry in disease. "It's a great step," says neuroscientist Brendan Depue of the University of Louisville, who was not involved in the work. "The next step is to do a drug study," Anderson says. "Could we make people better [at suppressing thoughts] by giving them drugs that enhance GABA?" —*Simon Makin*

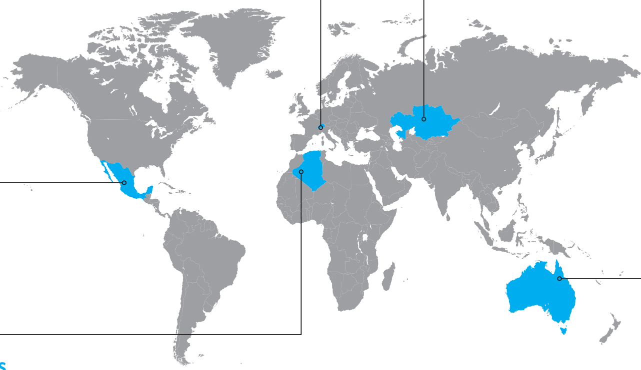
IN THE NEWS

Quick Hits

SWITZERLAND
The Swiss government has banned the practice of dropping live lobsters into boiling water, claiming the crustaceans can feel pain—a still debated conclusion. Cooks are now asked to stun the animals first.

KAZAKHSTAN
More than 200,000 critically endangered saiga antelope mysteriously died over a three-week span in 2015. Scientists now think this was caused by a bacterium that flourished because of a warmer, wetter spring and poisoned the animals' blood.

MEXICO
An unknown disease that wiped out 45 percent of native people in 16th-century New Spain (modern Mexico) might have been a type of *Salmonella*, a new study suggests. The bacterium may have been brought by Europeans colonizing the Americas.



AUSTRALIA
Researchers found that the rocks around Georgetown in northeastern Australia are very similar to rocks in Canada. This discovery provides the first strong evidence that a piece of land from North America latched onto the Australian mainland 1.7 billion years ago.

ALGERIA
Satellites captured images of up to 15 inches of snow covering the edge of the Sahara Desert, one of the hottest places on Earth. This much snow has been recorded there only two other times in the past 37 years.

ANTARCTICA
A global campaign has proposed creating the world's largest wildlife reserve around Antarctica—an area five times the size of Germany. Backers hope this measure will curb krill fishing, which diminishes a food source for larger animals.

—Yasemin Saplakoglu

For more details, visit www.ScientificAmerican.com/apr2018/advances

EARTH SCIENCE

Glacial Sprint

What causes a Pakistan ice river to dangerously surge every 20 years?

The Khurdopin glacier in Pakistan surged up to 20 meters a day in May 2017.

JESSE ALLEN *NASA Earth Observatory*

Most glaciers creep along at a pace that is, well, glacial. But one in northern Pakistan breaks into a gallop with astounding speed and regularity: Khurdopin glacier "surges" every two decades, moving roughly 1,500 times its normal pace. This sends ice tumbling into a nearby river, damming it to create a temporary lake that can suddenly inundate nearby villages. Now scientists in Europe have used new high-resolution satellite data to study Khurdopin before and during its most recent surge in 2017, revealing how the event developed on a near daily basis, in unprecedented detail. The observations are critical to monitoring the glacier's hazards and could help to predict when flooding might occur next.

About 1 percent of the world's glaciers exhibit such sudden and large bursts of speed. "It's not 100 percent clear why some glaciers surge and others don't," says Jakob Steiner, a geoscientist at Utrecht University in the Netherlands, who led the study. Some scientists think water permeates a glacier's base and acts as a lubricant to promote sliding. Sedi-

BIOCHEMISTRY

DNA Clock

Scientists move toward building molecular computers

Nature is a master at constructing biological machines and circuits, including the ones that maintain the body's internal clock, copy genes or help cells move. Now human engineers are learning to design and synthesize novel biochemical devices such as nanoscale factories, biological circuits and even molecular computers.

This work has so far relied mostly on using existing cellular components (enzymes, for example), but some researchers prefer to start from scratch. For these "molecular programmers," DNA is the coding language of choice, and crafting circuits and machines to rival those found in nature is the ultimate goal. Recently they took a big step closer by creating the first oscillator—a molecular clock—made solely of DNA.

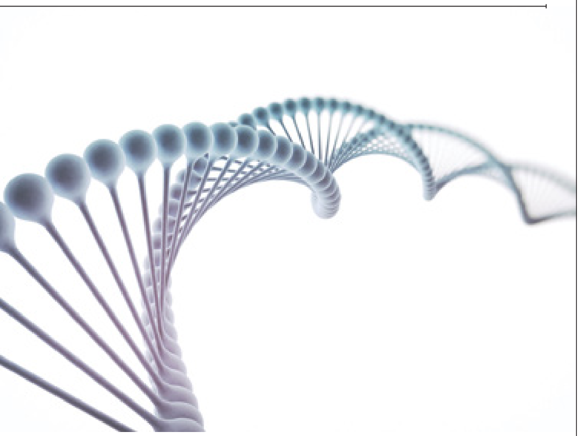
This milestone achievement, reported last December in *Science,* shows that DNA is not simply a passive carrier of genetic information. Instead it is a molecule that—even on its own—"is capable of complex behavior," says senior author David Soloveichik, an electrical and computer engineer at the University of Texas at Austin. Building a DNA oscillator is a biological engineering feat in itself and would likely be integral for potential breakthroughs in synthetic biology, such as controlling the timing of events in artificial cells, scheduling the release of drugs and synchronizing molecular computers.

To create the device, Soloveichik, Niranjan Srinivas, then a doctoral candidate at the California Institute of Technology, and their colleagues built a DNA compiler—a series of algorithms that allows a programmer to issue molecule-building instructions without having to get into the nitty-gritty biochemistry. Software translates those instructions into DNA sequences that are synthesized and mixed together. The strands then self-assemble into molecular machines.

Using its compiler, the team programmed a prototype DNA oscillator that generates repeating patterns of "ticks" and "tocks." In principle, Soloveichik says, the same formula can be used to produce more complex behavior, such as changing the clock's speed in response to chemical ments between a glacier and the ground may also facilitate slippage.

Steiner and his team analyzed new satellite images of Khurdopin that revealed features as small as three meters across. As snow accumulated on the high-elevation end of the 41-kilometer river of ice, the crushing pressure changed the structure of the water molecules, causing the ice to melt at lower temperatures and allowing the mass to suddenly shift. Khurdopin surged up to 20 meters a day in May 2017, creating a lake that grew to 30 times its size before draining and washing away roads, bridges and farmland, the scientists reported in January in *The Cryosphere*.

"This work has characterized the surge in exceptional detail," says Duncan Quincey, a glaciologist at the University of Leeds in England, who was not involved in the study. Steiner and his colleagues plan to return to Pakistan this year to continue installing temperature and rain sensors around Khurdopin and training area residents to monitor the glacier and its transient lake. —*Katherine Kornei*



JESPER KLAUSEN *Getty Images*

signals. These clocks could eventually lead to chemical computation—after all, some of the first mechanical computers were simply sophisticated clocks.

Peng Yin, a systems biologist at Harvard University, who was not involved in the new research, says he is impressed by the work and calls it "an important advance for molecular programming, dynamic DNA nanotechnology and in vitro synthetic biology." And given that scientists believe early life was based entirely on DNA's close relative, RNA, Soloveichik adds that "showing that nucleic acids like DNA and RNA can behave in new and unexpected ways informs our understanding of the origin of life." —*Rachel Nuwer*

ECOLOGY

Bird, Interrupted

Oil- and gas-drilling noise hurts nearby avians

Constant noise—such as from the construction project next door or the car alarm that will not stop—can irritate anyone. And birds are no exception. A recent study found that sounds from oil- and gas-drilling operations contributed to chronic stress in three species of songbirds, mimicking what occurs in people with post-traumatic stress disorder (PTSD).

Nathan Kleist, then a doctoral student at the University of Colorado Boulder, and his colleagues placed artificial nest boxes at various distances from gas-drilling pads in the San Juan Basin of New Mexico. Loud compressors there ran 24 hours a day.

Of the three species Kleist and his colleagues studied, mountain bluebirds and ash-throated flycatchers avoided nest boxes closest to compressors. Western bluebirds, in contrast, nested at sites along the full noise gradient. The researchers measured levels of the stress hormone corticosterone in adult females and nestlings of the three species at all the nest boxes over three years.

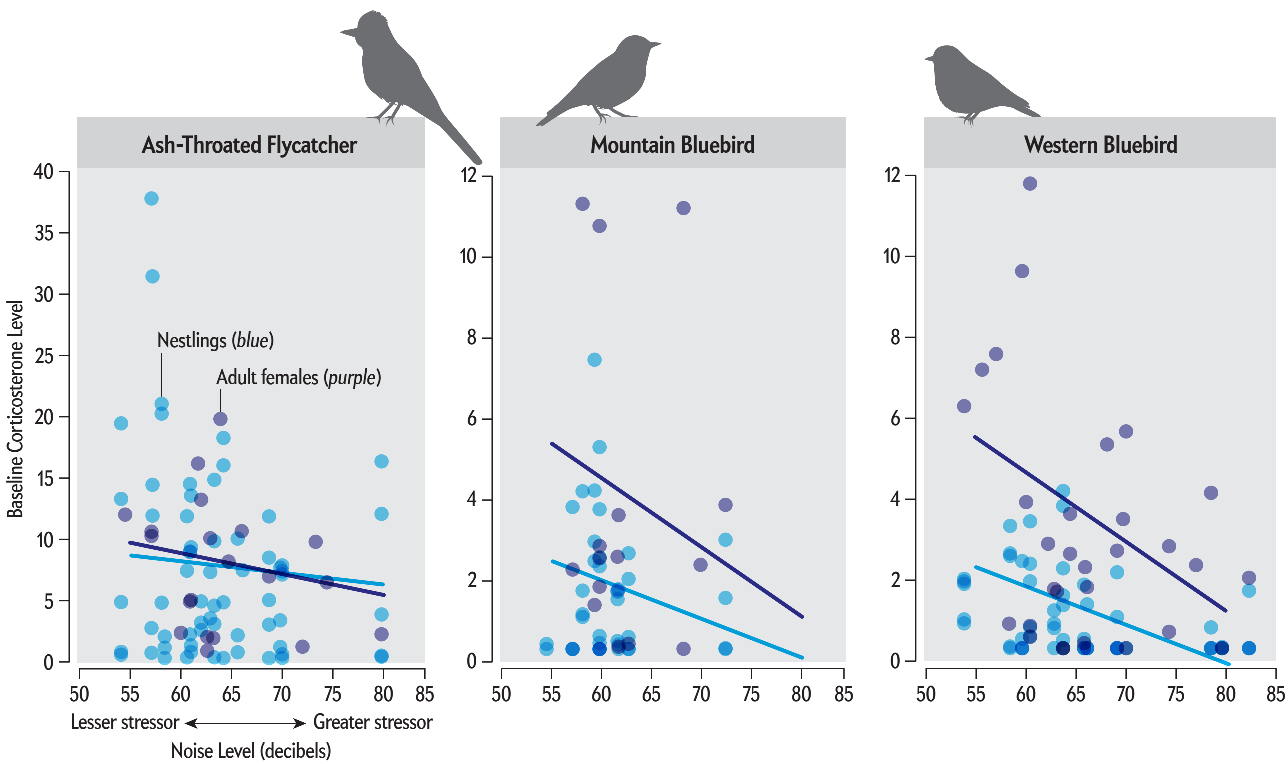
The team found a linear relation between distance from the compressors and baseline corticosterone; birds nesting closest had lower stress hormone levels. This may seem counterintuitive, but hormone levels can increase or decrease depending on the type and timing of stress. A sustained change in either direction indicates chronic stress, and research on humans suffering from PTSD shows that their baseline levels typically decline.

The scientists also found that eggs in western bluebird nests closest to the compressors were less likely to hatch than eggs farther away. Nestling growth was stunted closer to compressors in all three species, the team reported in January in the *Proceedings of the National Academy of Sciences USA*. "With even modest increases in background noise, we could see these effects," Kleist says. Nestlings farthest away experienced stunted growth as well (predators are more common at quieter sites, and heightened vigilance might reduce the birds' ability to feed their young). Nestlings at intermediate distances had the highest growth rates.

Michael Romero of Tufts University, who studies stress responses in wildlife and was not involved in the study, says, "The neat thing about this paper is that it showed environmental stress lowered [reproductive success]." Even wildlife in highly protected areas is not immune. "Most protected areas in the United States are experiencing increased background noise," Kleist notes, making this "potentially a widespread issue."

—*Amy Mathews Amos*

Sounds from oil- and gas-drilling operations contributed to chronic stress in three species of songbirds, mimicking human PTSD.



For new hatchlings and their mothers, noisier environments were associated with lower baseline levels of corticosterone, a hormone involved in stress responses. This negative correlation may seem counterintuitive, but a lower baseline has also been observed in humans with PTSD. Chronic stress can cause a sustained increase or decrease.

SOURCE: "CHRONIC ANTHROPOGENIC NOISE DISRUPTS GLUCOCORTICOID SIGNALING AND HAS MULTIPLE EFFECTS ON FITNESS IN AN AVIAN COMMUNITY," BY NATHAN J. KLEIST ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 115, NO. 4; JANUARY 23, 2018

Graphic by Amanda Montañez

BIOPHYSICS

Back to Black

These bird feathers can absorb almost all light

JOEL SARTORE *Getty Images*

Many male birds-of-paradise employ bright colors and iridescent feathers in their mating displays—but a few species also sport superblack plumage. Now researchers have teased out the structural secrets behind these feathers, which rival even the deep, velvety darkness of human-made materials designed to absorb light.

Feathers, like most opaque objects, typically get their color from pigments in surface coatings (much as melanin colors skin) or from tiny surface structures that reflect light, such as those found on iridescent butterflies and beetles. But superblack feathers are the opposite of iridescent, says Dakota McCoy, an evolutionary biologist at Harvard University and co-author of a recent study on the topic. This plumage absorbs up to 99.95 percent of the visible light that hits it, reported McCoy and her colleagues in January in *Nature Communications.*

A closer look at these specialized display feathers exposes their light-trapping trick: microstructures called barbules, located near the feathers' tips, are covered with a multitude of even tinier branching structures. In contrast, most flight-feather barbules have Velcro-like hooks that can snag neighboring barbules to form a solid yet flexible aerodynamic surface. When light strikes a superblack feather's forest of barbules—which tilt at about 30 degrees toward the outer tip of the feather—it gets reflected into cavities between the tiny structures rather than outward, McCoy says. Even when coated with vaporized gold, these feathers still appeared black, whereas feathers that derive their black color from pigments looked golden when similarly coated, she adds.

The team's findings reveal a new type of feather microstructure, according to evolutionary biologist Matthew Shawkey of Ghent University in Belgium, who was not involved in the study. "This structure enhances the blackness produced by the feathers' pigments," Shawkey says.

Black feathers found on other birds-of-paradise—and some found elsewhere on one of the species the team analyzed—reflect between 10 and 100 times more light than the superblack feathers do, McCoy says.

She and her colleagues propose that the inky feathers evolved as a way to emphasize brighter-colored ones, helping to attract potential mates. In all the superblack species the researchers examined, the special feathers were always immediately adjacent to bright, lustrous ones. During mating displays the males hold these plumes so that the feathers appear their darkest from the females' point of view, McCoy notes.

"This is definitely not about camouflage," Shawkey says. "This superblack plumage is enhancing the contrast with those bright-colored feathers nearby." —*Sid Perkins*

HEALTH TECH

#Flu

Mining social media to predict outbreaks

Forecasting influenza outbreaks before they strike could help officials take early action to reduce related deaths, which total 290,000 to 650,000 worldwide every year. In a recent study, researchers say they have accurately predicted outbreaks up to two weeks in advance—using only the content of social media conversations. The findings could theoretically be used to direct resources to areas that will need them most.

A team at the Pacific Northwest National Laboratory in Washington State gathered linguistic cues from Twitter conversations about seemingly non-flu-related topics such as the weather or coffee. Based on this information, the researchers nailed down when and where the next flu outbreaks were likely to occur.

The investigators used a "deep learning" computer model that mimics the layers of neurons and memory capabilities of the human brain. Their algorithm analyzed how Twitter language style, opinions and communication behaviors changed in a given period and how such changes related to later reports of flu outbreaks.

"The beauty of the deep-learning model we use is that it considers emotions and linguistic clues over time to predict the future," says computer scientist Svitlana Volkova, who led the study, which was published last December in *PLOS ONE.* Previous efforts to forecast flu outbreaks via the Internet—including studies that used Twitter and Wikipedia records and a project called Google Flu Trends—have scanned specifically for flu-related words. In contrast, Volkova's work examined 171 million general tweets and outperformed other models that were based exclusively on word searches or clinical data suggesting an imminent outbreak.

"Estimating flu in specific, localized populations pushes the limits of what we thought we could do [with social media], and it opens the door to new possibilities," says Mark Dredze, a computer scientist at Johns Hopkins University, who was not involved in the new study.

Epidemiologist Matthew Biggerstaff of the U.S. Centers for Disease Control and Prevention cautions that we are still in "early days" when it comes to flu forecasting. But researchers are increasingly looking to the Internet to supplement official data, which are limited to a small proportion of actual cases because many infected individuals do not seek medical care. Furthermore, such a tool might one day help identify flu trends in regions where public health data are not available at all. —*Rachel Berkowitz*

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

Why a Lethal Cancer Is on the Rise

Pancreatic cancer will soon be the second-biggest cause of cancer deaths

By Claudia Wallis

We can all be grateful that pancreatic cancer is pretty rare—accounting for about 3 percent of all cancers. Its toll, however, is another story. Five years ago it was the fourth-leading cause of cancer deaths in the U.S. Today it's number three and expected to soon overtake colon cancer for the number-two spot, right behind lung cancer. Even more frightening, this lethal condition is becoming more common. In the U.S., its incidence has crept upward by about 0.5 percent annually for more than a decade. France, Japan and Taiwan have all reported rapid jumps.

What's behind these trends? There are multiple intersecting factors at work. The rising rank in mortality is, in some ways, a good thing; it reflects advances in battling other malignancies. Better screening and treatment have meant that patients with other types of cancer—particularly breast, prostate and colon cancer—are living long enough to die of something else. Unfortunately, innovations such as immunotherapy have not worked well for pancreatic cancer, so along with liver cancer, it is causing an outsize and growing portion of cancer-related deaths.

The expanding caseload is a little harder to explain. Some of it, too, reflects progress: refined ways of testing biopsied tissue and higher-resolution imaging have meant that mystery tumors that once couldn't be seen or were labeled "of unknown origin" can now be identified, and some turn out to be pancreatic. The aging of our population also contributes: it's pushing up the rates of many kinds of cancer. The longer we live, the more we accumulate genetic errors that can cause tumors and the less effective our DNA cleanup crew becomes. In the case of pancreatic cancer, more than three quarters of new patients are between 55 and 84 years old.

Other forces are at work as well. Smokers face more than twice a nonsmoker's risk of pancreatic cancer, and even though smoking has slumped in the U.S., there is a 30- to 40-year lag time before we see a corresponding drop in cancer rates. In theory, pancreatic cancer should be waning, thanks to the dramatic falloff in smoking that began in the 1970s. But sadly, a new villain on the block is taking up some of the slack: soaring rates of obesity and type 2 diabetes, which are also risk factors.

Oncologist Robert A. Wolff has been treating pancreatic cancer at the University of Texas MD Anderson Cancer Center for 20 years. "Since I've been practicing, I've seen a shift from smoking to obesity as the driver," he says. "An average patient of mine has a body mass index between 30 and 35 [obesity is defined as 30 or more], has diabetes or prediabetes, is hypertensive and takes a lipid-lowering agent." Toss in a history of smoking, and such patients, he says, "are just time bombs for pancreatic cancer."

Obesity and type 2 diabetes raise the risk of many forms of cancer. Among the suspected reasons: chronic low-level inflammation, too much insulin, excess hormones and growth factors released by fat tissue, and metabolic abnormalities. Researchers are looking for early signs of pancreatic cancer in the blood or tissue of adults age 50 and older who were newly diagnosed with diabetes. Nearly 1 percent of such adults will develop the disease within three years, says Lola Rahib, a scientist at the Pancreatic Cancer Action Network, which supports the research. The challenge, she says, is to find biomarkers precise enough to avoid "costly and emotional" false positives and negatives. The quest for cancer blood tests—known as liquid biopsies—is one of the hottest areas in oncology, notes Otis Brawley, chief medical and scientific officer at the American Cancer Society, but there's a long way to go: "The tests reported so far have really terrible specificity."

Even if blood tests could someday detect pancreatic cancer at an early stage, treatment would have to improve a lot for them to do much good. Unlike many cancers that are curable if detected early, pancreatic tumors are quick to metastasize. "The cells break away like a crumbling popcorn ball," Brawley says. Still, some modest progress has been made. Five-year survival rates for pancreatic cancer have inched up from 6 to 9 percent in recent years.

Wolff believes that newer, precision medicine therapies will ultimately help his patients, particularly the 10 percent or so whose cancer is more driven by heredity than way of life. But the bigger message is prevention, he says: "It's thought that easily 30 percent of pancreatic cancer is preventable. Cutting back on obesity, better diets, more exercise, no smoking. What a concept!" SA

Illustration by Celia Krampien

David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Automotive Touch Screens Are Awful

New cars have amazing technology everywhere but the dashboard

By David Pogue

When I went car shopping recently, I was amazed by the autonomous technologies in most new models: automatic lane-keeping, braking to avoid collisions and parallel parking, for example.

But I was appalled by the state of *dashboard* technology. Technology sells, so car companies are all about touch screens and apps these days. Unfortunately, they're truly terrible at designing user interfaces (UIs)—the ways that you, the human, are supposed to interact with it, the car. A good user interface (*a*) is easy to navigate, (*b*) puts frequently used controls front and center, (*c*) gives clear feedback as you make a change and (*d*) is apparently beyond the capabilities of today's car companies. I asked my Twitter followers to help me nominate the World's Worst Car UI Designs—and I was flooded with responses. Here are some samples:

Harry Myhre writes that on the 2017 Cadillac XT5, there's no physical volume knob. You have to repeatedly tap a touch strip on the dash or a button on the wheel, neither of which is powered on until the system has booted. Same thing on the 2017 Honda Accord, says @RandyTaradash. "It annoys me to no end that I can't turn the car on without the ability to immediately turn down the radio." Similarly, "you can adjust wiper settings in a Tesla 3 only on the touch screen," writes @briantroberts. "The last thing I want to do when I can't see out of my car is find a button on a screen!"

The 2013 Subaru Crosstrek turns on its backup camera when you're in reverse. But @dfrctionspikes notes that when his phone connects via Bluetooth, a full-screen message appears—"Confirmed connection with the mobile telephone"—completely blocking the view from the camera! On the 2017 Nissan Leaf, you adjust the music volume with up/down buttons on the center console but right/left buttons on the steering wheel—and changing stations is up/down on the steering wheel but left/right on the console (notes @atmendez)! In the 2018 Subaru Outback, setting the clock requires—incredibly—19 steps. They're in three different places: you start on the center touch screen, move to the plastic buttons on the dashboard and then use the up/down/select buttons hiding behind the steering wheel (Elchanan Heller).

When you try to cancel navigation on a 2013 Volvo XC60, a touch screen message asks if you're sure. Your choices: "continue" or "cancel." "Five years of this, and I still have to stop and think," Mike Murphy says. If the 2016 VW Golf SE senses a car in your blind spot, a yellow icon lights up in the side mirror. Inopportunely, @aleidy points out, the turn signal also flashes a signal in the side mirror—in the same color! (We won't even get into how almost every modern car auto plays the first song alphabetically on your iPhone every time you plug it into the sound system. Dozens of people wrote to say how sick they are of hearing Ed Sheeran's "A Team" or "Aaron Burr, Sir" from *Hamilton*. A $1 song on the iTunes store—10 minutes of silence called "A a a a a Very Good Song"—has become a hit because it solves this idiotic problem.)

These people aren't just complaining about bad UI because it's constantly frustrating: in a car, bad UI is dangerous. Every second you spend searching a touch screen or button cluster and not focusing on the road is a second you are a death risk to yourself and others. Why can't car companies hire real app designers to clean up their UIs? Surely, in a world of several million phone apps, there are plenty of talented coders who could help. Heck, my 13-year-old can point out what's wrong with most of these cars.

There are small pockets of hope. For example, Ford's new CEO, Jim Hackett, is a disciple of Ideo (the Silicon Valley design firm responsible for the first Apple mouse, the Palm V organizer and the Swiffer). He set up Greenfield Labs within Ford—a group of designers, psychologists, anthropologists and data scientists who are collaborating with Ideo to bring human-centric design to cars.

Well, okay. Here's hoping their work bears fruit fairly soon. Because at the moment, the car companies' dashboard interfaces are a disaster. Or, to put it another way: you or I could do UI better. SA

SCIENTIFIC AMERICAN ONLINE
READ MORE ABOUT TERRIBLE DASHBOARD TECHNOLOGY:
scientificamerican.com/apr2018/pogue

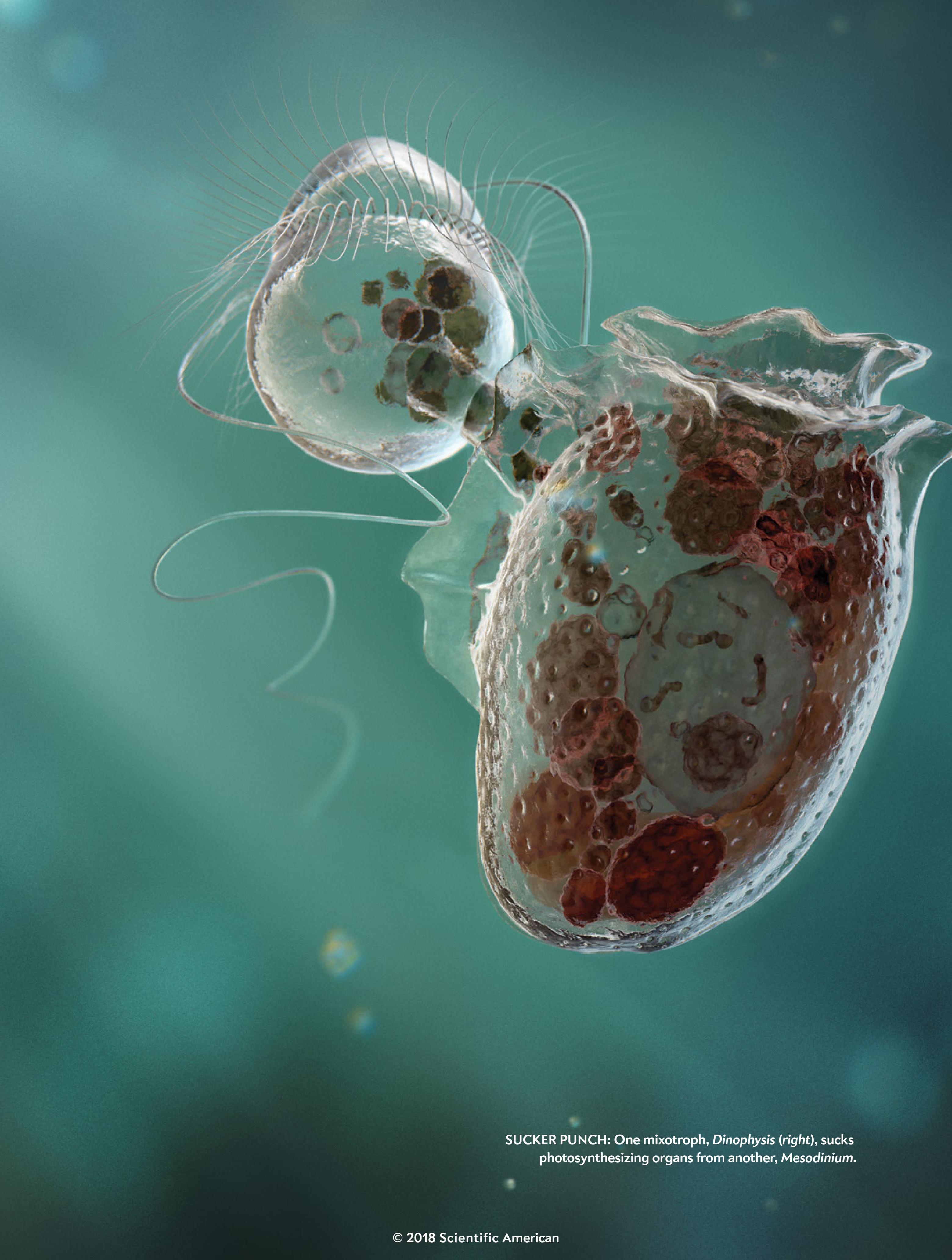
Illustration by Jay Bendt

THE PERFECT BEAST

Mixotrophs, tiny sea creatures that hunt like animals but grow like plants, can change everything from fish populations to rates of global warming

By Aditee Mitra

Illustration by Mark Ross Studios



SUCKER PUNCH: One mixotroph, *Dinophysis* (*right*), sucks photosynthesizing organs from another, *Mesodinium*.

Aditee Mitra specializes in mixotroph and zooplankton research and is a plankton systems dynamics modeler and a lecturer in bioscience at Swansea University in Wales.

SUMMER SUNLIGHT FLICKERS THROUGH WARM WATERS OFF THE COAST OF SPAIN. The sea looks calm and peaceful. Near the surface, invisible to the naked eye, a swarm of microscopic plankton, some orange-pink and others dark green, swim in lazy circles, capturing the sun's rays and using the solar energy to make nutrients through photosynthesis.

Suddenly, a tentacled creature called *Mesodinium*—at 22 microns, a giant next to some of the three-micron sun-gathering plankton—comes zigzagging through the waters, drawn by sugars and amino acids leaking from the smaller organisms. Its tentacles shoot out and engulf the hapless green prey, or nanoflagellates, which are completely consumed and digested.

The predator is pickier, though equally brutal, with its pink-colored prey, called cryptophytes. While it digests and destroys most pieces, the attacker takes in the organelles responsible for photosynthesis whole. Within minutes the pale *Mesodinium* starts to turn darker red as it fills its body with the stolen parts—chloroplasts and nucleosomes—which remain intact and functional. *Mesodinium* is not able to take in and use carbon dioxide as true photosynthesizers are, so it relies on its victims' chloroplasts to accomplish that task. The creature's dual strategy of hunting for food like an animal and photosynthesizing like a plant is known as mixotrophy.

Mesodinium does not, however, get to hold onto its loot for long. Nearby lurks yet another mixotroph, slightly larger and with different hunting skills: the dinoflagellate *Dinophysis*. It starts circling the other creature and then shoots out harpoonlike threads that immobilize the *Mesodinium*. The captor then administers the coup de grâce. It lances its target with an appendage called a peduncle, something that looks and acts like a straw, and sucks out the innards, including the stolen chloroplasts. These now third-hand photosynthetic factories are assimilated into the new host and begin churning away within the *Dinophysis,* giving it energy for life. Remnants of the original thief, the butchered *Mesodinium,* drift away.

These single-celled killers are only two examples of countless billions of mixotrophic plankton that swim in our seas. For a long time, most marine scientists dismissed mixotrophs as minor curiosities, compared with the two main groups of single-celled plankton that are supposed to dominate the base of the ocean's food web. One of these groups, plantlike phytoplankton, uses light energy and inorganic nutrients such as nitrates to proliferate. The other group, animallike zooplankton, eats these phytoplankton. In this way, nutrients are passed up the food web to bigger animals. Next to these two purists, mixotrophs were deemed to be inefficient oddballs, jacks-of-all-trades but masters of none. (There are some rare examples of mixotrophs on land, such as the carnivorous Venus flytrap plants.)

This traditional view of the ocean food web is wrong. Through experiments, observations and models of plankton populations, my colleagues and I have recently uncovered evidence that most single-celled plankton are neither purely plantlike nor pure plant eaters. The great majority are, in fact, mixotrophs. This means the bottom of the food web—and thus everything above it—is not controlled the way we thought it was. If most plankton are really mixotrophs, their numbers are not sharply limited by photosynthesis but can increase through eating. And solar energy, when available, can give an extra boost to eating-driven growth. These abilities have a ripple effect on many things, from the atmosphere to fish populations. Greater mixotroph activity, for instance, affects

IN BRIEF

The ocean food web—key to the earth's ecosystem—has been thought to depend on two groups: plantlike and animallike plankton.

But new evidence shows many plankton are "mixotrophs" that use solar energy like plants yet hunt and kill prey to live.

These hybrid creatures have giant effects on global carbon levels, fish populations and harmful algal blooms.

how quickly the oceans remove climate-warming carbon dioxide from seawater and air and lock it away in sea-bottom sediments. Mixotroph groups may be less susceptible to the waxing and waning of sunlight as seasons change. Such versatility and resilience have advantages. Populations of beneficial mixotrophs can provide sustenance for more fish larvae and increase the human food supply. But there can be negative consequences, too. Some mixotroph species cause harmful algal blooms that close shellfish hatcheries and lead to widespread fish kills.

If this new view of marine biology holds water—as recent findings by ourselves and other scientists have shown—it means the idea of an ocean ecology based on "plantlike" and "animallike" plankton is no longer tenable. There is a different, strange and powerful player amid the waves.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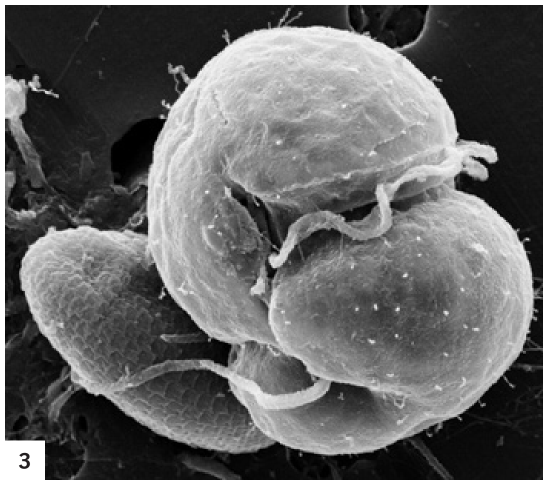
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TINY MONSTERS: Mixotrophs come in several varieties. Some, such as *Ceratium* (*Tripos*) *furca* (*1*), can photosynthesize on their own and eat prey. But members of the order Nassellaria (*2*) steal photosynthetic organs from plankton victims. Species of *Karlodinium* (*3*) act as *C.* (*T.*) *furca* does.

STEVE GSCHMEISSNER *Science Source* (*1*); FRANK FOX *mikro-foto.de* (*2*); VINCENT LOWKO *Mote Marine Laboratory* (*3*)

ATTACK OF THE TRIFFIDS

MIXOTROPHS are like something out of science fiction. The harpoons and peduncles of *Dinophysis* seem, on a smaller scale, like features of the planet-conquering plants in the famous 1951 sci-fi novel *The Day of the Triffids,* by John Wyndham. Triffids could use their roots to extract nutrients from the soil and to walk around. But they also had venomous stingers that they used like whips, blinding or killing humans and then feasting on the decomposing bodies.

The first time I heard of plankton mixotrophs was a little more than a decade ago, during my Ph.D. research on microzooplankton, which are smaller forms of animallike plankton. (The smaller plantlike organisms, likewise, are called microphytoplankton.) Textbooks described mixotrophs as a weird oceanic rarity. Yet with their dual ability to photosynthesize and hunt, combined in a single cell, mixotrophs appeared to be nature's perfect beasts. Because evolution tends to favor efficiency, it surprised me that mixotrophy was not more common. Searching for more information about it, I found a whole suite of exciting publications by Diane Stoecker, a plankton ecologist at the University of Maryland's Horn Point Laboratory, whose field and laboratory work suggested that mixotrophy existed among ocean plankton. I got in touch with Stoecker, and our discussions convinced me that more mixotrophs were out there. But how many, and what were they doing?

My own expertise is in building mathematical models of food webs to understand the behavior of different organisms in them. In essence, these are simulations that run on a computer. In searching through ocean ecosystem models, I could not find one that simulated the details of mixotrophs' double lives. Nor could I find funding for a project to build one; scientific review committees did not think mixotrophs were very important. So I spent my days working as a biodiversity officer for the local government in Bridgend, Wales, and in the evenings I worked on the model with my marine biologist husband, Kevin Flynn. By the spring of 2009 we had a working simulation, one that could represent different populations of mixotrophs, some hunting more and some doing more photosynthesis. It was published that year in the *Journal of Plankton Research*.

Our goal was to show that a model including dual-natured plankton could simulate marine ecology more realistically than other models that segregated ocean populations into predators and plants. We changed mixotroph characteristics in the model until we had simulations that captured real-life observations of nutrient flow within food webs, as well as interactions among other plankton types such as bacteria and tiny crustaceans called copepods. These food web dynamics, which we published in 2010 in the *Journal of Marine Systems,* were very different from the segregated plankton models.

We needed to go beyond computer simulations, however. We had to gather evidence supporting our hypothesis that mixotrophs were critical drivers of the ebb and flow of nutrients through all parts of the ocean and all creatures in it. This time there was money. Impressed by the success of our models, a foundation called the Leverhulme Trust supported a series of meetings in Europe and the U.S., where for the first time, researchers who worked with mixotrophs in the field and the lab could share what they knew.

A WORLD OF HYBRIDS

AT THE FIRST MEETING in 2011, our group (we dubbed ourselves "Team Mixotroph") made a list of all the plankton species known to both hunt and photosynthesize. Scientists had, over the course of decades, identified mixotroph species in water samples across all marine systems, from coasts to midocean areas and from the poles to the equator. They carried out experiments in labs onboard the research ships. And in some instances, they brought back the plankton to their institutes and carried out additional experiments using different nutrients, prey or light intensities to find out how the mixotrophs behaved under different environmental conditions. Until our group started combining these observations, most researchers thought they were looking at small and unusual occurrences rather than a common life-form throughout the world's oceans.

These scumlike blooms are not toxic, but they do block sunlight, putting a crimp in a nutrient cycle that feeds tiny fish larvae. Fewer blooms mean more fish.

Bringing these data together drove us to the conclusion that there was a lot of mixotrophy happening in the sea and that it was ecologically essential. For example, Per Juel Hansen, a plankton ecophysiologist at the University of Copenhagen, and his colleagues demonstrated that without sufficient cryptophyte prey (those pink plankton mentioned earlier), the *Mesodinium* population would not be able to acquire stolen chloroplasts and would die out. Stoecker and her team, as well as Hae Jin Jeong and his colleagues at Seoul National University, showed that when mixotrophs were actively photosynthesizing, they ate other plankton at higher rates than those that were not performing photosynthesis: one mode enhanced the other. And when light and nutrients were abundant, these particular mixotrophs had a much higher growth rate than did plankton stuck with only a single process.

In 2012 we started looking beyond the mere presence of mixotrophs in marine ecosystems and began to identify different groups based on what they eat, how they eat and how they photosynthesize. It turns out there are four distinct types, and each occupies a different place along a spectrum of mixed behavior.

The first criterion for discriminating among different types of mixotrophs was to identify the source of their photosynthetic abilities. Did they have an inherent capacity for using light to make food, or did they have to attack and steal photosystems from their prey? We called the group with their own genetic capabilities to produce and maintain the body parts for photosynthesis constitutive mixotrophs. This group includes a lot of benign and ecologically important creatures that are critical links in ocean food chains. But it also contains plenty of troublemakers. We see their effects in destructive algal blooms when their populations get out of hand. For example, the mixotroph *Karlodinium* is renowned for causing massive fish kills across the world, from the Chesapeake Bay to Malaysian coastal waters. *Prymnesium,* another constitutive mixotroph that has caused similar fish kills off the coast of Texas and in the backwaters of the Norfolk Broads in England, releases a chemical that destroys the integrity of cell membranes belonging to competing plankton. As a result, these plankton swell up and explode. Then *Prymnesium* consumes the debris. Toxins produced by another species, *Alexandrium,* make their way into mollusks as those animals ingest plankton-laced water. Entire oyster, mussel and clam fisheries are then closed because humans who consume seafood contaminated with *Alexandrium* can get paralytic shellfish poisoning.

The second group does not have inherent photosynthetic capabilities and has to hijack them. These are called nonconstitutive mixotrophs and include *Mesodinium* and *Dinophysis*. This group is a big collective. Its members' use of photosynthesis had been considered a supplemental survival mechanism employed only when there was not a lot of prey around. Now we realize that they harness solar energy much more often, and it is usually a crucial part of their way of life.

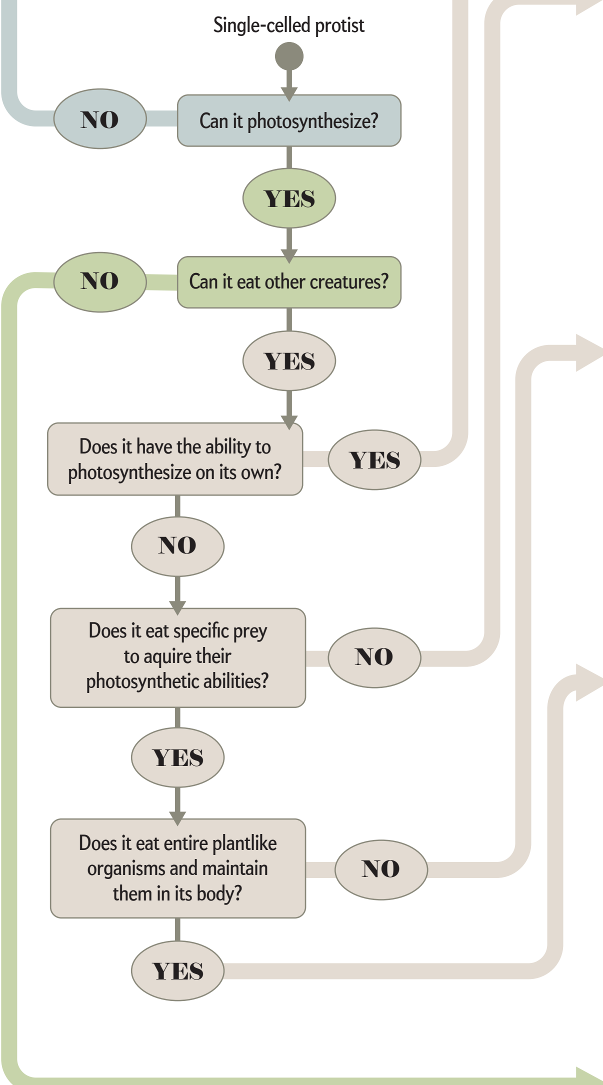
The nonconstitutive mixotrophs can be subdivided into generalist and specialist species. The plastidic ciliates *Laboea* and *Strombidium,* for instance, are generalists that steal chloroplasts from many different types of plankton. Generalists cannot maintain these looted parts for more than a few days and must constantly attack new prey for replacements. They tend to be helpful mixotrophs, contributing nutrients to food webs that support fisheries, and thus play a key role in global food security.

Specialists, on the other hand, depend solely on a particular type of prey and seem to be better equipped by evolution to integrate stolen photosystems into their own physiology; they can maintain their pilfered assets for weeks to months. Some, such as *Dinophysis,* can be harmful to humans. Shellfish exposed to *Dinophysis* can give people life-threatening food poisoning, and large blooms, such as some that have occurred in the Gulf of Mexico, have closed oyster farms.

Some specialists can be split off into yet another group with a remarkable kind of behavior. They do not just steal body parts, like *Mesodinium* does, but instead take in and enslave entire colonies of photosynthetic prey. The colonies live and proliferate within the

A New Plankton Menagerie

Microplankton, single-celled marine organisms, are one of the most critical forms of life on our planet, sustaining our global food web. Scientists used to think they were like either plants or animals. New evidence indicates most microplankton really live as mixotrophs: they combine plantlike photosynthesis with animallike hunting and eating in a variety of strategies. Now, to classify a single-celled plankton (also called a protist), biologists ask a series of questions:



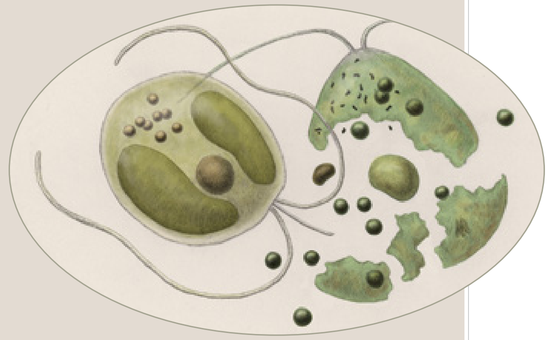
Microzooplankton

These creatures have no plantlike abilities to sustain themselves with photosynthesis and so must eat other plankton to survive.

Mixotrophs

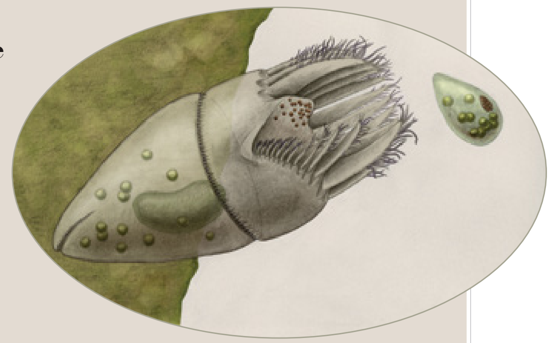
Constitutive Mixotroph

These predatory cells have physiology that also lets them use sunlight and nutrients to create energy. *Prymnesium parvum,* one such creature, is seen here attacking *Dunaliella tertiolecta*.



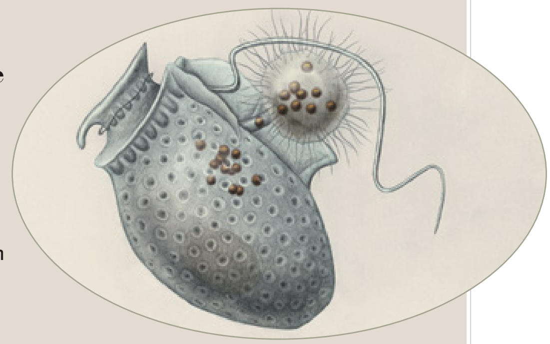
Generalist Nonconstitutive Mixotroph

These creatures use photosynthetic organelles taken from a variety of prey. Here *Strombidium oculatum* is stealing a body part from one victim, a member of the genus *Ulva*.



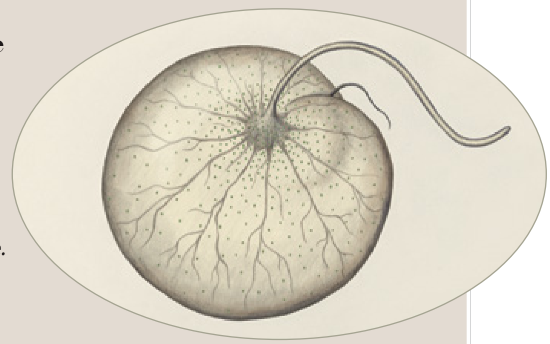
Plastidic Specialist Nonconstitutive Mixotroph

These predators steal parts from specific victims, killing them in the process. *Dinophysis acuminata* is seen sucking organelles from *Mesodinium rubrum.*



Endosymbiotic Specialist Nonconstitutive Mixotroph

Creatures in this group keep colonies of photosynthesizing prey within their body. Here *Noctiluca scintillans* is filled with *Pedinomonas noctilucae.*



Microphytoplankton

Organisms in this group act like land plants, surviving through photosynthesis.

SOURCE: "DEFINING PLANKTONIC PROTIST FUNCTIONAL GROUPS ON MECHANISMS FOR ENERGY AND NUTRIENT ACQUISITION: INCORPORATION OF DIVERSE MIXOTROPHIC STRATEGIES," BY ADITEE MITRA ET AL., IN *PROTIST,* VOL. 167, NO. 2; APRIL 2016

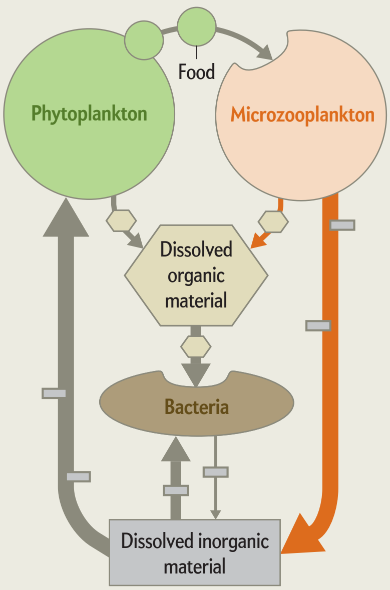
Illustration by Rebecca Gelernter

The Mixotroph Effect

When scientists include mixotrophs among ocean plankton, rather than assuming plankton are either purely plantlike or animallike, their categorization results in big changes in the way that nutrients move through a food web and when populations of important microorganisms grow and shrink. Researchers learned this after they modeled the traditional two-type plankton ecology and compared it with a new model that included mixotrophs that plunder other plankton for photosynthesizing parts. The scientists also created a third model with mixotrophs that have innate photosynthesizing ability. The results of both mixotroph models more closely matched real-world observations than did the old, traditional model.

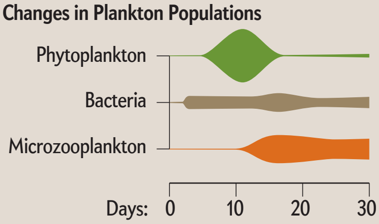
Traditional Scenario

Phytoplankton use solar energy and inorganic material to make food, and microzooplankton eat the phytoplankton. Marine bacteria then break down released organic material—waste products—for reuse. It is a tight cycle that limits population sizes.

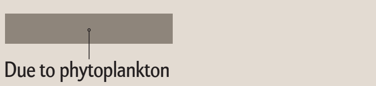


CLASSIC ONE-TWO SEQUENCE
Traditionally, over a 30-day cycle, phytoplankton (*green*) bloom first. Only then can predatory microzooplankton (*orange*) eat enough to increase their own group size. This hunger, of course, depletes the phytoplankton.

Changes in Plankton Populations

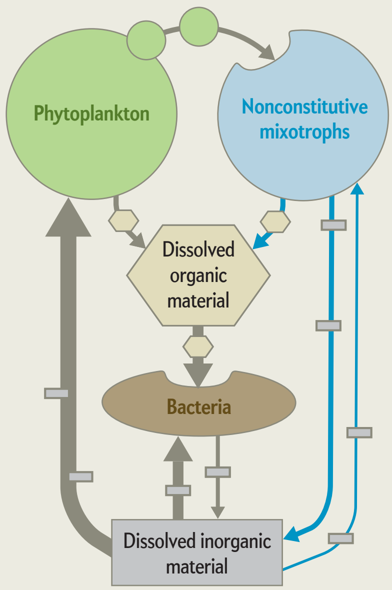


Carbon Dioxide Removed from Seawater
(Total: 30 grams of carbon per square meter)



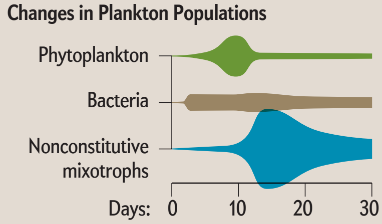
Photosynthetic Animals

When animals that can also photosynthesize, the nonconstitutive mixotrophs, substitute for purely animallike microzooplankton, their hybrid abilities let them retain more nutrients. The thin blue arrow leading away from that group indicates less nutrient loss.

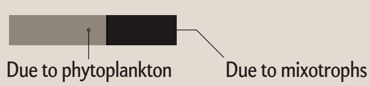


POPULATION BOOM
Nonconstitutive mixotroph populations (*blue*) can grow larger than traditional predators because they eat and also gain energy from stolen photosynthetic plankton parts. But growth tails off after they run out of parts to steal.

Changes in Plankton Populations

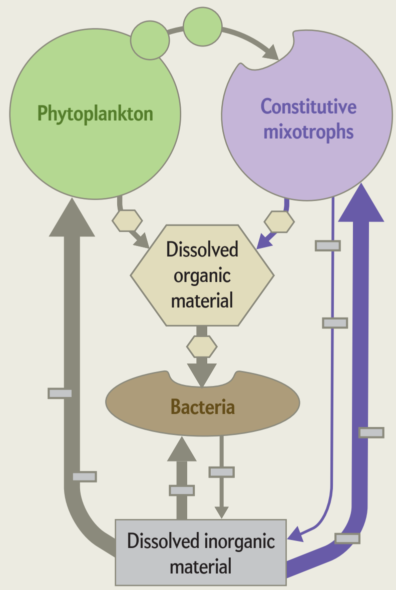


Carbon Dioxide Removed from Seawater
(Total: 30 grams of carbon per square meter)



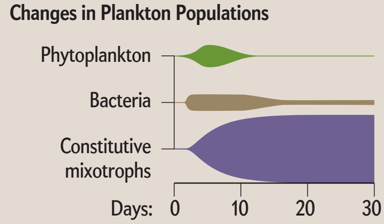
Plants That Eat

Replacing traditional microzooplankton with plants that can hunt, the constitutive mixotrophs, leads to a different population pattern. They can utilize lots of inorganic material, shown by the wide purple arrow, and act as predators. This sustains the group for an extended period.

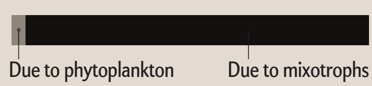


SELF-SUFFICIENT GROWTH
With innate photosynthetic abilities, constitutive mixotrophs (*purple*) need just a little help—extra food—from traditional phytoplankton to grow. Their population increases early and stays big through 30 days.

Changes in Plankton Populations



Carbon Dioxide Removed from Seawater
(Total: 65 grams of carbon per square meter)



SOURCE: "DEFINING PLANKTONIC PROTIST FUNCTIONAL GROUPS ON MECHANISMS FOR ENERGY AND NUTRIENT ACQUISITION: INCORPORATION OF DIVERSE MIXOTROPHIC STRATEGIES," BY ADITEE MITRA ET AL., IN *PROTIST*, VOL. 167, NO. 2; APRIL 2016

Graphic by Jen Christiansen

host, feasting on nutrients and enjoying protection from outside predators. These planktonic greenhouses include microorganisms called foraminiferans and radiolarians and are found throughout the oceans. Over hundreds of millions of years, foraminiferans have played a vital role in the global biological carbon pump, taking in large amounts of the element, sequestering it when they sink to the seafloor and later releasing it in smaller amounts as they decompose. Analyzing ancient layered deposits of foraminiferans has helped us to assemble records of past climate changes and to link them to mass extinction events. Not all these floating greenhouses are harmless, however. One type, the green *Noctiluca* species, is capable of causing harmful algal blooms in polluted coastal waters.

GLOBAL REGULATORS

FROM PLANTS that eat to animals that photosynthesize and from tiny two-micron organisms to relatively large one-millimeter plankton, mixotrophs span a wide range of ocean life. Why does this matter? Because it turns out that small organisms can have a variety of large impacts.

There is, for instance, an enormous nutrient-scarce area covering thousands of square kilometers in the middle of the central Atlantic Ocean. Scientists used to think that phytoplankton competed with marine bacteria for dissolved inorganic nutrients such as iron and phosphates in this area, which did not leave much to go around. But Mikhail Zubkov, a microbial biogeochemist then at the National Oceanography Center in England, and his colleagues found a sizable population of constitutive mixotrophs—the ones that do their own photosynthesis—in this area when they sampled the waters during research cruises.

From these observations, Team Mixotroph developed two food web simulators. One was based on the traditional model of plant-bacteria competition, and the other added the mixotrophs. The team found that the mixotroph simulation was the one that best matched the nutrient amounts and cycles that Zubkov had observed. Instead of competing with plantlike phytoplankton, the bacteria grew using sugars and other nutrients that leaked out of the mixotrophs. Then the mixotrophs turned around and ate the bacteria, which gave them more phosphates and iron than they could pull from the seawater. And the model only fit observations if the mixotrophs were constitutive.

There was another key effect. With mixotrophs, and not traditional phytoplankton, the levels of carbon fixation—carbon dioxide taken out of seawater by the organisms—were significantly increased. The finding suggests that if these hybrids were not around, global amounts of carbon, which contribute to planetary warming, might be even higher.

Mixotrophs are especially important in coastal seas, where their effects on fisheries can be profound. In 2017, using a North Sea plankton model with mixotrophs of varying types, we found that when small mixotroph species eat marine bacteria, their populations grow larger, and as a result, they can outcompete other plankton that tend to form algal blooms. These scumlike blooms are not toxic, but they do block sunlight, putting a big crimp in a nutrient cycle that feeds tiny fish larvae and helps them to grow. Fewer blooms means more fish.

For fish health, it is also important that mixotrophs, as our observations have shown, turn out to be the dominant plankton form during summers. Pure plantlike plankton grow in the spring but then decline, so delicate fish larvae cannot depend on them. But mixotrophs are still around, and they are good, rich food that sustains the fish during this period.

A DUAL FUTURE

MIXOTROPHS ARE AT THE CENTER of so much in marine science, be it climate change and fisheries projections, reconstructing ancient time lines of carbon cycling or predicting destructive algal blooms. The challenge now is to use both real-time observations and our models to establish what the different mixotroph groups are doing in different locations during different seasons. This is important because as our climate changes, we need to know which environmental conditions would lead to a bloom of the toxic *Karlodinium,* or the ecologically damaging, green *Noctiluca,* or the fisheries-sustaining plastidic ciliates. We have very recently completed the first steps toward this goal, mapping the presence of different mixotroph groups across the global seas. We next need to measure population sizes during varying seasons because changing light and temperature drastically affect their growth and proliferation.

There are still marine scientists who point out these conclusions rest on our simulations as much as they rely on real-world observations, and that is a valid critique. It is why we need to get more scientists to examine mixotroph activity beyond the lab, out on the high seas.

Last year I applied to the European Commission for a grant to train scientists to do this work. In stark contrast to my fellowship application 10 years earlier, this grant was funded, with glowing comments from scientific reviewers. Our expanding Team Mixotroph will be able to bring the next generation of marine researchers up to speed. Together we hope to figure out the many ways in which the oceans' perfect beasts may control our imperfect world. SA

MORE TO EXPLORE

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Defining Planktonic Protist Functional Groups on Mechanisms for Energy and Nutrient Acquisition; Incorporation of Diverse Mixotrophic Strategies. Aditee Mitra et al. in *Protist,* Vol. 167, No. 2, pages 106–120; April 2016.

Mixotrophy in the Marine Plankton. Diane K. Stoeker et al. in *Annual Review of Marine Science,* Vol. 9, pages 311–335; January 2017.

FROM OUR ARCHIVES

The Basis of Aquatic Life. Leon Augustus Hausman; December 1924.

scientificamerican.com/magazine/sa

MEDICINE

The Cancer Tree

Evolutionary studies indicate that the genetic changes enabling a cancer to develop arise shockingly early within the primary tumor. This discovery points to a promising new approach to therapy

By Jeffrey P. Townsend

Illustration by Marcos Chin

Jeffrey P. Townsend is an associate professor of biostatistics at the Yale School of Public Health and of ecology and evolutionary biology at Yale University.

BIOLOGISTS HAVE LONG BEEN STUDYING GENES TO UNDERSTAND THE HISTORY of branching on the tree of life, which unites all living creatures on earth—be they marmosets or microbes. One leaf on this sprawling ancestral tree, nestled among the apes, is *Homo sapiens*. Each individual in our species is an assemblage of cells, which cooperate to generate our body.

IN BRIEF

Evolutionary trees of genetic mutations reveal the history of a cancer, as well as how carcinogenic cells in different tissues relate to one another.

Early mutations in certain "driver" genes appear to be responsible for the formation of both the primary and the metastatic tumors.

Cancer therapies targeting driver genes that are mutated early might prove to be the most effective.

In the future, evolutionary trees of mutations in individual patients may indicate strategies to treat resistant cancers.

Normally the cells obey a covenant, established by trial and error more than 600 million years ago, in the first forms of multicellular life. The covenant decrees that if cells are to live together, they have to follow basic rules: repair their DNA when it is damaged; listen to their neighbors about whether to divide or not; and stay in the tissue where they are supposed to be. Typically mutations that cause cells to violate these restrictions and start to grow and spread incessantly—the hallmarks of malignant cancer—are quashed by controlled death. The mutated cells detect their own problems and commit suicide or are killed by the immune system before they can do any harm.

On occasion, though, mutations accumulate against which the cellular surveillance system does not work, and tumors grow and spread. A malignant evolutionary tree sprouts within.

Researchers know of a few mutations that drive tumorigenesis, the formation of the initial tumor. What makes cancers particularly lethal, however, is metastasis, the escape of diseased cells from the primary tumor and into formerly healthy tissues, where they lodge to generate new tumors. In the belief that further mutations were required to propel metastasis and that these occurred relatively late in the history of the primary tumor, oncologists often sought to identify them and to target them with drugs.

Around 2010, however, technological advances enabled scientists to inexpensively sequence the entire human genome (that is, to deduce the genome's ordering of bases, or constituent units of DNA). Research groups at several institutions began to study the genetic sequences of tumors comprehensively. To their dismay, the investigators found that even within a single patient, the tumors often contained a baffling variety of mutations.

Evolutionary biologists such as me see diversity as a source of valuable information, however. Along with colleagues at Yale University and other institutions, I decided to investigate how the mutations were related to one other. We sequenced the expressed portions of the genomes—those sections of DNA known to control the production of proteins and thereby to determine the properties of cells—of cancer patients. Further, we used that information to create evolutionary trees of the mutations associated with the disease. The branches of the trees illustrate how the genes within tumors change as the cancer grows from a few cells to a metastatic monster.

A TANGLE OF BRANCHES

OUR STUDIES REVEALED that the branches linking the primary tumors to metastases within a patient sprout profusely and seemingly randomly, one from the other, like the branches of a mythical poison tree. Even more surprisingly, the first branches of this evolutionary tree can emerge from deep within the ball of the original tumor. Distinct cells in the primary tumor can be ready to evolve into more aggressive forms—each with its own genetic mechanisms for spreading—many years before the initial tumor is first diagnosed.

These findings are scary but also offer new hope. They imply that instead of concentrating on later mutations, cancer researchers should preferentially study genes that are altered early in the primary tumor, or seed, that gave birth to the cancer tree. Targeting these mutant genes with drugs might give patients a better chance of recovery.

A linear model has guided cancer research for decades. It states that a specific series of mutations lead to tumorigenesis. Only after that do some cells in the primary tumor acquire one or more further mutations that endow the ability to metastasize. If one could construct an evolutionary tree of the mutations, it would resemble a typical grass: tall, straight and possessing a single core from which, near the very top, a few leaves and seeds would emerge.

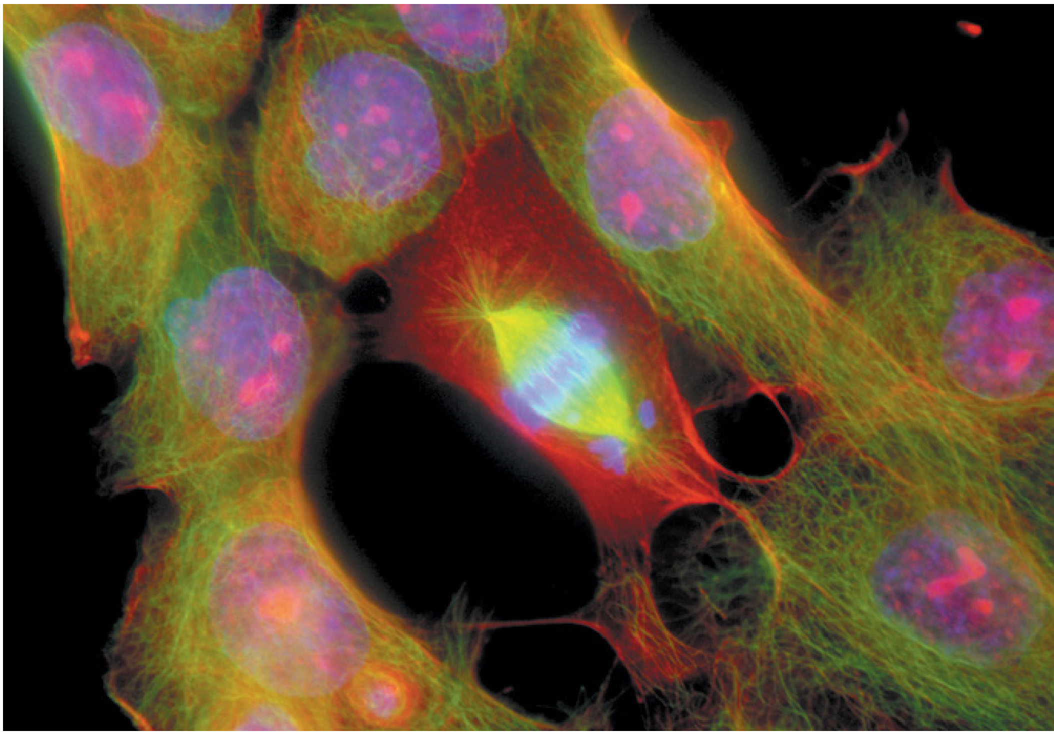
This theory does not square with what evolutionary biologists know about the history of life-forms. Ongoing mutation and selection propel organisms to constantly diverge from one another, generating a diversity of genetic lineages rather than a single, homogeneous population. Indeed, early studies by Marco Gerlinger of the Institute of Cancer Research in London and others hinted that even within primary tumors, different regions of tumor cells had different genetic sequences.

In 2010 members of my laboratory at the Yale School of Public Health and I, along with pathologist David Rimm, geneticist Richard Lifton and pharmacologist Joseph Schlessinger, all at the Yale School of Medicine, set out to answer three questions raised by these observations. First, are one or more specific mutations necessary for metastasis and present in all patients? Second, can metastatic lineages diverge relatively early in the history of the primary tumor, before most mutations have accumulated? Third, if we discovered a diversity of mutations in primary tumors and metastases, could we use evolutionary trees to calculate when they tend to occur? Answering these questions would reveal the genetic trajectories leading to the birth of the primary tumor and its metastases.

POISON FRUIT

WE HAD NO IDEA how powerful our evolutionary tools would turn out to be. Rimm obtained autopsy tissues from primary and secondary tumors, as well as from neighboring healthy parts of the affected organs, of 40 patients who had died of 13 different types of cancers. For each sample, our team sequenced all parts of the genome that are known to be expressed in any tissue and at any time. Our studies revealed anywhere between dozens and thousands of mutations that were different between the germ-line, or normal, genetic sequence of the patient (which he or she had inherited from a single fertilized egg) and one or more samples of the cancerous tissues.

To understand how these samples related to one another, Zi-Ming Zhao, then a postdoctoral associate in my lab, constructed molecular evolutionary trees. This type of tree is used to understand our relationship with chimpanzees, gorillas and orangutans; the apes' relationship with other mammals; mammals' relationship with birds and other animals; and animals' relationship with fungi, plants and bacteria. Scientists compute these trees by comparing how organisms' traits (or the sequence of bases in their DNA) diverge from one species to another and by finding the most plausible graph in which each life-form in question has a place on a tree's branches.

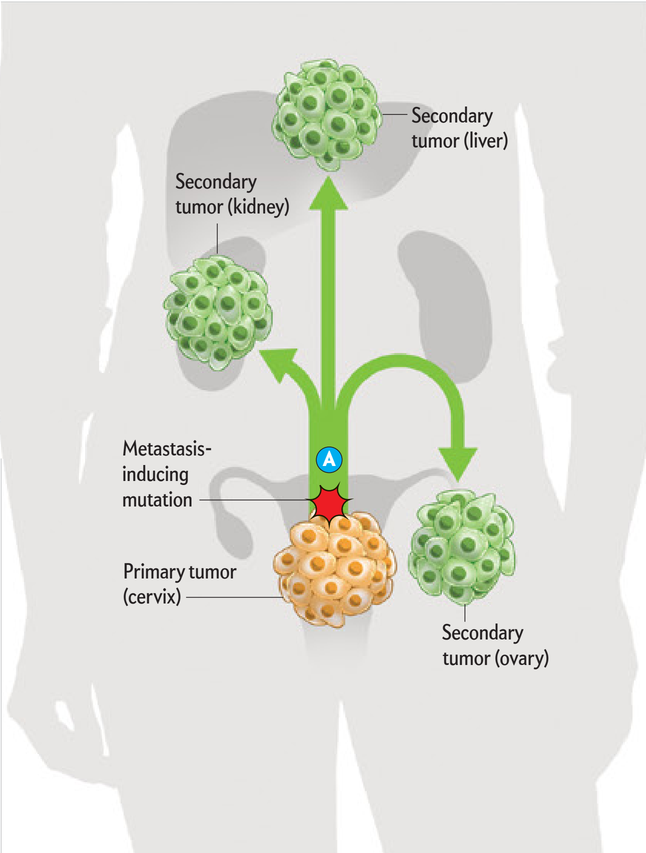


METASTATIC liver cancer cells, as seen in a polarized-light micrograph. In the center is a dividing cell.

JENNIFER C. WATERS *Science Source*

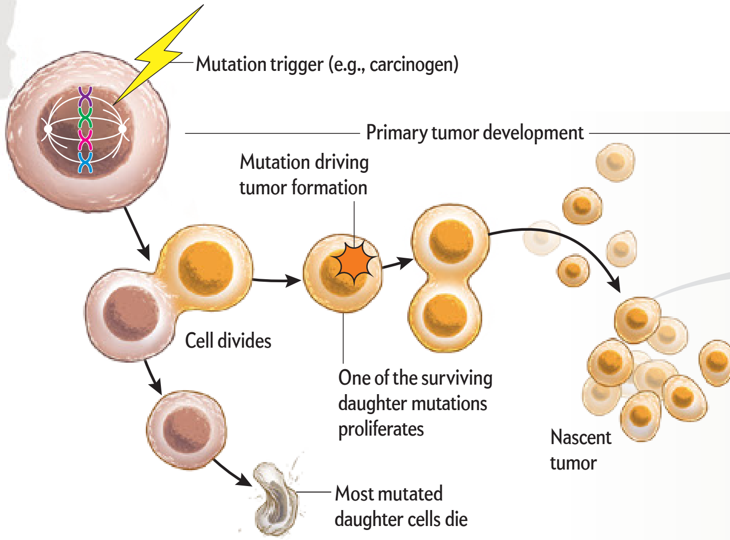
Applying these techniques to cancer is tricky, however. Ordinarily, we use only present-day sequences as data and figure out what we can about the ancestors with that information. In cancer trees, however, we know the sequence of the ancestor: it is the germ-line sequence obtained from healthy tissue. Without modification, traditional approaches would assume that the normal sequence was an additional "descendent" lineage—producing trees that did not reflect the history we were interested in. We modified the classical approaches, requiring the genetic sequence of the healthy tissue to be the ancestor of the primary and metastatic lineages, and computed the trees that were most likely to explain the succession of changes.

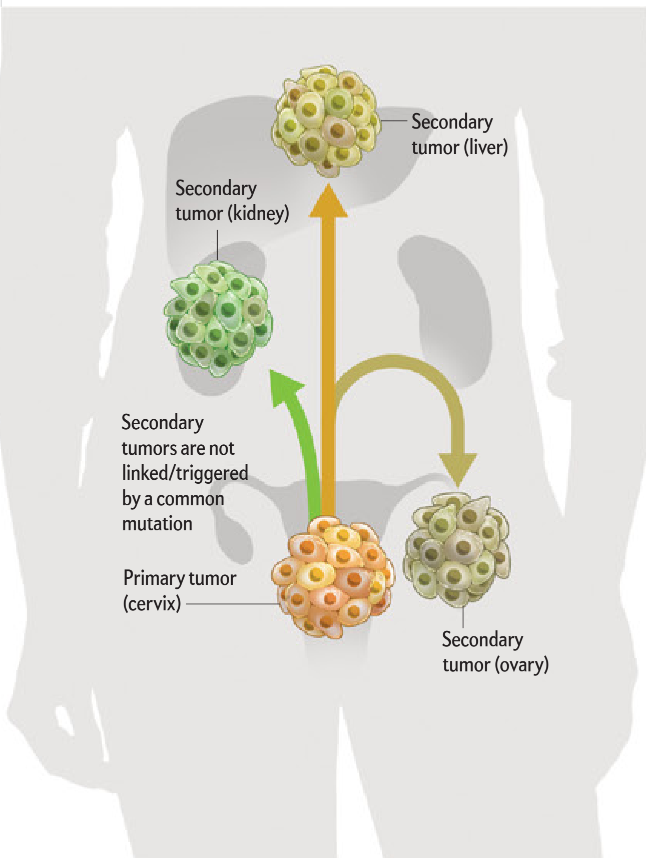
These reoriented evolutionary trees revealed something striking. According to the long-standing linear model, all metastases would descend from a single lineage of cells that broke free from the primary tumor and spread to other sites. If indeed metastasis occurred

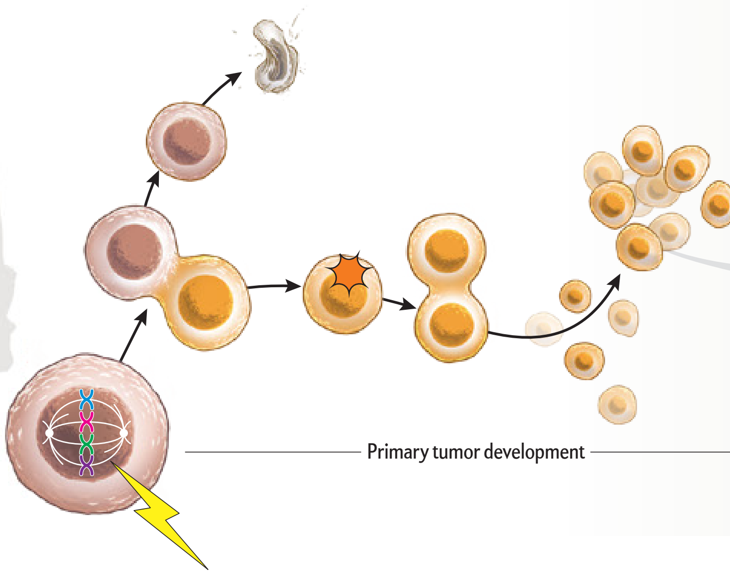


Linear Model

For decades cancer researchers have held that a specific series of mutations drive tumor formation. Only after those changes do some cells in the primary tumor acquire one or more further mutations that endow the ability to metastasize. If, for example, a tumor forms in the cervix, a single additional mutation (A) might enable metastasis, allowing cancer cells to spread to the liver, kidney or ovary. The linear model predicts that all the secondary tumors would descend from a single lineage of cells (B) that broke free from the primary tumor and spread to other sites.





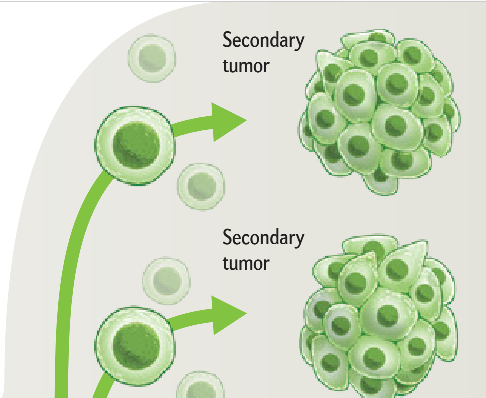


Branching Model

The author's evolutionary trees of cancer cells revealed that multiple genetic lineages (C) within the primary tumor lead to the secondary tumors. In consequence, metastatic tissues can be more closely related to the primary tumor than to one another. These findings suggest that instead of targeting genes hypothesized to prompt metastasis, oncologists might achieve better results by focusing on "driver" genes that seem to be responsible for both tumor formation and metastasis.

Linear or Branching?

What makes cancers particularly lethal is metastasis: the escape of diseased cells from the primary tumor into formerly healthy tissues. The linear model has long prompted oncologists to seek mutations they believed to be responsible for metastasis, which they then could target with therapy. The author's evolutionary trees of cancer cells in actual patients indicate, however, that the classic linear model does not fit the data. Instead of one or more key mutations inducing metastasis, the branches of the cancer tree that lead to secondary tumors sprout nearly randomly from the primary tumor. No mutations are specifically required for metastasis. These findings indicate that targeting genes that drive tumor development itself may prove to be the most effective strategy in cancer therapy.



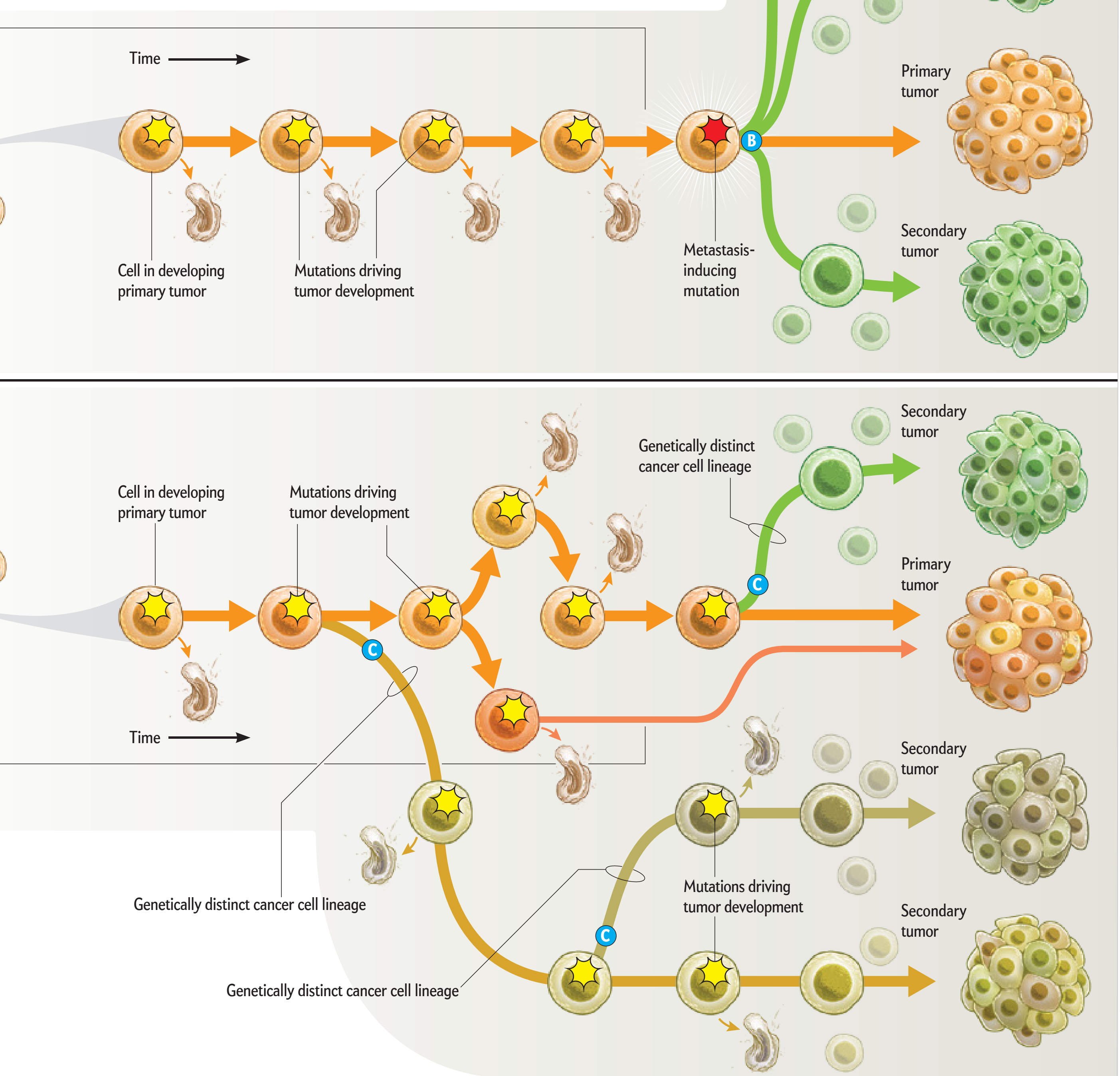


Illustration by Matthew Twombly

in this way—deriving from a final mutation in a single-file march of DNA changes—we would expect the genetic sequence derived from each secondary tumor to be more closely related to those of other secondary tumors than to any part of the primary tumor.

That is not what we saw. As we started studying the tumor "trees," we spotted patients whose primary tumor tissue was closely related to some metastatic tissues but not to others. The finding implied that not one but multiple genetic lineages within the primary tumor had at some point gone metastatic. In fact, this pattern showed up more than a third of the time in our core set of well-resolved trees.

TIME TREES

WE WERE STUNNED to realize that the classic linear model did not fit the actual data. Instead of a single, rare event inducing metastasis, the evidence indicated that the early genetic changes that jump-start tumor proliferation are also responsible for a lineage's ability to metastasize.

Furthermore, in cell lineages that evolved to metastases, we could finger no single gene as the culprit. Apart from the key genes already known to drive tumorigenesis (such as the *KRAS* gene, which is mutated in the primary tumors of almost every patient with pancreatic cancer), no particular gene in metastatic tissues was mutated in several patients. In fact, the mutations found in branches that led to secondary tumors were indistinguishable from those in lineages that never left the primary tumor. Factors other than mutation, such as epigenetic changes (alterations in how a gene is expressed) in a primary tumor cell—or the details of its microenvironment—were more likely to blame for metastasis.

Epigenetic modifications in a cluster of primary tumor cells, driven by, say, chance exposure to a carcinogen, might increase the cells' propensity to migrate. Also pertinent is the location of a particular cell with respect to other types of cells. For example, some tumor cells might spread through the body because they happen to be close to a blood or lymph vessel, whereas other cells with identical mutations might not because they are not close enough. These other factors potentially influencing metastasis may have little or nothing to do with the later mutations that show up in our evolutionary trees.

Once it was clear that divergent lineages within the primary tumor sometimes give rise to different metastases, we wondered how early in the patient's lifetime these metastatic lineages diverged. Our molecular evolutionary trees do not answer this question: the lengths of the branches correspond not to real time but to the number of mutations that distinguish different parts of the cancer, such as primary tumors from metastases. They do not tell us how long it took for one tumor to give rise to another.

We wondered if we could employ another technique from evolutionary biology—the construction of time trees—to understand the history of cancer progression within the human body. In contrast to a molecular evolutionary tree, the length of a branch in a time tree measures the amount of time that elapsed before one creature evolved from another. Such graphs, obtained by comparing the traits of interest (such as genetic sequences) and combining these with temporal information (such as mutation rates), enable scientists to measure when key changes occurred. They have been used on fossil data, for instance, to reveal the timing of the Cambrian explosion, when diverse multicellular life appeared nearly 550 million years ago.

Of course, we had no buried fossils to calibrate cancer evolution across someone's lifetime. We could, however, do even better. In many cases, we had primary tissue that had been extracted before autopsy. Furthermore, we had medical records for each case—providing the dates of birth, diagnosis, biopsy, surgical removal of a tumor and autopsy. These dates served as calibration points. The cancer could not have originated before the year of birth, for example, and must have existed when the primary tumor was diagnosed. And tissue from biopsies, as well as from tumors that had been extracted, gave us snapshots of cancer evolution. The corresponding dates allowed us to calculate the rate of mutation. We also accessed published data gathered in the past by radiologists on the rates at which cells in the primary tumor typically divide. (Radiologists have gathered this information to gauge the amount of radiation necessary to destroy a tumor by radiotherapy.)

Atila Iamarino, then another postdoc in my lab, used all this information to turn the molecular evolutionary trees into time trees. We got a first glimpse of how the evolution of cancer relates to the life span of a patient and to how long he or she had been treated. We could estimate, for example, when the first genetic mutation differentiating the cancer cells from healthy tissue arose. In young patients, this divergence typically occurred just a few years before diagnosis; in older patients, it could have taken place decades earlier.

DEEP ROOTS

THE FIRST MUTATION to genetically distinguish tumor tissue from normal tissue typically arose years—sometimes decades—before the cancer was diagnosed. Just as disturbing, in nine out of 10 of our subjects, at least one metastatic lineage had already diverged by then. In seven cases, this malignant branch had separated from the trunk closer to the time of the primary tumor's origin than to the death of the patient.

These observations struck us as deeply significant. Cells that proceed to metastasis can genetically differentiate from other cells in the primary tumor early in the evolutionary and temporal history of cancer. So early, in fact, that often they have diverged even before the primary tumor is diagnosed.

We had hoped to identify crucial metastasis-inducing mutations that would be suitable targets for pharmacological intervention. Because little was special about the genetics of the metastatic lineages, however, we turned our attention away from the branches and toward the evolution of the original tumor. We wondered whether the trunk of the evolutionary tree plays a special role in the origination of cancer. To answer this question, we examined whether mutations in this trunk were occurring in DNA that alters the cellular function of genes that were already known to play a role in cancer.

They were. For example, the well-known tumor suppressor gene *p53,* which inhibits the proliferation of cells, was mutated in many patients early in the evolution of diverse tumors. So was the proto-oncogene *KRAS.* (A proto-oncogene is a gene that, if mutated, becomes an oncogene, which prompts a cell to divide incessantly.) Almost every patient with pancreatic cancer, for example, had an early mutation at the 12th site of the *KRAS* gene.

The frequent presence of such key genes in the roots of cancer lineages implies that they play formative roles in the origin of tumors, as well as in their metastases. We speculate that as genetic drivers of tumorigenesis accumulate, the probability of metastasis becomes little more than a numbers game: the larger the number of cancer cells present, the greater the chances that they will find themselves at a location, or adopt an epigenetic state, that facilitates spreading.

Further studies are needed to clarify how these key genes might influence the chances of tumorigenesis and metastasis. Even so, the early drivers deserve redoubled attention. Drugs targeting them may be key to cancer treatment—both early in the development of primary tumors and in late-stage cancers.

REGROWTH

RECENT CLINICAL TRIALS have demonstrated that it is also possible to unleash the body's own immune system to destroy cancer cells. For both targeted drugs and immunotherapy, however, tumors seem to evolve resistance. Does resistance derive from specific mutations, as the primary tumor does? Or is it a symptom of the microenvironment and other factors, as metastasis appears to be? We do not yet know, but evolutionary trees can shed light on this question.

Our time-tree studies had revealed that some lesser-known genes that are also suspected to drive cancer were mutated, too, but those changes tended to occur later in the history of the disease. That is, they were not in the trunk but in the branches of the cancer tree—so that mutations in these genes were typically present only in some of the patient's tumors but not in others. In consequence, therapies directed toward such mutations, which some oncologists might prefer, could kill the mutated branch, but the remainder of the cancer tree would continue to proliferate and threaten the life of the patient. Doctors using such targeted drugs would do well to supplement them with treatments designed to kill other kinds of cancer cells as well.

On the other hand, if a drug targets an early mutation that is present in all of the cancer tissue, resistance might arise from the growth of cells featuring specific new mutations. Pathologist Katerina Politi of the Yale School of Medicine and her colleagues have identified changes to the *EGFR* gene—another major driver of cancer (in particular, lung cancer) when mutated—as indeed playing a significant role in resistance. To understand why and how resistance evolves as a patient is treated, our research group has begun to use evolutionary techniques. We are computing patients' cancer trees and scanning for mutations on the branches that lead to treatment-resistant tissue, such as a recurrent tumor. Excitingly, our preliminary studies suggest that resistance does seem to be driven by genetic changes that may derive from the kind of treatment the patient is undergoing.

We speculate that as genetic drivers of tumor formation accumulate, the probability of metastasis becomes little more than a numbers game: the larger the number of cancer cells present, the greater the chances that some will migrate.

Every year the number of therapeutic drugs developed to target specific mutations increases, as does the potential to prescribe complex combinations of traditional chemotherapy, radiotherapy and immunotherapy. No longer do oncologists regard one type of cancer as a homogeneous disease. Rather each case is its own entity. Studying the genomics of individual patients will have an enormous impact on cancer care in the future. To use these new tools wisely, oncologists will have to become de facto evolutionary biologists, examining the genetic variation present in each patient's cancer tissues and devising a strategy to destroy the cancer tree, root and branch. SA

MORE TO EXPLORE

Inferring the Origin of Metastases from Cancer Phylogenies. Woo Suk Hong et al. in *Cancer Research,* Vol. 75, No. 19, pages 4021–4025; October 2015.

Early and Multiple Origins of Metastatic Lineages within Primary Tumors. Zi-Ming Zhao et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 113, No. 8, pages 2140-2145; February 23, 2016.

FROM OUR ARCHIVES

How Cancer Spreads. Erkki Ruoslahti; September 1996.

The Circle of Life. Mark Fischetti; Graphic Science, March 2016.

scientificamerican.com/magazine/sa

PARKES OBSERVATORY, a radio telescope in Australia, made the first detection of a mysterious brief radio flare from the distant universe.

ASTRONOMY

Flashes in the Night

Astronomers are racing to figure out what causes powerful bursts of radio light in the distant cosmos

By Duncan Lorimer and Maura McLaughlin

ONE DAY IN EARLY 2007 UNDERGRADUATE STUDENT DAVID NARKEVIC came to us with some news. He was a physics major at West Virginia University, where the two of us had just begun our first year as assistant professors. We had tasked him with inspecting archival observations of the Magellanic Clouds—small satellite galaxies of the Milky Way about 200,000 light-years away from Earth. Narkevic had an understated manner, and that day was no exception. "I've found something that looks quite interesting," he said nonchalantly, holding up a graph of a signal that was more than 100 times stronger than the background hiss of the telescope electronics. At first, it seemed that he had identified just what we were looking for: a very small, bright type of star known as a pulsar.

ROBERT B. GOODMAN *Getty Images*

IN BRIEF

A strange burst of radio light from the distant cosmos mystified scientists when they spotted it in 2007.

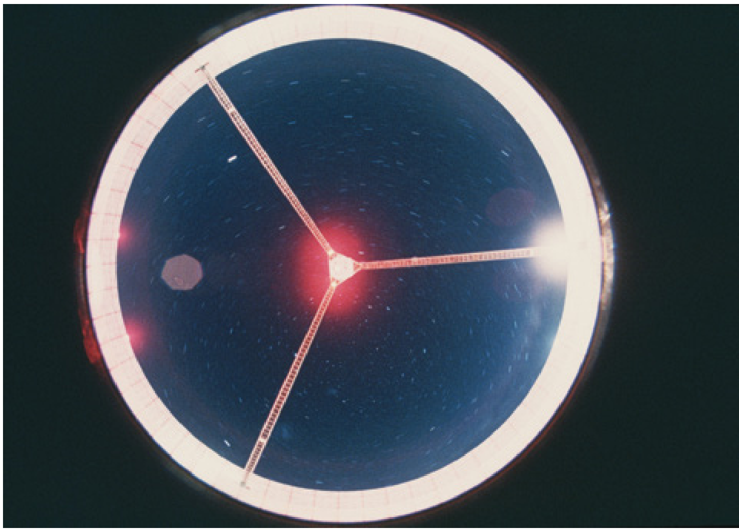
Astronomers doubted that the flash was celestial until they found similar blasts, dubbed "fast radio bursts."

A quest is on to discover more of these strange bursts and identify what causes them.

Theories include compact stars, supernovae and even exotic possibilities such as cosmic strings.

Duncan Lorimer is a professor of physics and astronomy at West Virginia University's Center for Gravitational Waves and Cosmology. His research interests are primarily focused on the demographics of pulsars and fast radio bursts.

Maura McLaughlin is an astronomer at West Virginia University. Her main research interests are neutron stars and their environments. She is currently chairing the North American Nanohertz Observatory for Gravitational Waves, which aims to use pulsars to detect gravitational waves.



LOOKING UP at the sky from the dish of the Parkes Observatory, astronomers view a field full of stars. After the initial Lorimer burst discovery, Parkes detected several more fast radio bursts.

ROGER RESSMEYER *Getty Images*

These dense, magnetic stars shoot out light in beams that sweep around as they rotate, making the star appear to "pulse" on and off like a lighthouse. Astronomers knew of nearly 2,000 pulsars at the time, and we were leading a hunt for distant and especially bright ones. The search relied on software that one of us (McLaughlin) and her graduate adviser had recently developed to search for individual pulses in radio observations. The code had to account for an effect called pulse dispersion, which works like so: as radio waves travel through space, free electrons floating in the interstellar medium will spread out the waves just like a prism spreads light. The free electrons act as a plasma through which the higher-frequency radio waves travel faster and arrive earlier at the telescope compared with the lower-frequency waves. The farther away a source is from Earth, the more electrons the radio waves will encounter on their journey, resulting in a greater time delay between the high- and low- frequency radio waves. Because we did not know how far away any new pulsars might be, the software scanned the data for signals that might fit many different possible amounts of dispersion, called dispersion measures, or DMs, so that we could be sure to catch pulsars at a range of possible distances.

At the time of Narkevic's discovery, he was analyzing five-year-old observations made by the Parkes radio telescope in Australia, which can survey large areas quickly by observing 13 positions on the sky—called beams—at once. He visually inspected the signals the software detected to weed out the more than 99 percent that were nothing but noise or human-made interference. The signal he found was perplexing not only because it was so bright but because it came from a region of sky a few degrees to the south of the Small Magellanic Cloud, where we would not expect any pulsars associated with the dwarf galaxy. Most surprisingly, the signal had a very high DM—many times higher than we would expect from something in the Milky Way and 50 percent higher than expected even if it were associated with the Small Magellanic Cloud. It suggested that the source was around three billion light-years away, well beyond our local group of galaxies.

If the burst really came from this far, it must have been emitted before dinosaurs roamed Earth. The finite speed of light and the short duration of the signal tell us that it cannot have come from something larger than 10 light-milliseconds across, or about 3,000 kilometers—much smaller than the sun's 1.4-million-kilometer diameter. Although a pulsar could fit within this size restriction, the amount of energy it emitted would have been more than the sun lets out in an entire month and over a billion times more than the brightest pulsar pulses.

What kind of object could be responsible for such a spectacle? Our first priority was to establish whether the pulse could have been produced by human-made interference. Unlike the flashes from pulsars, this one did not appear to repeat; we found only one pulse in the roughly two-hour observation. Still, closer inspection revealed that the arrival times of the pulse's various frequencies exactly followed the expected pattern for interstellar dispersion, a very unlikely coincidence for interference. Additional proof that this burst was astrophysical and not from a human-made radio signal was that it seemed to originate from a single spot on the sky. It showed up brightest in one of the 13 Parkes receiver beams, whereas three others detected it more faintly—precisely what we would expect for a celestial signal. Nearby human interference, in contrast, would typically appear in all 13 beams.

It seemed that Narkevic had actually stumbled on something totally new—a type of cosmic signal that would take up more and more of our research focus and puzzle the entire astronomical community. This odd signal, we figured, may not be the only one of its kind. Based on the duration and field of view of the Parkes observation, we estimated that several hundred such bright radio bursts could be going off all over the sky every day, unnoticed. Later in 2007 we published a paper positing that this event was the prototype of a new population of radio sources of unknown origin. We theorized that if we could identify and understand them, we could not only learn about a new type of cosmic event, but we could also estimate their distances through dispersion measurements and use them to do something as grand as map out the large-scale structure of the universe. But first we had to prove the burst was real—a quest that would take many surprising turns and almost end in retreat.

TRUTH OR FICTION?

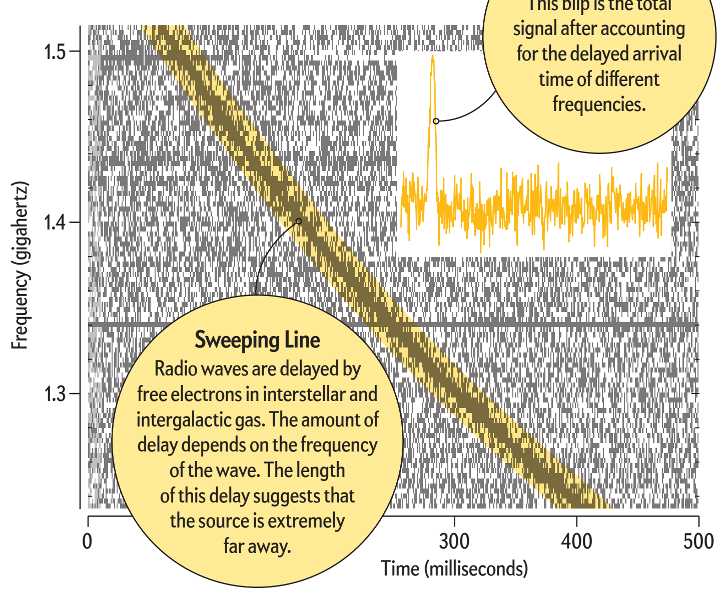
AT FIRST, OTHER RESEARCHERS WERE INTRIGUED by our discovery—quickly nicknamed the "Lorimer burst"—and began proposing explanations for its origin and searching for more like it.

Shortly after our discovery, Matthew Bailes of Swinburne University of Technology in Melbourne and one of the co-authors on our discovery paper, observed the Lorimer burst sky area for 90 hours using the Parkes telescope. But he found no evidence for any other flashes. This follow-up necessarily took place six years after the archival observation that showed the original burst, so it did not rule out the possibility of multiple bursts on timescales of hours or even years around the original observation.

So Bailes and his then doctoral student, Sarah Burke-Spolaor, conducted another search using more archival data from Parkes but in a different area of the sky. In a paper published in 2010 they reported finding 16 events that shared many characteristics with the Lorimer burst. In fact, some had nearly identical DMs and similar durations and pulse shapes. There was, however, a striking difference: every one of these newly discovered bursts appeared in all 13 beams of the Parkes receiver, strongly suggesting that they could not be associated with a source in space. Instead they must have originated from either the ground or the atmosphere—for instance, a lightning strike. To recognize the masquerading nature of these sources, Burke-Spolaor and Bailes dubbed them "perytons" after the mythical winged stag that casts a human shadow.

The Original Burst

This surprising signal, first spotted in 2007 and named "the Lorimer burst," seemed to represent an unknown type of cosmic flash. The inset box shows the brightness of the total radio light over time—the signal was here and gone in a moment. The sweeping line in the larger plot, shown against a background of static, shows the arrival time of the burst at different radio frequencies.



The discovery of perytons made many scientists skeptical of the Lorimer burst. As further radio surveys failed to capture any additional bursts, most astronomers began suspecting that the Lorimer burst was a peryton, too. The number of papers speculating on the nature of the signal started to wane. At one conference in 2011 there was even a show of hands to see what fraction of the audience believed that the Lorimer burst was real. One of us (Lorimer), sitting in the front row, did not dare to look back at the rest of the audience to see the result of the poll!

Four years after the original detection, McLaughlin, along with a postdoc and an undergraduate student, searched a large radio pulsar survey for more bursts. After not finding a single other similar event, even she began to doubt the Lorimer burst. In fact, she and her collaborators wrote a paper that claimed that it was unlikely to be astrophysical after all—a conclusion that feels embarrassing now.

But around this time the field was spectacularly reinvigorated. The first promising event came in 2012, when Evan Keane, now at the Square Kilometer Array Organization, headquartered in Manchester, England, happened on another highly dispersed burst in archival data from Parkes. In the meantime, Bailes had been leading an effort that upgraded the Parkes telescope with state-of-the-art digital instruments, providing unprecedented sensitivity to highly dispersed bursts. His passion paid off: in 2013 researchers found four more bursts with a wide variety of DMs in a new Parkes survey. In the paper that discussed the first results of this survey, led by doctoral student Dan Thornton, who was then at the University of Manchester, the scientists described the events as fast radio bursts (FRBs) in honor of their short durations. Crucially, unlike the perytons, these four bursts were detected in only one beam, making them consistent with an astronomical origin rather than Earth-based interference.

With those discoveries, the astrophysical nature of FRBs became increasingly certain. Then, in a moment of redemption and humor, a 2015 paper by Emily Petroff, then at Swinburne, and her colleagues showed that the Parkes perytons occurred predominantly around lunchtime, when impatient astronomers opened the on-site microwave oven before it was fully turned off. It was a great relief to verify that the timing of neither the Lorimer burst nor the other FRBs overlapped with the lunchtime habits of hungry scientists.

REPEATING FLASHES

SOON, THANKS TO DEDICATED SEARCHES at a number of telescopes by a growing community of researchers, more FRB sightings began popping up. The Green Bank Telescope in West Virginia captured one in a different frequency range of the radio spectrum than the Lorimer burst, providing more evidence that the burst was real and not the product of some peculiarity of the receivers tuned to the original frequency band.

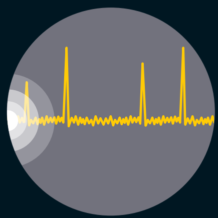
The plot thickened in 2016, when a team led by Laura Spitler

SOURCE: DUNCAN LORIMER

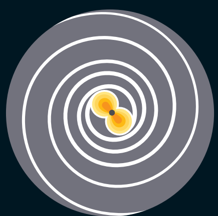
Graphic by Amanda Montañez

Possible Culprits

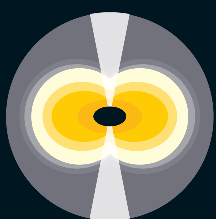
Scientists have several theories for what could be causing the Lorimer burst and similar flashes of radio light dubbed "fast radio bursts" (FRBs). Possibilities range from especially powerful versions of regular astronomical phenomena such as supernovae to exotic theoretical options such as cosmic strings. At least one FRB repeats and thus must be caused by a persistent source—but others could be one-off events.



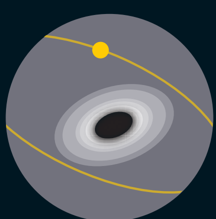
Giant Pulsing Neutron Star
Neutron stars, the dense remnants of dead stars, release light in sweeping beams that appear to pulse on and off as they rotate. A particularly powerful neutron star could be responsible for a fast radio burst.



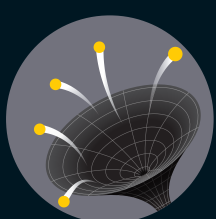
Colliding Neutron Stars
If two neutron stars hit each other, the bang could release a bright flash of light and produce a black hole or perhaps one really big neutron star.



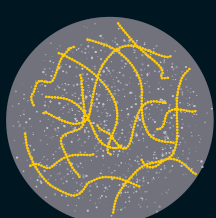
Energetic Supernova
When massive stars die, they collapse in an explosion called a supernova. Perhaps FRBs are especially energetic supernovae.



Magnetar Interaction
Highly magnetized neutron stars, called magnetars, release light powered by their magnetic energy rather than their rotation. If one of these was swirling around a black hole gobbling up matter (called an active galactic nucleus), the interaction could result in an FRB.



Evaporation of a Primordial Black Hole
Some theorists speculate that the big bang could have created primordial black holes sprinkled throughout space. If one of these spontaneously evaporated, a flash of radio light could result.



Cosmic Strings
These defects in spacetime are another exotic possible result of the big bang. If they existed, they could have sparked flashes as they interacted with the plasma that filled the early universe.

of the Max Planck Institute for Radio Astronomy in Bonn, Germany, reported detecting repeated flashes from a burst that had originally been seen in data taken in 2012 at the Arecibo Observatory in Puerto Rico. Until then, astronomers had generally concluded that these were one-off events. But some three years after the original discovery, known as FRB 121102, Spitler and her colleagues saw 10 additional bursts. The arrival times of these bursts do not seem to be periodic, and the radio pulses' precise duration and other characteristics vary.

This discovery triggered multiple campaigns of follow-up observations with radio telescopes worldwide. One of these used the Very Large Array (VLA) in New Mexico, a collection of 27 radio antennas observing in tandem, to regularly search for events on millisecond timescales in the same area of the sky as FRB 121102. This survey had the unique capability to pinpoint radio bursts' locations on the sky several orders of magnitude better than a single radio dish could. After roughly six months of observations, the team—led by Shami Chatterjee of Cornell University—discovered and localized a burst. Soon an even more precise location for this FRB came through the technique of very long baseline interferometry, where signals from multiple telescopes around the world are combined to synthesize a much larger virtual telescope with exquisite resolution on the sky. The finding, led by Benito Marcote of the Joint Institute for VLBI ERIC (JIVE) in the Netherlands and his colleagues, pinpointed the repeated bursts from FRB 121102 with an uncertainty of less than one arc second ($1/3{,}600$ of a degree).

This was the first time astronomers had found such a precise location on the sky for an FRB—which then led scientists to be able to find the source galaxy of the burst. A team led by Shriharsh Tendulkar of McGill University tracked FRB 121102 back to a dwarf galaxy that had a mass roughly 20,000 times as small as the Milky Way and that lay about 20,000 times farther than the most distant known pulsar. These findings established more firmly than ever before that FRBs are powerful and extremely distant phenomena.

SEARCHING FOR SOURCES

BY NOW WE HAVE ESTABLISHED that FRBs are real cosmic phenomena, but we still have a long way to go to figure out what causes them.

One major question is whether these bursts originate from one-time events—such as supernovae—or whether they come from enduring objects, such as pulsars that periodically emit bright flashes. The case of the repeating burst, FRB 121102, suggests the latter. Although it is the only FRB for which astronomers have detected multiple bursts so far, it is possible that *all* FRBs repeat and that the isolated bursts seen from others represent the very brightest of a distribution of energies. In that case, we would rule out single events and look toward persistent cosmic sources.

In this category, many scientists favor explanations involving compact stars such as pulsars. These objects result when a large star dies in a supernova, and much of its mass collapses in on itself. The density of this bizarre object becomes so great that even atoms cannot withstand the crush, and their protons and electrons smoosh together to become neutrons. The end product is a star about as wide as Manhattan made almost entirely of neutrons, called a neutron star. These stars rotate extremely quickly and send out light from two poles. The pulsars

Graphic by Nigel Hawtin

we have been discussing occur when these beams are pointed toward Earth and we see light pulsing on and off. The repeating bursts seen from FRB 121102 have properties that are broadly consistent with extremely energetic pulses emitted by a young neutron star. So FRBs could ultimately just be pulsars after all—albeit a rare and especially powerful form.

A closely related idea is the possibility that FRBs come from so-called magnetars: highly magnetized, slowly rotating neutron stars whose emission is powered by their magnetic energy rather than their rotation. One intriguing aspect of the VLA observations of FRB 121102 is the presence of a persistent bright radio light, distinct from the FRB bursts, in the host galaxy. Astronomers have speculated that this radio light is an active galactic nucleus—a supermassive black hole in the process of gobbling up stars and gas—and that the FRB is produced by the interaction between a magnetar and this nucleus.

A variant of this idea is that the repeating bursts are coming from a magnetar but one that is buried in the dense remnant of an explosion from a superluminous supernova (around 10 times more energetic than a typical supernova) that went off a few decades ago. One team of researchers noted that the host galaxy of FRB 121102 is similar to those that harbor a phenomenon known as gamma-ray bursts, which are thought to be connected to extremely young magnetars formed during superluminous supernovae. Very recently, this team measured the magnetic field along the line of sight to FRB 121102. These observations show that, regardless of its source, FRB 121102 must be located in a relatively highly magnetized region such as in a dense supernova remnant or around a supermassive black hole at a galaxy core.

We cannot rule out one-off events just yet, though. Perhaps some bursts repeat and some do not, indicating that different FRBs have a variety of originating sources. In fact, a new study led by Divya Palaniswamy, then at the University of Nevada, Las Vegas, showed that if all FRBs repeat at the rate observed in FRB 121102, then we should have seen multiple events in several other cases. It is therefore perhaps more plausible to consider that some FRBs originate in one-time cataclysmic events. This leaves us with a number of candidate sources.

At the top of the list is the collision of two neutron stars. Such a smash would likely release a powerful blast on contact as the two compact stars merge to form a single gargantuan black hole. A second possibility for a one-time event is the explosion of a particularly energetic supernova.

Theorists have also floated more exotic suggestions. One of these is the idea of cosmic strings—topological defects in space and time theorized to have formed in the early universe. These warps would have raced at light speed through the cosmos, which was then filled with hot plasma, producing sparks as they interacted with the plasma. Although the theory that those sparks are FRBs is not ruled out by the current observations, it is highly speculative. Scientists have also pointed to so-called primordial black holes—small black holes created by the birth of the universe that so far have not been detected. If one of these primordial black holes spontaneously evaporated, it could release radiation that might match an FRB signal. If either of these ideas proved true, the Lorimer burst would be the first observational evidence for these exotic phenomena.

MAPPING THE SKY

AFTER A DECADE OF WORK, the field of FRB science is now poised to enter a transformative phase thanks to new and updated telescopes. The wide-field-of-view Australian Square Kilometer Array Pathfinder opened in 2012 and soon began finding FRBs. As of this writing, 50 bursts are now known. Existing facilities such as the VLA and the Molonglo radio telescope at the University of Sydney are being refurbished to greatly enhance sensitivity and sky coverage. New and improved radio telescope facilities coming online now—the Canadian Hydrogen Intensity Mapping Experiment and China's Five-hundred-meter Aperture Spherical radio Telescope (FAST), among others—should significantly increase our sample of FRBs and provide a much better understanding of the source population.

Some of the new telescopes can localize FRBs with arc-second precision in real time, greatly enhancing our ability to locate them in the sky. This location information allows us to rapidly follow up with observations in other wavelengths to search for the burst's host galaxies. Even more exciting is that some models for FRBs, such as neutron star mergers, predict that they should also release gravitational waves.

Amazingly, astronomers can now detect these ripples in spacetime at the Laser Interferometer Gravitational Wave Observatory (LIGO), which made the Nobel Prize–winning discovery of gravitational waves for the first time in 2015. With this new technology, there is now a real possibility of jointly detecting light and gravitational waves from these sources. Such a detection would allow for measurements of FRB properties—such as the mass of the burst's source—that are simply not available through other means. We anticipate making major progress in finding and understanding these cosmic messengers very soon.

If we can indeed solve the mystery of the identity and origin of FRBs, we may be able to use these new signals for an ambitious project: to map out the universe. Astronomers are still in the early stages of tracking how matter is spread through space and visualizing the large-scale structures it forms. FRBs could give us a big leg up in our cosmic cartography efforts. They are the only extragalactic sources we know of that have short enough timescales to measure intergalactic dispersion and hence determine how dense matter is along our line of sight. The density in the intergalactic medium is a critical prediction of various models for the large-scale structure of the universe, so information from FRBs could allow us to test which models are correct.

Now that we have a global array of FRB detections all over the sky with independent distance measurements, this work will provide new tests of our fundamental understanding of how the cosmos formed and evolved. Narkevic's initial discovery has turned out to be "quite interesting," indeed. SA

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ENVIRONMENT

THE ARCTIC CLIMATE IS SHATTERING

MELTD

ICEBERGS launched from Greenland's fast-moving Jakobshavn glacier float past the town of Ilulissat under the midnight sun.

OWN

RECORD AFTER RECORD, ALTERING WEATHER WORLDWIDE

By Jennifer A. Francis

Jennifer A. Francis has been a research professor in the department of marine and coastal sciences at Rutgers University since 1994. She specializes in Arctic climate change and its links to weather worldwide.

TWENTY-FIVE SCIENTISTS, including me, had an epiphany about the Arctic in 2003. The National Science Foundation had invited us to a retreat in Big Sky, Mont. Before this gathering, each of us had been focusing our Arctic research on our own narrow topics. As we shared our perspectives, we came to a frightening realization: the changes we had been finding individually were connected. They fit together perfectly. The Arctic system as a whole was careening toward a precarious new state. And hope of stopping it already seemed unlikely.

We published a paper with a stunning, controversial conclusion: At the current rate of change, there was a real possibility that within a century, the world could witness a summer Arctic Ocean that would be ice-free, a state not seen for thousands of years. Today I am startled again because it now appears that the ocean will likely be free of summer ice by 2040—a full 60 years earlier than we had predicted little more than a decade ago.

The Arctic is changing exactly the way scientists thought it would but faster than even the most aggressive predictions. The recent behavior is off the charts. In just three years more than a dozen climate records that had each stood for many decades have crumbled, including those for disappearing summer sea ice, decreasing winter sea ice, warming air and thawing ground.

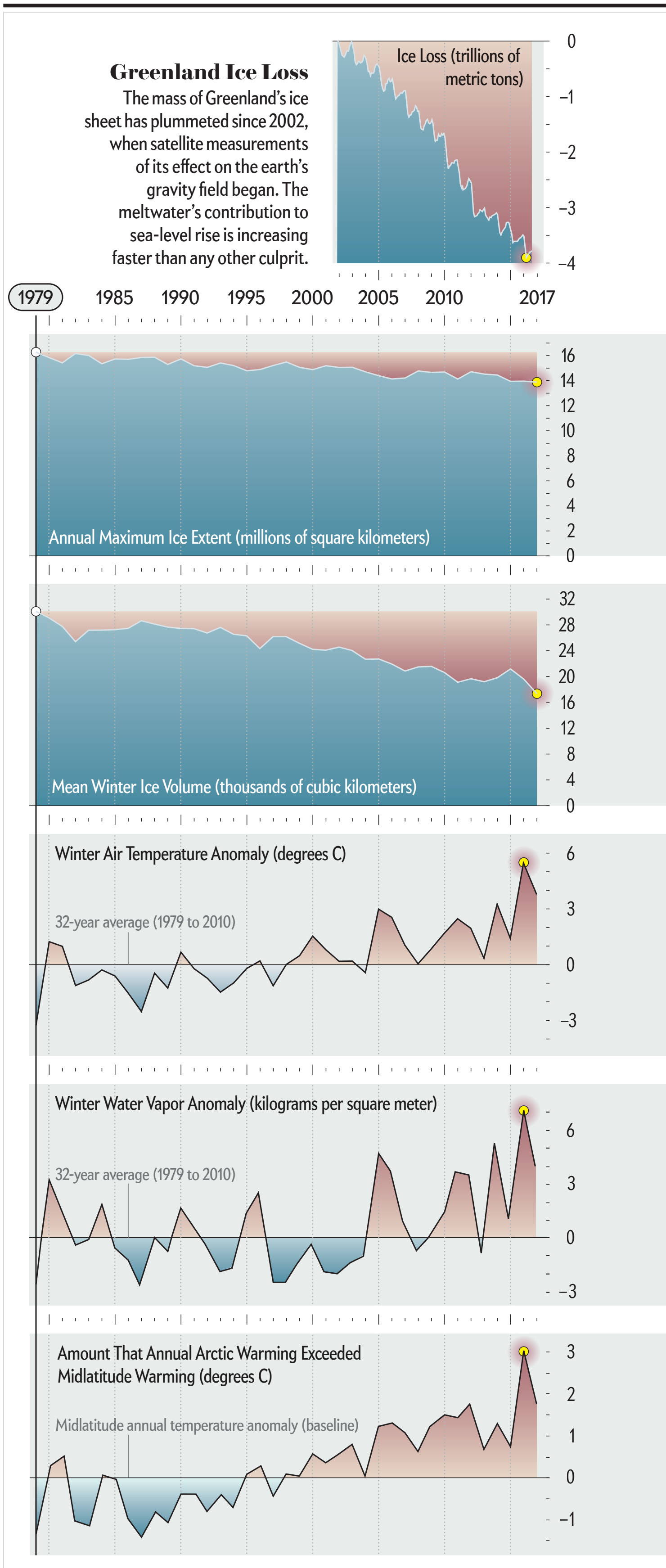
These trends signal trouble for people around the world. The last time the Arctic was only slightly warmer than today—about 125,000 years ago—oceans were 13 to 20 feet higher. Goodbye Miami, New Orleans, the naval base in Norfolk, Va., most of New York City and Silicon Valley, as well as Venice, London and

IN BRIEF

The Arctic climate is changing rapidly, breaking at least a dozen major records in the past three years.

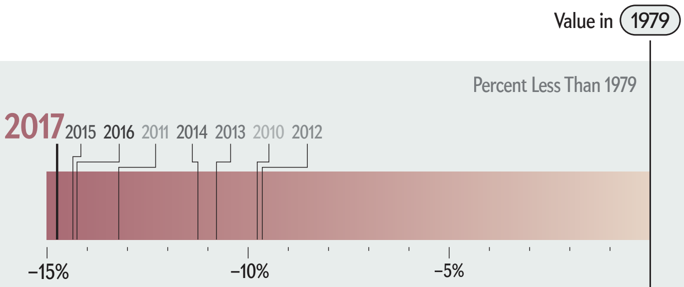
Sea ice is disappearing, air temperatures are soaring, permafrost is thawing and glaciers are melting.

The swift warming is altering the jet stream and polar vortex, prolonging heat waves, droughts, deep freezes and heavy rains worldwide.



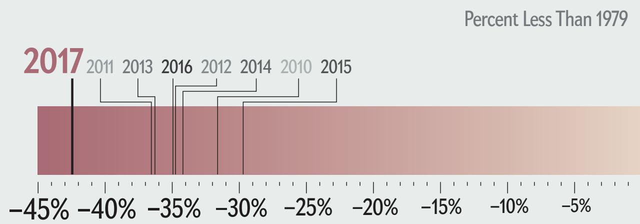
Record-Breaking Arctic

The Arctic region is changing dramatically, and the rapid transformation will affect billions of people around the world. In the past three years alone numerous climate records up north have been broken, in some cases by stunning margins. Six notable examples are shown here. Red numbers in the bar charts indicate all-time records; values for recent years reflect a trend toward those excesses. Individually, the effects alter the environment and daily life for people throughout the region. Together the effects are reshaping weather across the Northern Hemisphere, culminating in Arctic amplification (*final graph*), which raises the chance for extreme conditions year-round.



Winter Sea Ice Extent

As winter deepens, ice spreads over the Arctic Ocean. But the maximum reach has declined steadily, especially across the Barents and Bering seas. Less ice cover allows the open ocean to send more heat and moisture into the air, significantly disrupting Arctic weather.

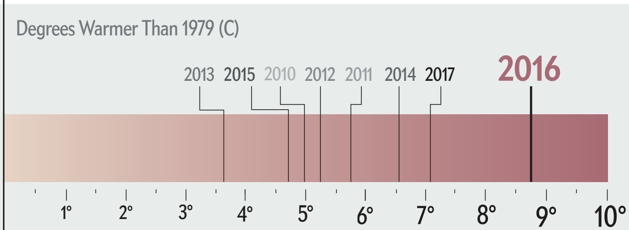


Winter Sea Ice Volume

By 2017 the amount of winter ice floating on the Arctic Ocean had dropped an astounding 42.5 percent since 1979. Winds can more easily push thin ice, trapping ships and coastal communities. Thinner ice also melts faster in warm months; summer ice volume has dropped 80 percent in the same time span.

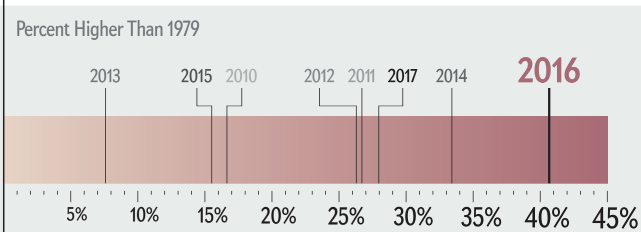
Winter Air Temperature

On certain days Arctic temperatures can soar 20 degrees Celsius above normal, and they are now elevated throughout the winter. In 2016 the mean winter temperature was almost nine degrees higher than in 1979. This trend can weaken the jet stream, bringing deep cold snaps and snows to the U.S., Europe and Asia.



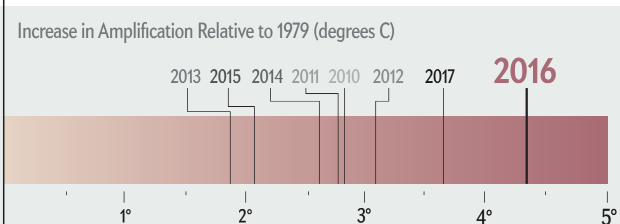
Winter Water Vapor

With less ice cover, more open ocean sends added moisture into the air. Even a small rise has big, underappreciated consequences: water vapor is a greenhouse gas that traps heat. It also condenses into clouds, releasing its latent heat. The clouds can enhance warming, too.



Arctic Amplification

The Arctic is warming faster than the rest of the world. This "amplification" means the average temperature in the Arctic is getting closer to the average temperature in the midlatitudes. The narrowing gap slows the jet stream year-round, raising the chances across the Northern Hemisphere for more persistent, extreme weather patterns—among them heat waves, floods, cold spells and maybe even longer-lasting hurricanes.



SOURCES: JPL GRACE MASCON OCEAN, ICE, AND HYDROLOGY EQUIVALENT WATER HEIGHT RL05M.1 CRI FILTERED VERSION 2. D. N. WIESE, D.-N. YUAN, C. BOENING, F. W. LANDERER AND M. M. WATKINS. PO.DAAC, JPL, APRIL 29, 2016. DATA ACCESSED FEBRUARY 14, 2018 (*Greenland ice*); JAPAN'S NATIONAL INSTITUTE OF POLAR RESEARCH AND JAXA, VIA ARCTIC DATA ARCHIVE SYSTEM (*ice extent*); PIOMAS, POLAR SCIENCE CENTER (*ice volume*); NCEP/NCAR REANALYSIS 1, PHYSICAL SCIENCES DIVISION, ESRL, NOAA (*air temperature, water vapor anomaly and amplification data*)

Graphic by Pitch Interactive

Shanghai. New research suggests that rapid Arctic warming also tends to reroute the jet stream in ways that could allow punishing weather patterns to linger across North America, central Europe and Asia longer than usual, subjecting millions of people to unyielding heat waves, droughts or relentless storms. Plankton are increasing throughout the southern Arctic Ocean, which may disrupt foods chains that support commercial fisheries. And the massive ice melt is adding to an enormous blob of freshwater south of Greenland that may be slowing the Gulf Stream, which could significantly change weather patterns for continents on both sides of the Atlantic Ocean.

What's driving this breakneck change?

LOSS OF "PERMANENT" ICE

SCIENTISTS EXPEND A LOT OF ENERGY watching the Arctic because it is so sensitive to climatic change. It is a "canary in the coal mine" for the earth's entire climate system. The long list of records that have been smashed during the past several years leaves no doubt that decades of unnerving climate simulations are on target. But the data have something even greater to say: our projections of changes on the way may be far too conservative.

In only 40 years the extent of ice across the Arctic Ocean in summer has shrunk by half. Yes, half. The volume of sea ice, year-round, is way down, too—about a quarter of what it was in the early 1980s. Until recently, scientists had thought it would take until at least the middle of this century to reach these extremes.

Summer sea ice is vanishing quickly because of feedbacks—vicious cycles that can amplify a small change. For example, when a bit of extra heat melts bright-white ice, more of the dark ocean surface is exposed, which reflects less of the sun's energy back to space. That absorbed heat then warms the area further, which melts even more ice, leading to yet more warming. In winter when the sun is not shining, other feedbacks take over. For example, sea ice floating on the Arctic Ocean acts like an insulating sheet, preventing heat and moisture under it from escaping into the atmosphere. When that ice recedes, more heat and moisture can warm the air, further retarding ice formation. Computer simulations generally show ice disappearing too slowly, contributing to the conservative estimates of future warming.

Disappearing sea ice is not the only transformation keeping researchers like me awake at night. The other two types of what used to be called permanent ice in the Arctic are also declining steeply.

Permafrost—soil that usually remains frozen year-round—has been thawing. Buildings constructed atop permafrost are collapsing, trees are toppling and roads are buckling. In addition to disrupting daily life for local residents, thawing soils also can release large quantities of heat-trapping gases into the atmosphere. When the organic matter that has been locked in permafrost for thousands of years thaws, bacteria break it down into carbon dioxide (if oxygen is present) or methane (if it is not). Arctic permafrost contains about twice as much carbon as the atmosphere holds now, so widespread thaw could greatly exacerbate global warming—which would lead to even faster thaw. Today's computer models do not adequately capture the impacts of thawing permafrost, again contributing to substantial underestimates of future global warming.

The third type of previously permanent Arctic ice is the frozen water on land, including glaciers and Greenland's enormous ice cap, which is more than a mile thick. Losing this ice has dire consequences worldwide because, unlike melting sea ice, the runoff into the ocean raises sea level directly. During the summer of 2016 the total mass of Greenland's ice sheet (estimated using satellite measurements of how it affects the earth's gravity) reached the smallest value since satellite observations began in 2002. The levels are also lower than any amount going back to the late 1950s, when the mass was estimated in other ways. A recent investigation suggests that the accelerating ice melt on Greenland's surface is hastened by warming effects linked to dwindling sea ice.

Strong Arctic warming can lead to prolonged heat waves, stalled hurricanes, relentless rains and more intense fire seasons.

HOTTER, WETTER AIR

REDUCED SEA ICE and rapid Arctic warming have other far-reaching effects. The combination may alter upper-level winds so that they carry additional heat and moisture from southerly latitudes toward the North Pole. In 2012 the then record Greenland surface melt resulted from an unusually strong and persistent ridge of high pressure in the atmosphere—a so-called blocking high. It brought not only heat and moisture from the south but also soot from wildfires around the Northern Hemisphere. That soot darkens ice and snow surfaces (lowering its albedo, or reflectivity), which then absorb more of the sun's energy, accelerating melt—another one of those vicious cycles.

Blocking patterns—large eddies in the jet stream—near Greenland appear to be occurring more often in recent decades, especially in summer months, which probably accounts for at least part of the upward trend in melting. Ice-mass loss during the summer of 2016 was the third highest on record, trailing 2010 and 2012. New work by my colleagues and me suggests that the greater number of blocking highs most likely is tied to global warming. Computer simulations struggle to form and break down blocks realistically, however, so it is hard to say how these patterns may act in the future.

Other Arctic behavior is equally outlandish. During the past two winters record-breaking heat waves near the North Pole were surpassed by more record-breaking heat waves. Waning and thinning sea ice is part of the cause, providing less of a barrier for the ocean's heat to enter the air. The jet stream's wild north-south swings also brought record pulses of warmth and moisture to far northern latitudes. Scientists and Arctic residents often fail to appreciate the strong effects that the extra moisture can create. For starters, water vapor is a greenhouse gas, so in a dry Arctic winter atmosphere, a little more moisture can trap substantially more heat. Moreover, when that moisture

MELTWATER atop a disintegrating ice cap in Svalbard, Norway, pours into the sea.

GETTY IMAGES

condenses into clouds, it releases latent heat, further warming the air. Finally, more clouds trap more warmth below them, one more factor contributing to the Arctic meltdown.

STUCK IN EXTREMES

ALTHOUGH WE HAVE MORE TO LEARN, it has become clear that rapid Arctic change is under way, the most dramatic in human history. Given this stark reality, atmospheric scientists are trying to pin down the effects that the changing Arctic may have on people and ecosystems around the world so society can decide how to react and prepare for the future.

An obvious example of global effects is coastal flooding. According to a new report by the Union of Concerned Scientists, about 170 U.S. coastal communities will experience chronic inundation within 20 years. By the end of this century, if nations keep emitting carbon dioxide as they have been, most large coastal cities around the world will face regular, disruptive flooding. This eerily prescient report was published just weeks before Hurricanes Harvey, Irma and Maria capped the U.S.'s most destructive and costly hurricane season ever.

There is also mounting evidence that strong warm-ups in the Arctic's lower atmosphere can affect winds in the jet stream and even higher, in the stratosphere, home to the polar vortex wind pattern that circles the Arctic. Northward peaks and southward valleys in the bending jet stream generate the high- and low-pressure centers we see on weather maps as a capital H or L. The bends control our weather in the Northern Hemisphere. But if extremely large bends occur more often, we can expect to see an uptick in extreme conditions where billions of people live. That is because large bends in the jet stream tend to progress more slowly from west to east, causing the weather systems they create to hang around longer. Think prolonged heat waves, relentless rains and stalled tropical storms like Hurricane Harvey, which swamped Houston in August 2017—as well as more intense fire seasons like the one in California last year.

Large waves in the jet stream, along with strong Arctic warming, can disrupt the polar vortex, prolonging deadly deep freezes or parades of snowstorms, including the long stretch of severe cold that gripped the northern U.S. in early January of this year. A polar vortex collapse can also perpetuate wild jet-stream swings that deliver crazy heat waves to Alaska and the far north, creating yet another vicious cycle that accelerates Arctic warming. Some studies suggest that Arctic warming is closely connected with these wavy patterns; others say proof of the connection is still tenuous. Research on this hot topic is advancing quickly.

A rapidly warming Arctic most likely will significantly alter habitats on land and at sea. Already, as sea ice recedes, plankton blooms have appeared in new areas during new seasons, enticing species of fish from lower latitudes to move into Arctic waters while native fish disappear. Earlier spring snowmelt across high latitudes has led to earlier greening of the tundra and earlier hatching of insects; migrating birds, which take their cues from the length of daylight hours, may arrive at Arctic food sites too late for the feast. Peoples of the Arctic are feeling the impacts, too; melting ice is keeping them from traditional hunting grounds and even forcing them to uproot towns threatened by coastal erosion from high storm waves in areas that used to be protected by ice along the shore. At the same time, big countries and big companies are swooping in to search for newly accessible natural resources, as tensions rise over who can claim which parts of the vast, rich seabed as theirs.

The revelation my colleagues and I had at the Big Sky retreat replays in my head every time another long-lived weather pattern wreaks havoc or another Arctic record is broken. Now my neighbors are catching on. Polls suggest that most Americans think that the loss of Arctic ice and the jet stream—which has fast become a household term—are conspiring to create weird weather. The old Arctic may have been ruthless, but it was stable. The new Arctic is less predictable and may be changing in ways that are irreversible, with ripple effects on life around the globe.

Are these impacts still avoidable? Yes and no. Because the climate's response lags behind the increases in greenhouse gas concentrations and because carbon dioxide has a very long lifetime in the atmosphere, future change is already baked into the system. But the magnitude and pace can be reduced if society moves quickly to slow emissions and if methods can be developed to extract carbon from the atmosphere in large quantities. Progress on both these fronts is rapid, though likely too little, too late, to preserve the earth and the Arctic as we have known them. Prepare for the unexpected. SA

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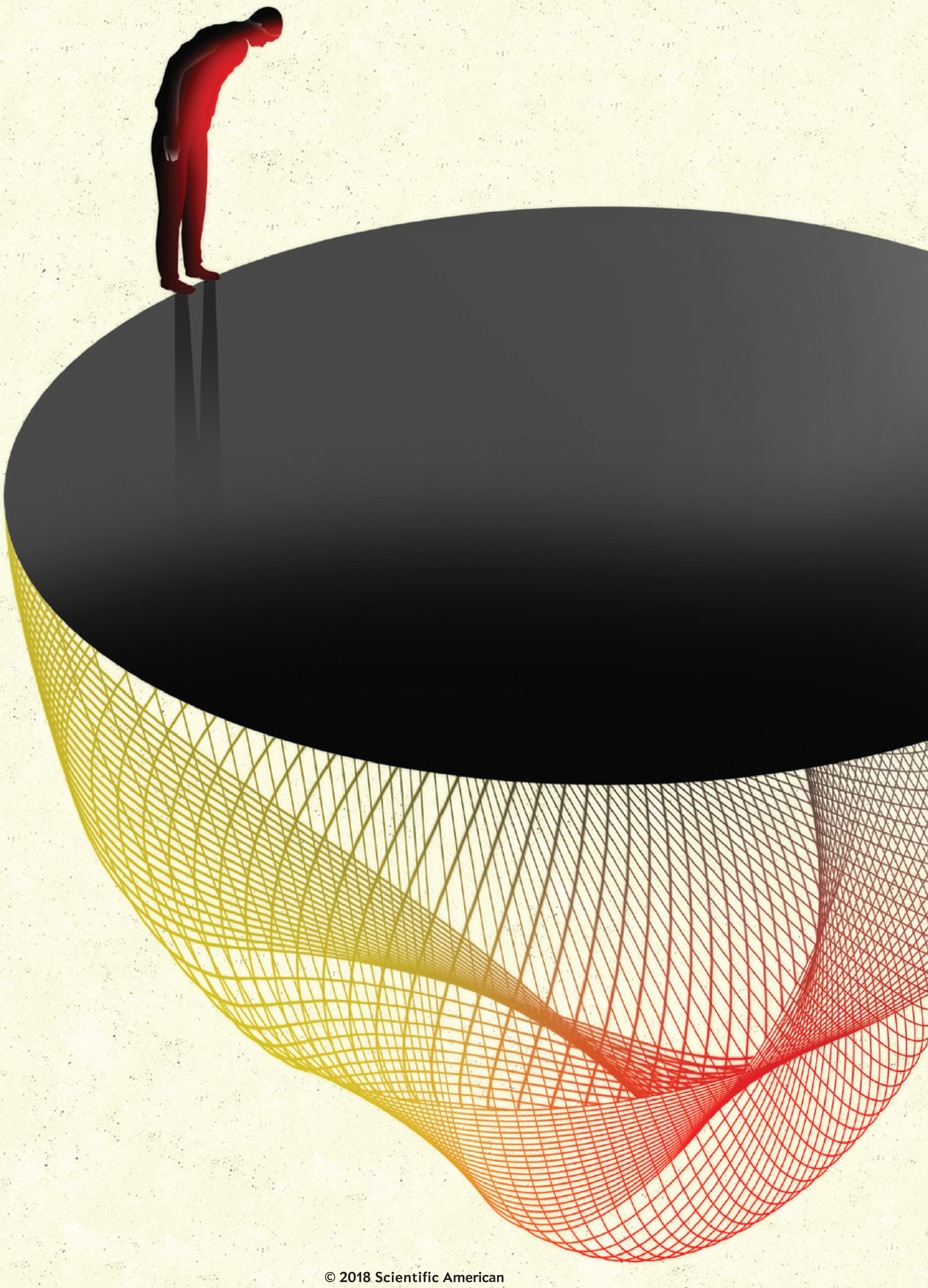
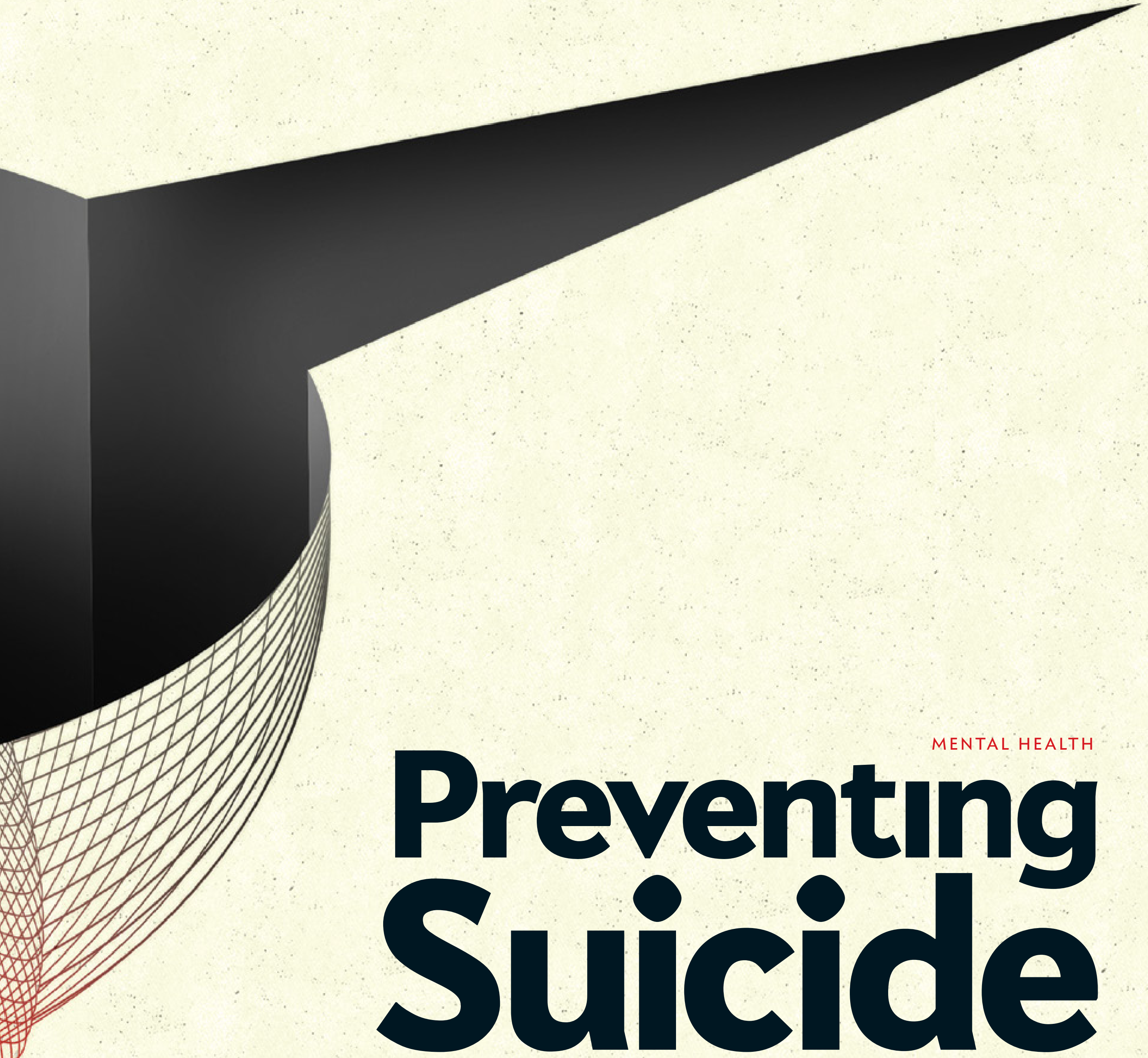




MENTAL HEALTH

Preventing Suicide

Social scientists have begun to close in on new ways to stop people from taking their own lives

By Lydia Denworth

Illustration by Brian Stauffer

Lydia Denworth is a Brooklyn-based science writer and author of *I Can Hear You Whisper: An Intimate Journey Through the Science of Sound and Language* (Dutton, 2014). She is working on a book about the science of friendship.

THIRTY MINUTES AND AN INDEX CARD. THAT'S WHAT CLINICAL PSYCHOLOGIST CRAIG BRYAN NEEDS TO conduct what he calls crisis response planning with a soldier who is suicidal. "Tell me the story about the day you tried to kill yourself," Bryan asks. Then he listens and follows up with the type of question intended to build trust and uncover warning signs. "How would you know that you're getting stressed out?" Planning mode comes next, identifying self-management strategies such as exercise. Bryan also asks about reasons for living. "What is good in your life even though things are bad?" Finally, on the card, a soldier handwrites a "safety net" checklist of emergency resources: a crisis hotline, a therapist, 911, an emergency room.

IN BRIEF

Suicide rates in the U.S. rose by 28 percent between 1999 and 2016—and the increase was steeper among the middle-aged, girls between 10 and 14, and veterans.

The problem has gained increasing attention among government agencies and psychologists working to pull the issue of suicide out of the shadows.

New ideas and pioneering technologies have begun to aid prevention efforts.

This simple approach differs in several respects from more traditional therapies. It focuses squarely on suicidal thoughts and behaviors rather than symptoms of depression, post-traumatic stress disorder or any other mental illness. It provides options for what people can do rather than telling them what they can't, unlike the long-standing contract for safety dating back to the early 1970s that asks suicidal people to promise not to harm themselves. It is fast and may not necessarily require a professional. And of greatest importance, it works. Last year Bryan and his colleagues reported that in a group of 97 soldiers with suicidal thoughts and behaviors, those who underwent crisis response planning were 76 percent less likely to attempt suicide in the next six months than those treated in other ways.

The strength of the result surprised even Bryan, who is executive director of the National Center for Veterans Studies at the University of Utah. But it provided additional evidence of something he already knew. "We're in the midst of a paradigm shift in suicide prevention," he says. "There's this new explosion of research that is calling into question a lot of the old assumptions that not only researchers but also health care providers and members of the public have had about suicide."

For decades suicide has lurked in the shadows, weighed down by stigma. Once considered a crime, the act of killing oneself is still viewed as a sin in some religions. Even those who know that suicidal thoughts and behaviors stem from a brain disease or a psychological disorder have avoided or misunderstood the subject—hospitals and schools have been reluctant to screen for it, pharmaceutical trials have excluded suicidal patients and funding institutions have been unwilling to support research. The few clinicians and scientists working in the field made little headway.

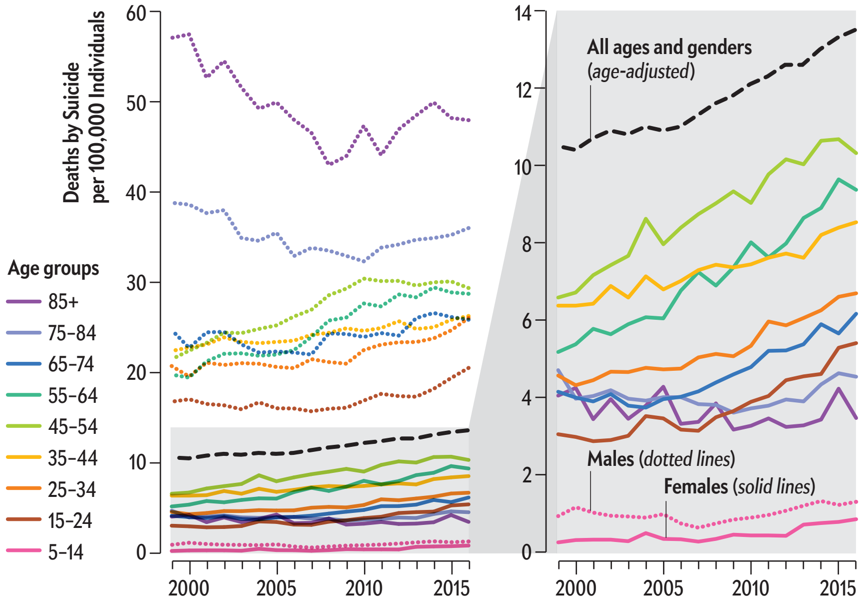
Meanwhile suicide rates have gone up. Between 1999 and 2016 the overall rate rose by 28 percent in the U.S. The rise was steeper among certain groups: for middle-aged women and men, it jumped 64 and 40 percent, respectively. Among girls between 10 and 14, the suicide rate more than tripled, although it is still very low. Since 2001 the suicide risk among veterans has also climbed—they are now 20 percent more likely than civilians to take their own lives. Almost 45,000 Americans died by suicide in 2016, making it the 10th leading cause of death. For every person who dies by suicide, nearly 300 consider it.

Finally, suicide has become too urgent a problem to ignore, with the rising rate among military personnel an especially powerful call to action. The U.S. Department of Defense, the U.S. Department of Veterans Affairs and the National Institute of Mental Health are pushing for progress, and a new generation of suicidologists are working to pull suicide out of the shadows and give it the focus required to save lives. That has meant confronting suicide head on as a condition and recognizing that all along the tortured path that leads to death by suicide—from the earliest warning signs to final attempts—old diagnostic strategies and therapies weren't working.

In their place, researchers have applied new ideas and pioneering technologies and begun to see promising results. From low-tech approaches like Bryan's checklist to the application of machine-learning algorithms to analyze medical records and patient thought patterns, a growing body of work suggests we might finally be able to bend the curve on suicide rates. Considerable challenges remain—translating ideas to practice, scaling them up and getting clinicians to adopt them. But for the first time, says Joshua Gordon, who took over as director of the NIMH in 2016 and promptly declared suicide one of his top three priorities, "we now have an evidence base for identifying people at risk and intervening to reduce that risk. I have a lot of hope that we can change things."

A Disquieting Upswing

Rates of suicide have registered an increase since 1999, after a fairly consistent decline from 1986 through 1999. Overall, the mortality rate for suicide per 100,000 people in the population has increased by 28 percent from 1999 to 2016, according to statistics compiled by the Centers for Disease Control and Prevention (*black line*). In recent years the suicide rate has most notably been on the rise for adolescents, young adults and middle-aged people. (Trend lines toward the bottom of the chart have been expanded at the right to illustrate the growth more clearly.)



SOURCE: CENTERS FOR DISEASE CONTROL AND PREVENTION

IDENTIFYING RISK

THE HUMAN INSTINCT for self-preservation is strong. What, then, drives people to contemplate hurting themselves? Theories of suicide have always postulated a mix of social isolation, overwhelming pain (primarily psychological) and hopelessness. There is still no consensus, but in 2005 Thomas Joiner, a clinical psychologist at Florida State University, added the concept of "acquired capability." It acknowledges that acting on suicidal thoughts requires the ability to overcome the natural aversion to injury and death, a goal not every anguished person can achieve. This insight has led to a new set of theories that separate ideation and action. The three-step theory of David Klonsky of the University of British Columbia and Alexis May of the University of Utah notes that disposition (such as personality), experience (combat exposure) and practicalities (availability of firearms) all contribute to suicide capability.

Better theories, however, have not yet translated into better estimates of who is most likely to attempt suicide. In 2016 an analysis that combined decades of research on risk factors found that predictive ability had not improved over the previous 50 years. "Clinicians are no better than a coin toss at predicting who's at risk," says senior author Matthew Nock, a clinical psychologist at Harvard University, who received a 2011 MacArthur Fellowship for his innovative research on suicide.

Depression, for example, has always ranked near the top of the list of warning signs, yet Nock's analysis revealed just how ineffective it is by itself in making a prediction—and most risk factors are traditionally evaluated on their own. Whereas many people who attempt suicide do suffer from depression, far more with depression do not attempt suicide. "Suicide cuts across all diagnoses; therefore, diagnoses don't matter as much," Bryan says. "We've had it flipped on its head for years. It's not that suicide is a symptom of psychiatric illness. It's that psychiatric illness is often a manifestation of the vulnerabilities that lead to suicidal behavior."

To more accurately identify those vulnerabilities, several research teams, including Nock's, have applied machine learning to electronic health records, one of a variety of promising avenues they are exploring. The algorithms search thousands of potential risk factors simultaneously, from age and race to medications, number of inpatient and outpatient visits, and diagnoses of schizophrenia or mood disorders and can be taught to make predictions far more efficiently than human beings. In a 2017 study, Colin Walsh, a data scientist at Vanderbilt University, and Jessica Ribeiro and Joseph Franklin, both at Florida State University (the latter was previously a postdoctoral fellow in Nock's lab), used this technique to review large numbers of records. Their study included 3,250 patients who had attempted suicide and another 1,900 patients who had not (the control group).

Their strategy achieved 80 to 90 percent accuracy at predicting retrospectively who would make an attempt within two years, and it was 92 percent correct at forecasting whether someone would do so within a week. So far the algorithms also generate a lot of false alarms, erroneously flagging risk for a suicide attempt. But researchers are working to improve accuracy and to test them widely. "The idea would be to have a software program that would run on medical records generating risk scores," Nock says.

Nock has also investigated new biological or behavioral signals that communicate risk reliably when patients can't or won't admit to suicidal thoughts. A four-minute implicit association test his lab developed proves remarkably good at measuring how people think about suicide, no matter what they say. In the test, during several initial trials, the words "death" and "me" appear on one side of the screen, and the words "life" and "not me" show up on the other side. Words related to each of these categories then appear at the center of the screen—"dead," "they," "survive," "I"—one at a time. Participants press one key if the new word belongs with the paired words on the left, another if it belongs on

Graphic by Amanda Montañez

the right. Then the pairing switches, and now "life" gets coupled with "me" and "death" with "not me." People who respond faster when "death" and "me" flash together are approximately three times more likely to attempt suicide in the next six months. These findings, first published in 2010, have been replicated several times with thousands of participants.

Recently Nock has launched a larger study in the emergency department at Massachusetts General Hospital that combines this implicit association test administered on iPads with machine-learning reviews of health records, as demonstrated by Walsh and his colleagues, along with self-report questions about known suicide risk factors on an iPad and blood work to look for genetic markers. "We've had some encouraging results here and there over the past few years," Nock says and then asks: "What if we put all these together in one calculator like they do for heart disease? You go to the doctor, and based on your height, weight, age and cholesterol, they say this is your probability of heart attack in the next year. Can we do the same thing for suicide attempts?"

Other experiments remain much further from practical use but are still intriguing. Nock's implicit association test caught the attention of cognitive neuroscientist Marcel Just of Carnegie Mellon University, who uses functional magnetic resonance imaging (fMRI) and machine learning to identify patterns of brain activity that correspond to thought patterns. For example, if a person in a scanner is given the word "jury," Just's method can detect that the subject is thinking about a group of people, authority and rules but not that those people are sitting in a courtroom trying to assess evidence. As Nock, Just, psychiatrist David Brent of the University of Pittsburgh and their colleagues reported in 2017 in *Nature Human Behaviour,* Just's neurosemantics method revealed that the brains of some suicidal people responded differently to positive and negative words related to life and death, correctly distinguishing 91 percent of the time between the 17 subjects who had thought about suicide versus the 17 who had not. Just now wants to replicate the work and see if it might be administered using electroencephalography, a less costly technique that monitors electrical activity in the brain, but that work is in the early stages.

Smartphones have begun to provide a solution for monitoring suicidal thoughts over long periods.

Luckily, technologies such as smartphones are more accessible than fMRI and have begun to provide a solution to the need to monitor suicidal thoughts during high-risk periods. "People who are at risk for suicide may respond to stressful situations more intensely than people who aren't at risk, but we can't always induce that kind of stress in the lab," says Evan Kleiman, a research associate in Nock's lab. The researchers are experimenting with tools for monitoring emotional and physiological changes in patients. There are smartphone apps that check in with a patient or wrist-worn biosensors that track skin conductance, skin temperature and heart rate. If a patient has a fight with a spouse at home, physicians will know right away of their charge's added stress. These technologies have contributed to the recognition that clinicians need to assess risk over hours, days or weeks rather than months or years. The Fitbit-like bracelets are being tested on inpatient units by adolescent and adult patients, and results are not in yet, but "we think there's great promise here," Nock says.

ASKING THE QUESTION

PREVENTIVE TECHNOLOGY REQUIRES that a person with suicidal thoughts or behaviors is receiving some form of treatment. Unfortunately, most people are not. Even those who see a health care provider are not always helped. About half of all suicide victims visited a medical setting within the 30 days before death (not necessarily because of suicide risk). But less than half of mental health professionals receive adequate training in suicide risk assessment or intervention during graduate or medical school, and more than basic mental health resources are not generally available in most U.S. emergency departments.

This situation is changing. Increasingly, a mantra of suicide prevention is: "Ask the question." To tackle suicide directly, we must ask about it directly. (Doing so will not put ideas into someone's head.) In February 2016 the administrative body that accredits hospitals recommended that they screen all medical patients for suicide risk. A good step, but not every institution knew how to respond. "People started scrambling and making up their own questions," says Lisa Horowitz, a pediatric psychologist at the NIMH. "Either they underdetect or they overdetect and overburden already strapped resources." Thus, an effort to ensure appropriate screenings and adequate follow-up is under way. In 2017 investigators from across the U.S. reported on an NIMH-funded study to test a screening tool in eight emergency departments. Screening alone did not affect subsequent suicide attempts compared with treatment as usual, but adding intervention to screening achieved a moderate but significant 5 percent reduction in suicide-attempt risk.

Horowitz now leads an effort to put a brief screening tool directed at young people between ages 10 and 24 in as many hospitals as possible. Called Ask Suicide-Screening Questions (ASQ), it begins: "In the past few weeks, have you wished you were dead?" Horowitz is still going through data on the tens of thousands of kids who have taken it, but she is encouraged: "People were worried this was opening Pandora's box, but what we are finding is that you can detect the risk and that it's manageable." Another striking finding: when queried about whether they wanted to be asked about suicide risk, 95 percent of kids surveyed said yes.

Among those who do not make it into medical settings, social media may offer other kinds of warning signs. Bryan and his colleagues reviewed the social media networks of 315 military personnel who died by suicide or other causes. In the 12 months before each person's death, they looked for differences in content—for example, mention of relationship or financial problems, suicidal thoughts or behaviors, or health or anger issues. By detecting patterns in such content, they could clearly differentiate between who had died by suicide and who had not. A follow-up study revealed just how variable the emotional lives of the soldiers were over that period. "When people kill themselves, in the time leading up to their death, they have good days and bad days," Bryan says. "It's tumultuous." In the past, data analysis used to regard these ups and downs as noise, but by realizing that they contained critical information—the variability was the signal not the noise—Bryan's team could estimate when individuals were most likely to kill themselves.

Now they are working out how to do this prospectively. Analysis of social media may become more relevant beyond a physician's office if friends and family know what to look for, Bryan says. But some clinicians can and do access posts and tweets that have no privacy restrictions. In addition, Bryan is already using the same analytic approach on session-by-session assessment data with patients and has found that it may improve tracking and monitoring of a patient's status.

A comparatively obvious way to lower suicide rates simply takes away the opportunity. Those thwarted do not all eventually find a way; nine out of 10 people who attempt suicide go on to live out their lives. After years of debate over cost and efficacy, the push for such "means restriction" is finally seeing results. A 2015 report in the *Lancet Psychiatry* found that placing safety nets under known suicide locations reduced death rates by 58 percent (the average moved from 5.8 to 2.4 per year). In December temporary 11-foot-high mesh safety fences went up above the existing waist-high railings on the George Washington Bridge, which spans the Hudson River between New York City and New Jersey and where 15 people killed themselves in 2017 and another 68 tried. Permanent fencing will be part of a larger restoration. At the Golden Gate Bridge in San Francisco, where more than 1,700 people have jumped to their deaths since it opened in 1937, a stainless-steel net is being built that will extend 20 feet beyond the walkways. In 2012 at New York University's Elmer Holmes Bobst Library, perforated metal walls were installed in the 12-story atrium after three students jumped to their deaths there.

Far more deaths might be prevented by making guns less easily accessible. Nearly half of suicide attempts involve a firearm, and more than 80 percent of those attempts result in death. According to a 2004 study in the *American Journal of Epidemiology,* having a firearm in the home is associated with an increased risk of suicide. But removing firearms as a method of suicide prevention gets tangled up with the politically explosive issue of gun control, so this is one area where change is not likely to happen soon.

TREATMENT THAT WORKS

BETTER PREDICTION and questions—even methods of thwarting attempts—only help if clinicians can turn to treatments that reduce suicidal thoughts and behaviors and restore quality of life. One notable approach, dialectical behavior therapy (DBT), has already proved itself—consistently reducing suicide attempts by about half in certain patient populations.

Developed in the 1980s by Marsha Linehan, a clinical psychologist at the University of Washington, to treat suicidal patients with borderline personality disorder, the therapy consists of an intensive regimen, requiring multiple meetings every week for a year and extensive training for therapists. Perhaps the difficulty in fielding enough trained professionals and the commitment required for treatment explains why DBT alone has been unable to make a dent in suicide rates.

To have a broader impact, treatments for suicide will have to scale up and be supplemented with options that are accessible outside of emergency rooms or even by a download from the iTunes Store. A 2017 study in the *American Journal of Psychiatry* showed that low doses of ketamine, an anesthetic drug, brought about a significant reduction in suicidal thoughts within 24 hours, considerably faster than other antidepressants. A gamelike app developed by Franklin and Nock also shows promise. It matches suicide-related images—blood, wounds and knives—with aversive pictures of snakes, spiders, and the like. It then applies classical conditioning methods—training someone to change his or her natural response to a stimulus—to make people dislike the idea of suicide. In three randomized trials with participants who had recent suicidal thoughts, a few minutes of daily play for a month consistently decreased risk of suicidal behavior, although the effects disappeared when playing stopped. The game, called Tec-Tec for therapeutic evaluative conditioning, is now available on the App Store.

Bryan has focused on identifying the ingredients that work in DBT and other cognitive therapies and on developing treatments that can be taught to non–health care providers. "The essential ingredients boil down to two underlying factors," he says. "The first is emotional dysregulation, the ability to identify what we are feeling and then the capacity to change it. The second key element is cognitive flexibility, the ability to generate options or not get stuck in certain thought processes, beliefs or assumptions." These two elements can be tackled through such tactics as mindfulness or relaxation training, restructuring negative thinking and encouraging social connections. Bryan's initial 12-session therapy, which he calls brief cognitive-behavioral therapy, incorporated these elements and reduced suicide attempts by 60 percent.

The crisis response plan, his 30-minute intervention, originally came about as an emergency piece of the longer therapy. "The idea was, let's do this while someone is in crisis and reduce the person's risk in the short term, then he or she will get connected with ongoing mental health treatment, and that will provide the long-term solution," Bryan says. But in a six-month follow-up of patients who had undergone only crisis response planning, the effect not only held, it strengthened. "That's gotten us to think very differently about treatments," he notes. "How could something so simple be so potent? That's where we are now. What do we need to do next to figure this out to make it work better?"

Asking *that* question more broadly might possibly move us toward achieving the ambitious goal set by the National Action Alliance for Suicide Prevention, a public-private partnership, of reducing suicide rates by 20 percent by 2025. That objective would provide tangible proof that the pain and hopelessness that lead a person to want to die can be anticipated, addressed and ameliorated. SA

MORE TO EXPLORE

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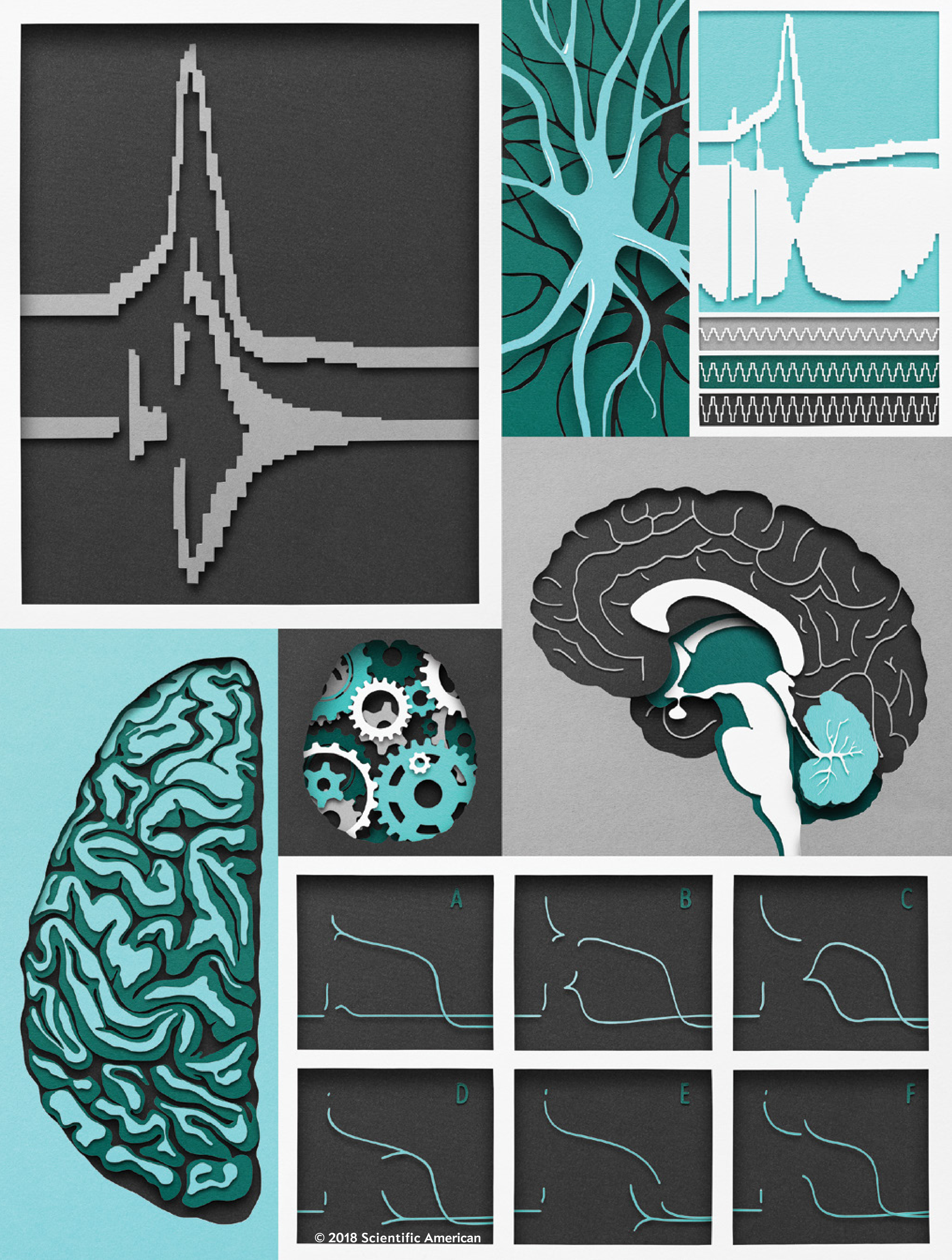
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NEUROSCIENCE

THE BRAIN, Reimagined

Physicists who have revived experiments from 50 years ago say nerve cells communicate with mechanical pulses, not electric ones

By Douglas Fox

Illustration by Owen Gildersleeve

Douglas Fox writes about neuroscience and extreme climates from California.

A YOUNG WOMAN WITH WAVY BROWN HAIR AND MAROON NAILS LAY ON a gurney in a hospital room in Copenhagen. Her extended left arm was wired with electrodes. A pop pierced the air every few seconds—an electric shock. Each time, the woman's fingers twitched. She winced. She was to receive hundreds of shocks that day.

The woman, attended to by several physicians in laboratory coats, was renting out her arm for 1,000 Danish kroner, about $187. Thomas Heimburg, a physicist trained in quantum mechanics and biophysics, sat on a stool, safely out of the way, sketching on his iPad the details of a harsh experiment that he hoped would produce profound results.

The physicians had injected the woman's arm with the anesthetic lidocaine—a dose strong enough to deaden her limb for surgery. At first, the nerves in her arm did not respond to the shocks. But the attendants gradually dialed up the current. At this moment, the jolts were 40 milliamperes, nearly 10 times their original strength—similar to the electricity coursing through a five-watt lightbulb.

Pop—another shock. The woman's hand twitched like a dying snake. Heimburg paid no notice as he stared at a computer monitor on the wall. A waveform depicting the electric signal in the arm muscle and nerve leaped across the screen in one large spike—evidence that the ever increasing shocks had started to overcome the anesthetic. The nerve was now firing as strongly as it did before the woman was anesthetized. Heimburg was pleased. "The things that are written in books," he said quietly, "they are in contradiction to this."

Heimburg, who works at the Niels Bohr Institute in Copenhagen, famous for physics research, hopes to contradict lots of things written in books. This experiment, which I witnessed in December 2011, was designed to investigate a long-standing medical mystery.

Physicians have administered general anesthetics for 170 years. They have discovered dozens of effective compounds. When given at progressively higher doses, the drugs all silence nerve functions in the body and brain in the same distinct order: first memory formation, then pain sensation, then consciousness, and eventually breathing. This same sequence happens across all animals, from humans to flies.

Yet no one knows how anesthesia actually works. The molecular structures of nitrous oxide, ether, sevoflurane and xenon are so different that it is unlikely they exert their common effects by binding to equivalent proteins in cells, as other drugs do.

Heimburg thinks anesthetics work in a radically different way: by changing the mechanical properties of a nerve. If that is true, it means that nerve cells, or neurons, throughout the body and brain are mechanical machines, not the electric circuits scientists have believed in for decades. In Heimburg's view, the electric pulses are simply the side effects of a physical shock wave that ripples down the nerve, similar to the way sound waves travel. He thinks anesthetics silence nerves by soaking into the fatty membranes that encase nerve fibers, rendering them too soft to transmit the shock waves, like a guitar string too slack to twang.

It was tempting to dismiss Heimburg as nutty when I watched that experiment. But in the seven years since then, he and his colleagues have rolled out an array of evidence: delicate measurements of how mechanical waves move through single nerve

IN BRIEF

Physicist Thomas Heimburg may upend the biology world. He says nerves do not fire electrically but mechanically. To prove it, he is reviving experiments done 50 years ago by a discounted neuroscientist.

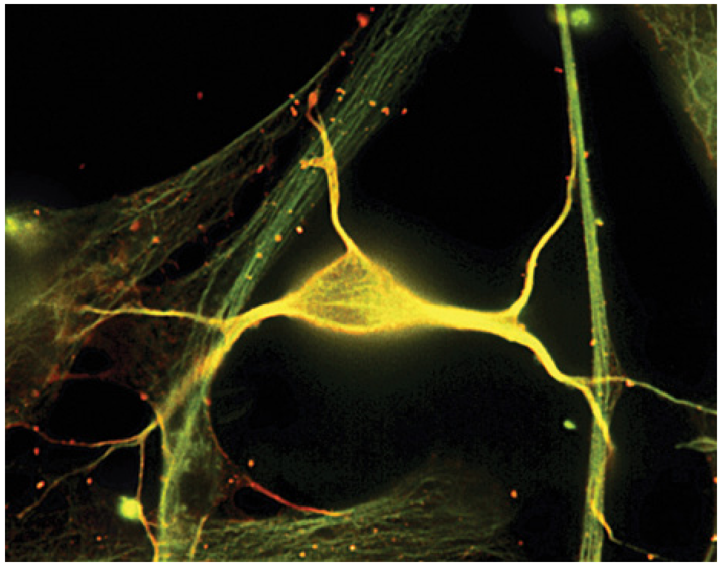
Heimburg's radical idea is that a signal traveling down a pipelike nerve fiber is a compression wave, like sound, which temporarily changes the fatty membrane that coats the pipe from fluid to crystalline.

Biologists think Heimburg is revealing only side effects of an electric pulse, yet a few are acknowledging the two actions might work in concert, which would transform explanations about how the brain functions.

cells and of how much and how quickly the membranes can expand and contract, as well as studies showing how anesthetics alter these properties. Other scientists are starting to take an interest. Now Heimburg is preparing for a crucial experiment that could clinch his case: measuring the heat emitted by a single nerve cell as a pulse shoots through it.

Heimburg's work continues to demonstrate that the nerve pulse is more complex than most biologists may realize. The mechanical components may have been overlooked because of an accident of history: 50 years ago off-the-shelf instruments could readily measure the tiny electric impulses in neurons but not the mechanical ones. Hardware limitations influenced which discoveries scientists made and which ideas entered mainstream scientific thought. Heimburg's experiments are now reopening a decades-old scientific schism.

The story of the mechanical neuron holds lessons for all of science about biases and accidents of history. It also could change our basic understanding of nerves, brains and intelligence. Scientists have struggled to explain how brains achieve such daunting feats as face recognition and conversation while relying on proteins in neurons that are electrically noisy and unreliable. Heimburg is showing how the mechanical waves may compensate for this noise. If his theory proves out, he could rewrite biology. Or he might just be wrong.



NEURON, or nerve cell (*yellow*), in the brain's hippocampus—the center of long-term memory—is supported by proteins (*green* and *red*).

ROBERT S. McNEIL *Science Source*

HOT NERVES

THE NEURAL PULSE that scientists have tried for so long to explain lasts for only an instant. Step on a thumbtack, and your brain senses the pain within a fraction of a second. The signal travels through nerve fibers at up to 30 meters per second.

The fibers resemble tiny hollow pipes, finer than a hair. The pipe wall is formed by an oily cell membrane. Charged sodium and potassium atoms, called ions, hover around the inside and outside of the membrane. By the mid-1900s researchers had learned to stick electrodes into nerve cells to monitor the voltage across the membrane wall. They discovered that as a nerve pulse travels down the membrane and passes the electrode, the voltage spikes for several thousandths of a second. In 1952 two British scientists, Alan Hodgkin and Andrew Huxley, reported that the spike happens as sodium ions stream through the membrane wall from outside to inside. The voltage then reverses to normal as potassium ions gush through the membrane from inside to outside. The Hodgkin-Huxley model became the foundation of modern neurophysiology.

Hodgkin and Huxley received a Nobel Prize in 1963. But a few scientists continued to unearth observations that undermined their model, observations that Heimburg has re-created, even though some of those scientists had been written off as misguided.

Ichiji Tasaki, a senior neurobiologist at the National Institutes of Health for many years, was one of them. In 1979 he conducted an unorthodox experiment. Gazing through a microscope, he gingerly placed a fleck of shiny platinum atop a fine white thread—a nerve fiber bundle of a crab, laid bare by dissecting the animal's leg—and trained a laser onto the platinum. By measuring the reflection of the laser light, he could detect motions that would show whether the nerve bundle briefly widened or narrowed as an electric pulse passed by. He and his then postdoctoral fellow, Kunihiko Iwasa, took hundreds of measurements. After a week, the answer was clear: every time a pulse shot through the nerve fibers, they briefly widened, then narrowed again, within a few thousandths of a second.

The ripple was minuscule: the membrane surface rose by only about seven billionths of a meter. But it coincided perfectly with the passing electric pulse, confirming a suspicion Tasaki had harbored for years: that Hodgkin and Huxley were wrong.

As far back as the 1940s, researchers had noticed that as an electric pulse passes through a nerve fiber, the translucent cell briefly becomes more opaque. By 1968 Tasaki and another team found evidence suggesting that as the pulse arrives, molecules in the membrane physically rearrange themselves, then revert to their original configuration after the pulse passes.

Then there was the heat. Researchers expected an electric pulse to release heat—common when electricity flows. But several teams discovered something strange. A nerve fiber's temperature rose several millionths of a degree Celsius as a pulse raced by, yet after it passed, the temperature quickly fell again. The heat had not dissipated; instead the nerve had reabsorbed most of it, also within a few thousandths of a second.

For Tasaki, the transient widening, the rearranging molecules, and the heating and cooling pointed to a startling conclusion: the nerve signal was not just a voltage pulse; it was every bit as much a mechanical pulse. Scientists who listened to nerves with electrodes were missing much of the action.

Tasaki would spend the rest of his life probing these effects. He came to believe that they originated not in the cell membrane but in a layer of protein and carbohydrate filaments just underneath it. According to his theory, as the voltage pulse arrives, the filaments absorb potassium ions and water—causing them to swell and warm—a process that then reverses itself after the pulse passes by.

As Tasaki pursued these ideas, he gradually fell out of step with the field. Other factors conspired against him. Having grown up in Japan, he spoke stilted English. "You [had] to know a lot of things to have a really substantive conversation with him," says Peter Basser, an NIH section head in neuroscience who knew Tasaki for 20 years. "And I think a lot of people thought he wasn't really as deep and perceptive as he was." And although Tasaki collaborated with visiting scientists, he did not produce student protégés who would carry his ideas forward.

Emblematic of the schism was the ideological rivalry that arose between Tasaki and another prominent NIH neuroscientist, Kenneth Cole, who adhered to the mainstream view. Although the two men occupied the same lab building from the 1950s to the 1970s, they barely spoke for 15 years, except at public presentations, where one would undermine the other by standing up in the audience and posing prickly questions.

Tasaki gave up his lab during an NIH reorganization in 1997 and moved into a small space in Basser's lab. He continued working seven days a week, well into his 90s. One day in December 2008, as he walked near his home, he lost his balance and banged his head on the ground. He died a week later at the age of 98.

By then, Tasaki's work had disappeared from sight. "I don't think anybody disputed that those things were being seen, because he was respected in the lab," said Adrian Parsegian, a biophysicist at the University of Massachusetts Amherst, who was at the NIH from 1967 to 2009. Rather Tasaki's findings "were explained away as not central" to nerve signaling—nothing more than side effects of the voltage pulse. The underlying scientific questions "didn't get resolved," he said. "One side got into the textbooks, and the other one didn't."

FATTY LIQUID BECOMES CRYSTAL

HEIMBURG CAME ACROSS Tasaki's work in the mid-1980s, while pursuing his Ph.D. at the Max Planck Institute for Biophysical Chemistry in Göttingen, Germany. Soon he found himself immersed in long sessions at the library, poring over old papers. He would eventually connect the dots in a different way than Tasaki had. He believed that the mechanical wave, the optical changes and the transient heat must occur in the fatty cell membrane of nerves throughout the body and brain, not in the protein and carbohydrate filaments below the membrane, as Tasaki had thought.

By the late 1990s Heimburg had begun doing his own experiments, compressing artificial cell membranes to see how they might respond to a mechanical shock wave. This work revealed something crucial: the membrane's oily lipid molecules are normally fluid and randomly oriented, but they hover close to what chemists call a phase transition. Squeeze the membrane just a little bit, and the lipids condense into a highly aligned liquid crystal.

These experiments led Heimburg to declare that a nerve pulse is a mechanical shock wave that travels down the nerve membrane. As it advances, it should squeeze the membrane's lipid molecules into a liquid crystal—a phase change that would release a small amount of heat, just as water does when it freezes. Then, as the tail end of the shock wave passes, a few thousandths of a second later, the membrane would revert to a fluid state, reabsorbing the heat. That brief transition into a liquid crystal and back would also cause the nerve membrane to widen briefly, just as Tasaki and Iwasa had seen when they shined a laser on that platinum fleck.

Heimburg's experiments went one crucial step further. They showed how the shock wave and phase transition might be linked to the voltage spike that occurs as the pulse passes by. Heimburg found that he could push a membrane into its liquid-crystal state simply by putting it under a voltage. "People applied voltage across biologic membranes for 70 years or so, and none of these electrophysiologists had ever checked" for a liquid-crystal structure, he said.

Textbook diagrams portray cell membranes as thin, passive sheets of insulation wrapped around pipelike nerve fibers. But physicists are starting to realize that cell membranes have surprising properties. They belong to a class of materials known as piezoelectrics, which can convert mechanical forces into electric forces, and vice versa. Quartz watches run on this principle. This means that a voltage pulse traveling down a membrane will carry with it a mechanical wave. And conversely, a mechanical wave traveling down a membrane will express itself as a voltage pulse.

When Heimburg and his fellow researcher Andrew D. Jackson first published the theory in 2005, they had still never observed one of these electromechanical pulses in motion. One of Heimburg's former students filled that gap. In 2009 Matthias Schneider, a biophysicist now at the Technical University of Dortmund in Germany, reported that he could trigger a mechanical wave by applying a voltage pulse to an artificial membrane. The pulse strength was similar to that found in nerve cells. The shock wave traveled at approximately 50 meters per second, similar to the speed at which thumbtack-triggered signals race from the foot to the brain. By 2012 Schneider had confirmed that the mechanical and voltage pulses were part of the same membrane wave.

Schneider's most important finding came in 2014, however. A key feature of a nerve pulse is that it is all-or-nothing. If a neuron receives a weak incoming shock, it will not fire a voltage pulse. If the shock is strong enough, it will fire. "There is a threshold," Schneider says. He found that the electromechanical waves on his artificial membranes were indeed all-or-nothing. The determining factor seemed to be whether the membrane was squished hard enough to force it into liquid-crystal form. Only then, he says, "you get a pulse."

ANESTHESIA EXPLAINED

WHY HAD HEIMBURG first committed to this view of nerves and anesthesia? Hoping to find out, I visited him at his office at the Niels Bohr Institute during the same week I witnessed the hospital experiment.

Heimburg had the bookshelves of a physicist, not a biologist, crammed with volumes by dead German physicists. Among them was a row of clothbound books by Hermann von Helmholtz, who in the mid-1800s formulated a key premise of thermodynamics, that energy can change form but cannot be created or destroyed. Helmholtz, incidentally, also measured the speed of nerve pulses. "I find it absolutely mandatory to read these old texts," Heimburg said. They document the gradual discovery of fundamental connections among energy, temperature, pressure, voltage and phase transitions. These principles underlie Heimburg's ideas about nerve function, the ideas of a physicist pushing his way into another field. "Thermodynamics

How Do Nerves Send Signals?

For decades scientists have endorsed a standard explanation for how nerve cells (neurons) transmit signals in the body and brain: each message is carried as an electric impulse that travels down a cell's long axon, jumping to the next neuron. But now a handful of physicists, who have performed exotic tests on the cells in action, say the signal is actually a mechanical pulse that ripples down the axon—akin to a sound wave or seismic wave. Some researchers say any physical pulse is just a side effect of the electric impulse. Settling these contentions could revise explanations of how the brain works.

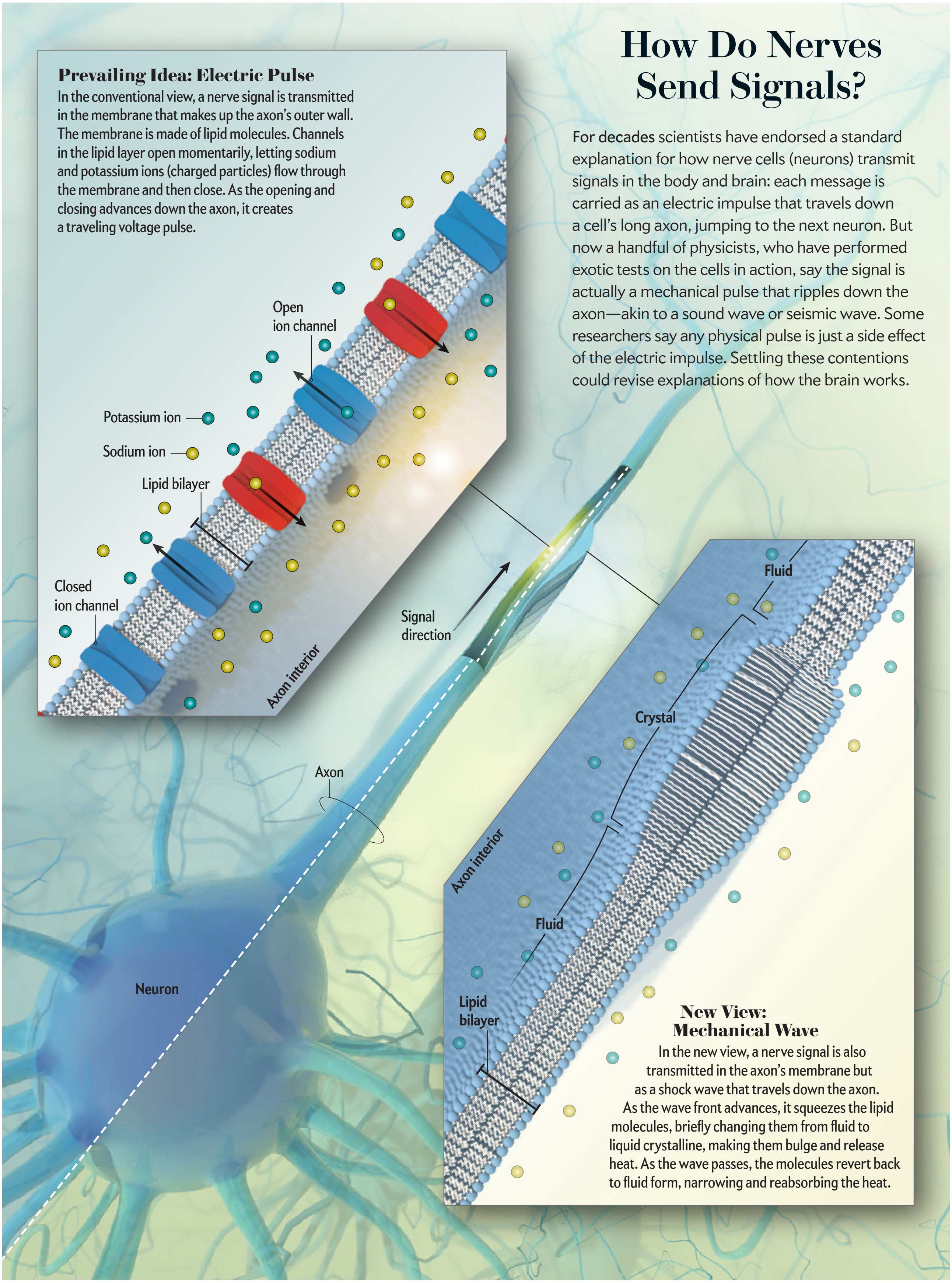


Illustration by Falconieri Visuals

is the most profound science that we have," he said. "If you know thermodynamics, you are wise."

He was quick to point out weaknesses in popular explanations about anesthesia. Biologists think anesthetics silence nerves by binding to and thus blocking ion channels—valves in a nerve membrane that open and close to allow sodium or potassium ions to flow through. Biologists say the flow of ions propels voltage pulses down a nerve fiber—commonly portrayed as an electric signal. But because different anesthetics have vastly different molecular structures, Heimburg could not believe they could all bind to ion channels. That explanation was "completely ridiculous," he said, with a hint of frustration, as if pointing out something that should be obvious. Something "deeper, more profound," must be at work.

Heimburg's ideas were shaped in part by an old volume entitled *Studien über die Narkose,* or *Studies of Narcosis,* published by Ernest Overton in 1901. It recounts a particular experiment that caught his attention. Overton took dozens of different anesthetics and put each into a flask of water with a layer of olive oil floating on top. He shook each flask, then waited for the water and oil to separate again. He measured how much of each drug ended up in the oil versus the water. The more potent an anesthetic was in animals, the more strongly it moved into the oil, a striking result later confirmed for modern anesthetics. Olive oil and cell membranes are composed of the same oily molecules, called fatty acids. Heimburg surmised that the drugs might work by soaking into the cell membranes, altering their physical properties.

Experiments with synthetic membranes support that idea. When Heimburg infuses a membrane with an anesthetic, it prevents the membrane from becoming a liquid crystal. It does so by lowering the temperature (and raising the pressure) at which the phase transition from fluid lipid to crystalline lipid occurs—just as salt or sugar lowers the freezing point of water.

Heimburg reasoned that preventing this transition in a membrane would stop a mechanical pulse from advancing down a nerve fiber, explaining why anesthetics deaden nerves. And notably, he predicted it should be possible to overcome this effect. To create higher pressure to solidify a membrane using an electric shock, you have to crank up the current—exactly what the physicians did to the woman's arm at the hospital in Copenhagen. Stronger electric shocks did indeed overcome the anesthetic. If anesthesia can be overcome by pushing harder on a membrane with electricity, then it should also be reversible by increasing the physical pressure on a membrane.

Biologists demonstrated this way back in 1942. They used two different anesthetics, ethanol and urethane, to inebriate tadpoles to the point that they stopped swimming. Then the scientists put the animals in a hyperbaric chamber and raised the pressure to 136 times that of the atmosphere. The anesthetic effect vanished: the tadpoles resumed swimming. When the pressure was lowered, the animals again fell motionless. "It's very surprising," Heimburg said, with a smile. "How would you have the idea to put drunken tadpoles under pressure?"

The existence of mechanical waves is not in doubt, says one neuroscientist in the middle of the controversy. "The question is whether neurons actually use them to do something useful."

NO TOLERANCE FOR DEBATE

TO THIS DAY, Heimburg is frustrated by the way biologists react to his ideas, which he calls soliton theory (a soliton is a self-sustaining wave that maintains its shape as it travels). He has faced opposition from the moment he published his theory in 2005 in the *Proceedings of the National Academy of Sciences USA,* despite that journal's high regard.

One critic, Catherine Morris, a prominent neurobiologist emeritus at the Ottawa Hospital Research Institute, told me that the whole line of work reeks of superiority from a physicist who thinks he can simply march into a different field and set people straight. She summed this up in a favorite witticism of hers: "It strikes me as this business that physicists do, saying, 'We can approximate this cow as a single point.'"

To some extent, Morris's reaction is understandable. It is one thing to say that nerves are mechanical as well as electrical. It is quite another to reject the concept that ion channels play a role in nerve conduction—which Heimburg and Schneider do, in their biggest and most problematic departure from mainstream biology. Never mind that scientists have discovered hundreds of ion channel proteins. Or that the ion flows can be selectively altered with drugs. Or that mutations scientists can create in the proteins change the way neurons fire. "They just blithely ignore vast amounts of biology," says Morris, who spent 30 years studying ion channel proteins.

Heimburg and Schneider acknowledge that these proteins must serve some function. But they point to experiments, some by Heimburg, showing that ions can flow across artificial membranes even without channel proteins. They attribute this flow to transient holes that appear as the membrane shifts between fluid and liquid-crystal phases, and they think it happens in nerves in the body and brain.

Their skepticism reflects a cultural tendency in physics: a belief that all things should be explainable through thermodynamic principles. Biologists, they say, have neglected these principles as they fixate on proteins. A similar brand of puritanism may have facilitated the eventual dismissal of Tasaki's theory. He "did not like the term 'ion channels,'" said former postdoc Iwasa when we spoke in late 2017. This iconoclastic outlook may have guided Tasaki to discover things that others could not have, Iwasa said, "but later on, it may not have helped" him.

Brian Salzberg agrees. He studies nerve physics at the University of Pennsylvania and began his neuroscience career in 1971, crossing paths occasionally with Tasaki. "He was a very clever experimenter, and I have no doubt that he measured real changes" in nerve thickness, Salzberg said earlier this year. "But he misinterpreted them." Salzberg says nerve fibers temporarily swell as a voltage pulse goes by in part because water molecules flow into the membrane through the same ion channels that let in sodium and then flow back out through the ion channels that let out potassium. If Tasaki had accepted the idea of ion channels, he might have been open to other interpretations of the mechanical wave.

But another powerful factor may have helped push Tasaki out of sight—holding an important lesson for all of science today.

IDEOLOGUES

IT IS INTRIGUING that the thermal energy of a firing nerve may be twice as large as the energy in the electric signal that has dominated neuroscience. The fact that these nonelectric features fell out of favor may stem, in part, from a quirk of history.

Tasaki was a gifted instrument builder who cut his scientific teeth in Tokyo during World War II. Faced with severe equipment shortages, he assembled his own instruments from stray electric components. Years later in the U.S., he used these skills to build exquisite, one-off instruments that measured the heat, or temporary expansion, of nerve cells.

Those devices, and expertise, never found their way to other scientists. Measuring the electric nerve signal was different. Scientists created easily transferable methods, such as inserting a tiny electrode into a cell membrane. As these techniques spread from one lab to another, so did the electrical view of nerve signaling. "There's a cultural bias," Parsegian admitted. "People look with a tool that they feel they understand, and they don't use one that they don't understand. It could have tilted the thinking."

Today the technical gaps are starting to disappear. As I checked in with Heimburg between 2011 and 2018, he gradually repeated one old experiment after another, using modern technologies to clarify the surprising things that Tasaki and others first saw decades ago. In 2014 Heimburg redid the drunken-tadpole experiment, using synthetic membranes instead of animals: as he cranked the pressure up to 160 atmospheres, the impacts of anesthetics were reversed—except that this time, Heimburg could link the effect directly to phase changes in the membrane. In 2016 he used microscopy to precisely measure, in a single cell, the mechanical wave that Tasaki and Iwasa first documented in 1979.

Heimburg, now 58, is seeking funding for what could be the most critical experiment of all: measuring the heat as a nerve pulse, or action potential, passes by. Tasaki had measured heat from bundles of fibers, but Heimburg plans to use a microchip that will measure the heat blip of a single neuron. This experiment could address a key criticism of his theory: that a nerve membrane's brief phase change from liquid to crystal should release, and reabsorb, more heat than Tasaki ever saw. Heimburg contends that the old experiments systematically underestimated the heat; because they measured many neurons, the heat reabsorption after early pulses canceled out the heat releases of later pulses. "The true signal is probably much higher," he told me in late 2017. If his measurements bear out, they could bolster his claim that the membrane transmits a mechanical wave.

Perhaps most significantly, other scientists are stepping in—outsiders who are not polarized by the old, calcified disputes. Nongjian Tao, a biosensor engineer at Arizona State University, is using lasers to track mechanical pulses in single nerve cells—like Tasaki and Iwasa did, except that Tao reflects his light directly off the nerve rather than a tiny platinum mirror, making the measurement more sensitive. He hopes to monitor hundreds of individual neurons in nerve networks at once, with lasers sensing mechanical waves as they ripple to-and-fro. Such work could answer a key question. "The existence of these [mechanical] effects is not in doubt," says Simon Laughlin, a neuroscientist at the University of Cambridge. "The question is whether neurons actually use them to do something useful."

Laughlin does not work on mechanical waves, but as someone who has studied ion channels for 45 years, he imagines that the waves could influence the little protein valves. Recent experiments show that the valves are extremely sensitive to mechanical forces in the membrane. If mechanical waves help to open and close ion channels, that could profoundly change our understanding of the brain because firing neurons mediate all thinking. Ion channels are notoriously noisy and jittery: even tiny thermal vibrations can cause them to pop open or close randomly. Information theorists have struggled for decades to explain how the brain can achieve reliable cognition using such unreliable channels. But mechanical waves could mean the openings and closings are purposeful. "That's a definite possibility," Laughlin says.

There are hints that this could be true. Some neurons in the mammalian cortex seem to violate the Hodgkin-Huxley theory. When they fire at high rates, their ion channels open more quickly, as a group, than expected. One explanation is that the channels are responding en masse to a sudden change in the membrane—the arrival of a mechanical wave that opens them more or less in unison, allowing them to fire faster than they otherwise could. The speed might allow them to transmit information at phenomenally quick rates—a possible basis for cognition. In this view, a nerve pulse is both electrical and mechanical.

Heimburg and Schneider occupy a strange place in all of this. They could perhaps one day share a Nobel Prize. Or they could end up nowhere, transfixed by the same insistence that gripped Tasaki for so many decades. The fact that some neuroscientists such as Laughlin and other experts such as Tao are interested in mechanical waves would seem like an important opening for the physicists. But Heimburg was steadfast when we spoke in February. "What many people try to do is somehow rescue the Hodgkin-Huxley model by just combining it with the view that we have," he said. "But I personally … would not accept any kind of compromise between the two models." SA

MORE TO EXPLORE

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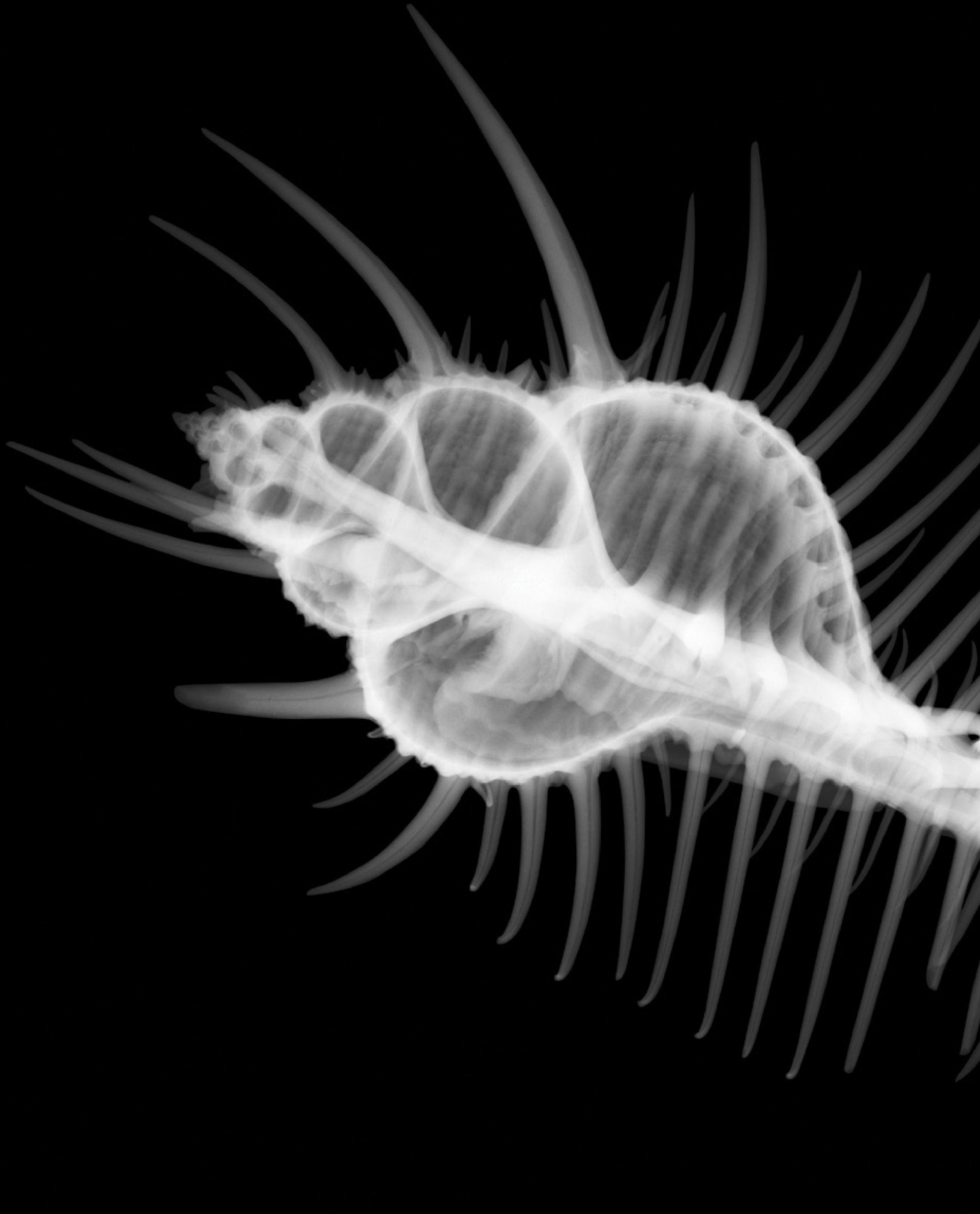


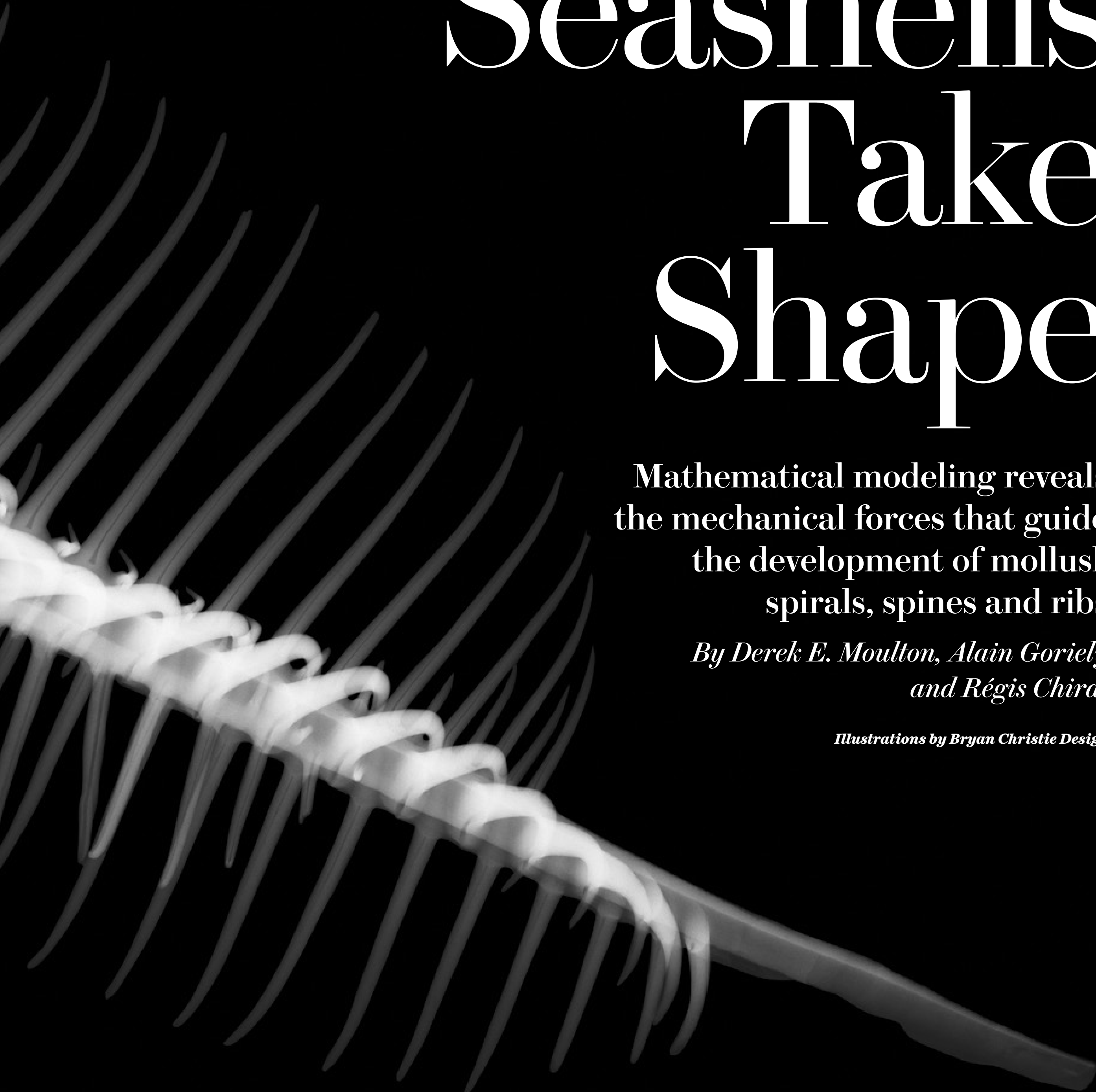
MATHEMATICS

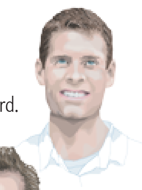
How Seashells Take Shape

Mathematical modeling reveals the mechanical forces that guide the development of mollusk spirals, spines and ribs

By Derek E. Moulton, Alain Goriely and Régis Chirat

Illustrations by Bryan Christie Design





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Alain Goriely is a professor of mathematical modeling at the University of Oxford.

Régis Chirat is a paleontologist specializing in fossil mollusks at the University of Lyon in France.

MOLLUSKS ARE FABULOUS ARCHITECTS. THEY BUILD HOUSES THAT PROTECT their soft bodies from predators and the elements—shells of uncommon strength, durability and beauty. Many of these shells have spectacularly complex shapes—logarithmic spirals bedecked with fractal spines or other ornaments, all executed with near-perfect mathematical regularity. Yet mollusks, of course, know nothing of math. How, researchers have wondered, do these humble creatures produce such intricate patterns so precisely?

IN BRIEF

Mollusks construct intricate shells with mathematical precision.

Mathematical modeling has revealed that the creatures need only to follow a few simple rules to produce these elaborate forms.

The findings help to elucidate how many unrelated mollusk species have independently evolved similarly shaped shells.

For more than 100 years scientists have recognized that cells, tissues and organs must respond to the same physical forces that govern other kinds of matter. But for most of the 20th century biologists focused on understanding how the genetic code directs the formation of biological patterns and on figuring out how those patterns function. In recent decades, however, investigators have begun to apply physics-based mathematical modeling to questions about biological form. Our own work along these lines over the past few years has yielded intriguing insights into how shells acquire their ornate structures.

Using the tools of differential geometry, a mathematical discipline that studies curves and surfaces, we have determined that the elaborate shapes of shells arise from a few simple rules that the mollusks follow when constructing their homes. These rules interact with mechanical forces produced during shell growth to generate myriad pattern variations. Our findings help to explain how Byzantine features such as spines have evolved independently in so many lineages of gastropods, which make up the largest mollusk group. These creatures need not undergo the same genetic changes to acquire similar ornaments, because the laws of physics do most of the work.

RULES OF CONSTRUCTION

THE BUSINESS OF BUILDING the shell falls to the mollusk's mantle. This thin, soft organ secretes layer on layer of a substance rich in calcium carbonate at the opening, or aperture, of the shell. It only needs to follow three basic rules to form the characteristic spiral seen in the shells of snails and their relatives, the gastropods. The first rule is *expand:* by uniformly depositing more material than it did on the previous pass, the mollusk creates a slightly larger opening at each iteration. This process generates a cone from an initial circle. The second rule is *rotate:* by depositing slightly more material on one side of the aperture, the mollusk achieves a full rotation of that aperture, building a doughnut shape, or torus, from an initial circle. The third rule is *twist:* the mollusk rotates the points of deposition. Follow just the expand and rotate operations, and you get a planospiral shell like that of the chambered nautilus. Add the twist step, and the result is what mathematicians describe as a nonplanar, helicospiral shell.

For some shell builders, that is the end of the story, as sleek and elegant a home as one could want. For others, some embellishment is in order. To understand how ornaments such as spines form, we must

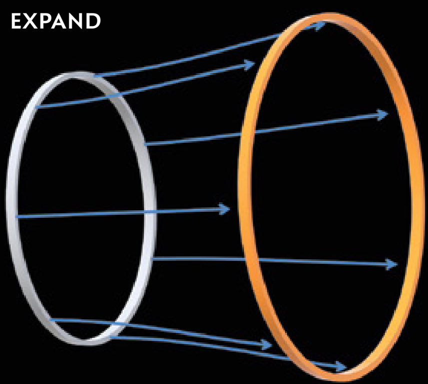
PRECEDING PAGES: NICK VEASEY *Getty Images;* OPPOSITE PAGE: BEN BRAIN *Getty Images* (Nautilus); NICK VEASEY *Getty Images* (*Turritella communis*)

Spirals

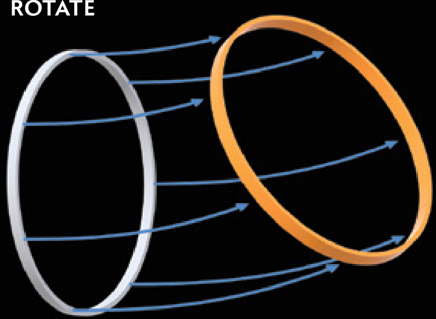
Mollusks follow just a few simple rules to create spiral shells. The first is *expand:* as the mollusk secretes successive layers of shell-building material at the shell opening, or aperture, it uniformly deposits more material each time to create an ever larger opening. The second rule is *rotate:* by depositing slightly more material on one side of the aperture, the mollusk builds a doughnut shape, or torus, from an initial circle. The third rule is *twist:* the mollusk rotates the points of deposition. Different combinations of these rules yield different spiral shapes.

EXPAND AND ROTATE
Nautilus

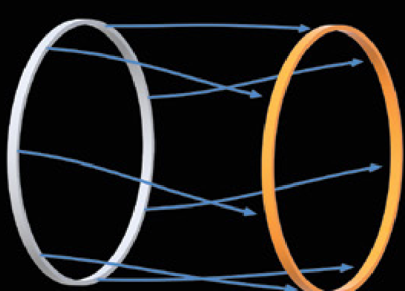
EXPAND

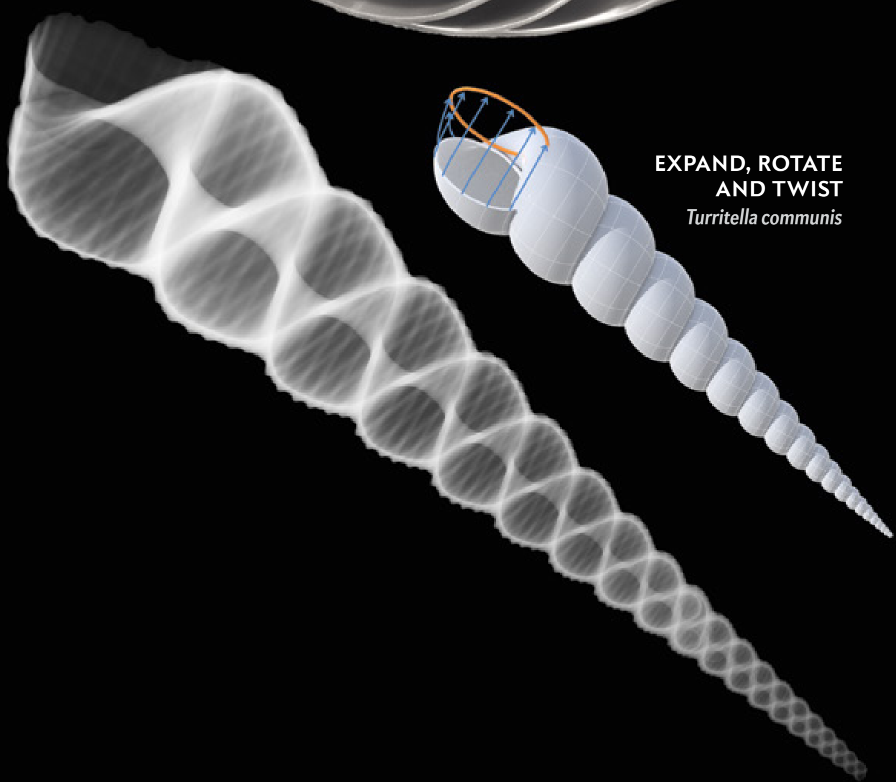


ROTATE



TWIST

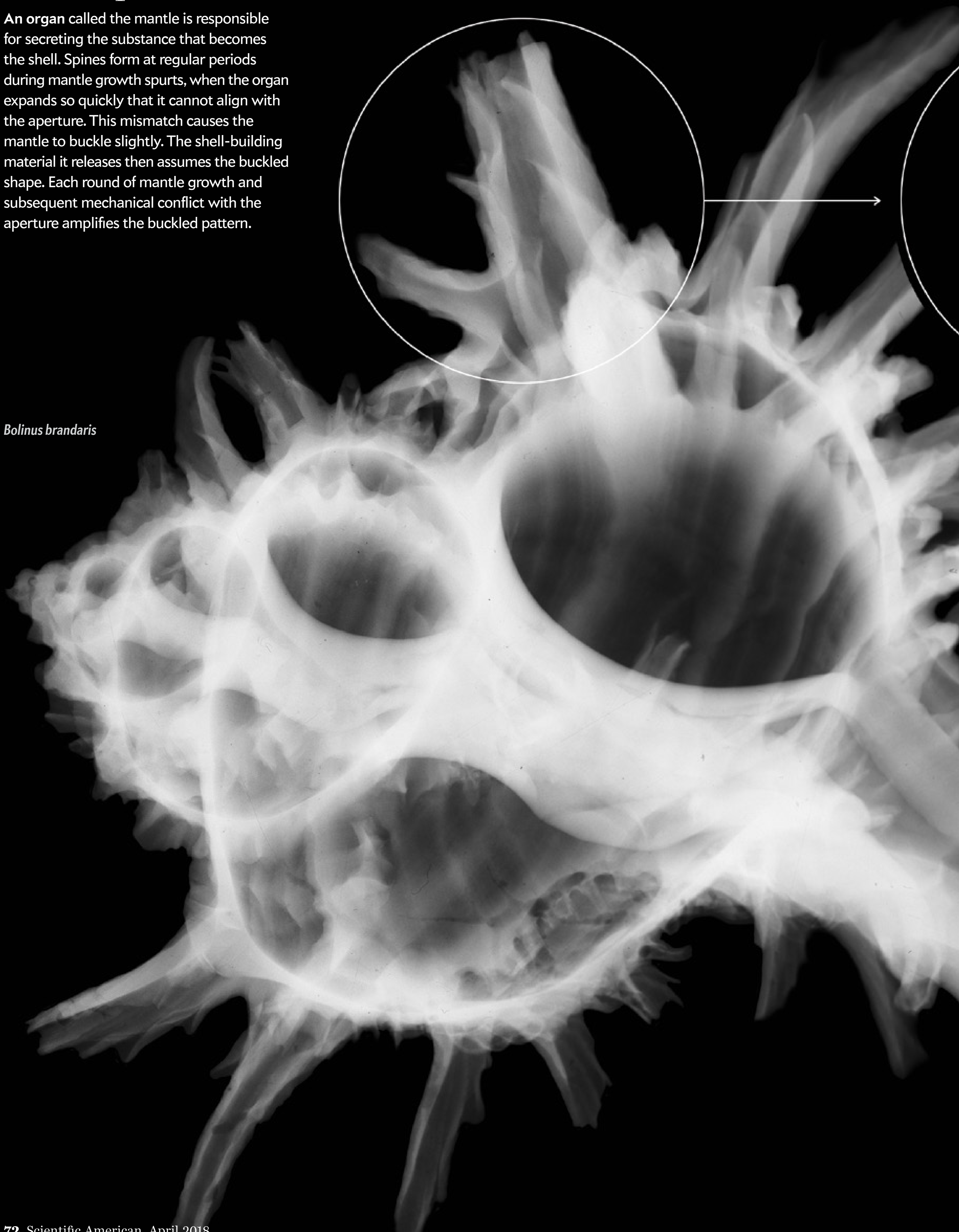




EXPAND, ROTATE AND TWIST
Turritella communis

Spines

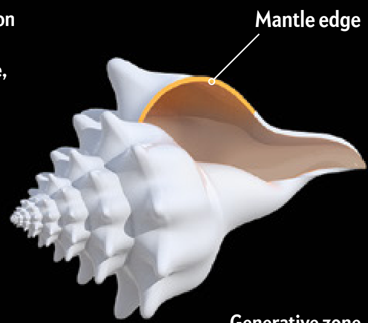
An organ called the mantle is responsible for secreting the substance that becomes the shell. Spines form at regular periods during mantle growth spurts, when the organ expands so quickly that it cannot align with the aperture. This mismatch causes the mantle to buckle slightly. The shell-building material it releases then assumes the buckled shape. Each round of mantle growth and subsequent mechanical conflict with the aperture amplifies the buckled pattern.

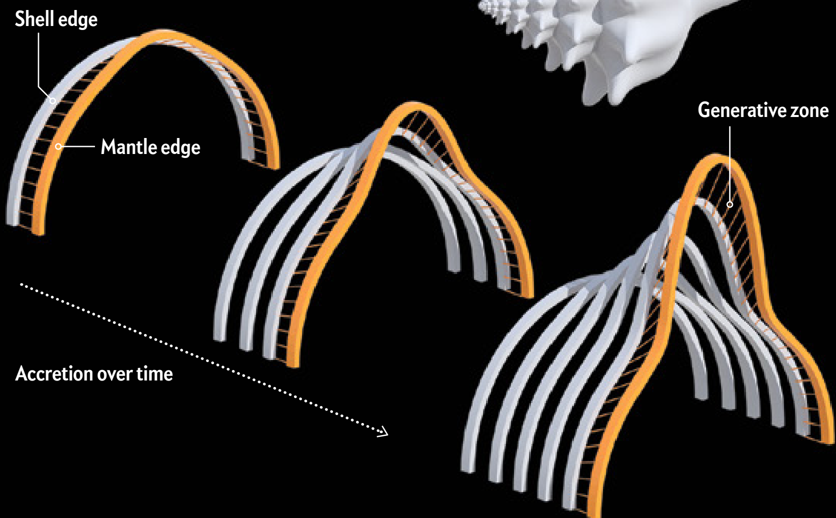


Bolinus brandaris

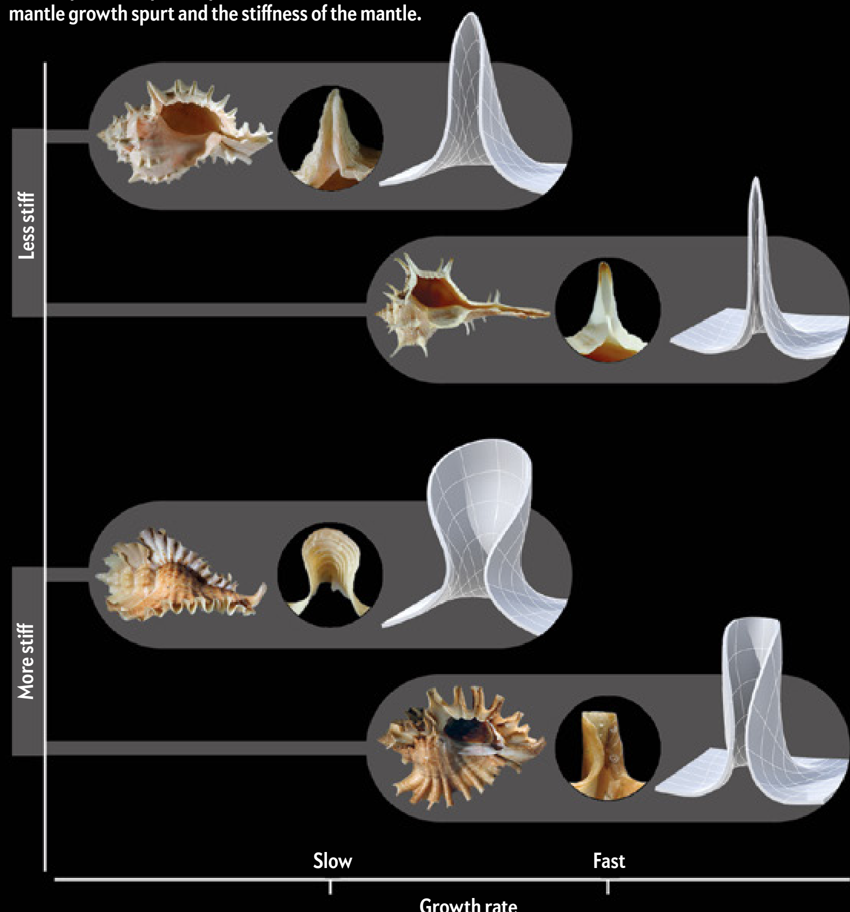
NICK VEASEY *Getty Images*

The mantle joins the shell via the generative zone, a region of secreted but not yet hardened material. Deformation of the mantle creates deformation of the generative zone, which is imprinted in the next layer of shell. The pattern is exaggerated with each round of growth.



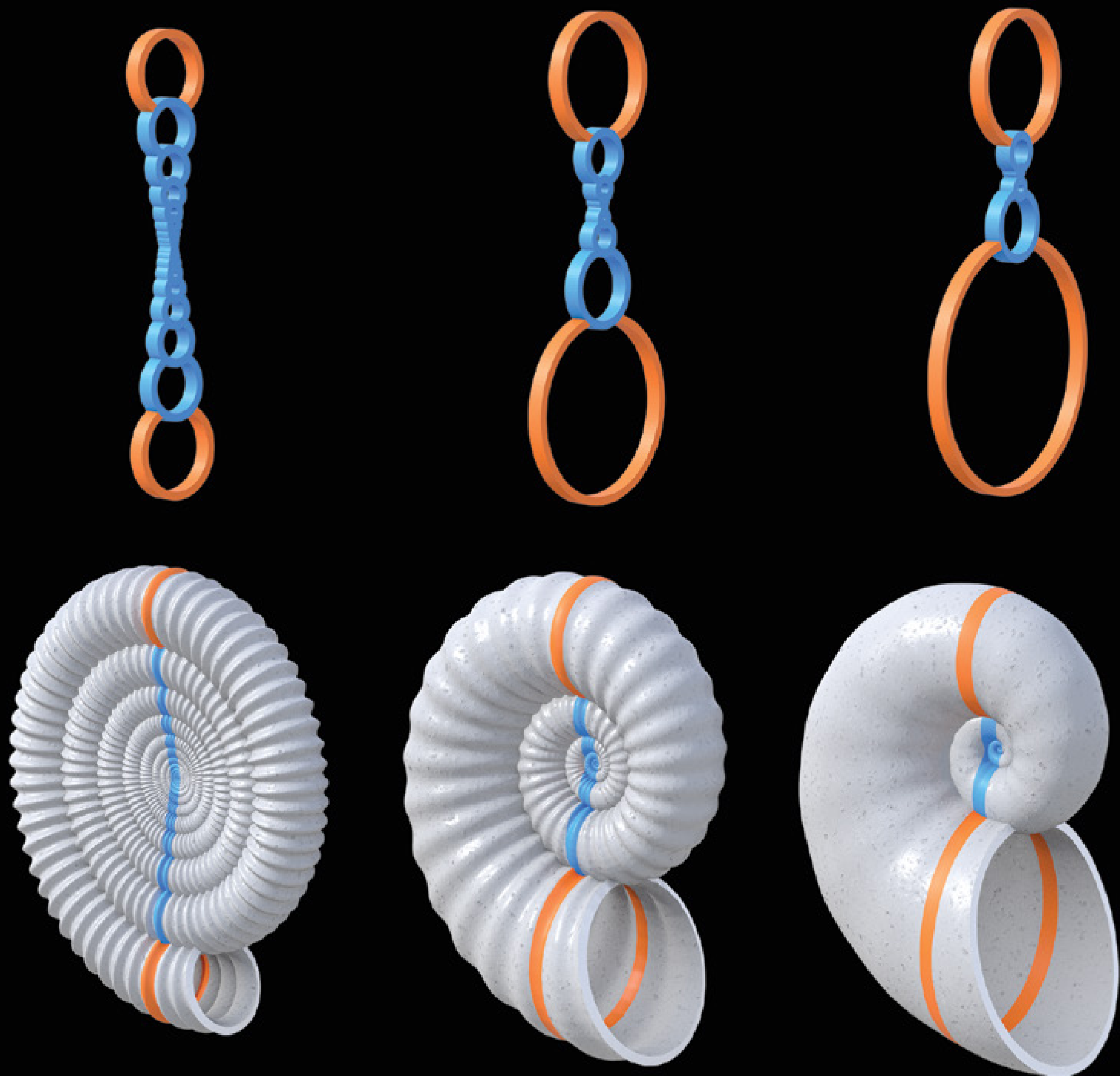


The shape of the spine depends mainly on the rate of the mantle growth spurt and the stiffness of the mantle.



Ribs

Shells of ammonites, a group of extinct mollusks, exhibit regular ribs that form perpendicular to the shell edge. Mathematical modeling indicates that this pattern of ornamentation is the product of the opposing forces of the mantle and the generative zone, which form an oscillatory system of tension and compression. Slow expansion of the mollusk aperture leads to dense ribbing (*left*), whereas rapid expansion leads to smooth shells (*right*).



examine the forces produced during shell growth. The shell secretion process revolves around an interesting mechanical system. The mantle is attached to the shell via the so-called generative zone, a region of secreted but not yet calcified material. It is in this interaction between mantle and shell that the potential for pattern formation exists. Any mismatch between mantle and aperture will physically stress the mantle tissue. If the mantle is too small for the opening, it will have to stretch to attach to it. If the mantle is too large, it will have to compress to fit. And if the generative zone becomes deformed because of these stresses, the new material the mantle secretes at that stage will assume the deformed shape and permanently solidify in the shell, further influencing the mantle at the next growth step. Essentially, if the shell does not grow at the exact same rate as the growing mollusk, deformations will arise, generating features we recognize as ornaments.

Spines constitute the most prominent ornamentation, typically protruding at a right angle to the shell aperture and often extending centimeters beyond the shell surface. These projections form at regular periods in which the mantle undergoes a growth spurt. During a growth spurt, the mantle develops so quickly that it has an excess of length and cannot align with the aperture. This mismatch causes the mantle to buckle slightly. The material it secretes assumes the buckled shape. By the next increment, the mantle has grown further and has again exceeded the aperture, which has the effect of amplifying the buckled pattern. We reasoned that this repeated process of growth and mechanical interaction gives rise to a row of spines, the precise pattern of which is determined primarily by the rate of the growth spurt and the stiffness of the mantle.

To test this idea, we developed a mathematical model of a mantle growing on a foundation that evolves at each iteration. As we experimented with typical growth and material properties in the model, a wide variety of spine patterns emerged, similar to the forms that are observed in real shells, confirming our hypothesis.

THIS OLD HOUSE

SPINES ARE NOT the only flourish that mollusks may add to their shells. Another type of pattern is found on the shells of ammonites, a group of extinct mollusks related to today's cephalopods (nautiluses, octopuses and their cousins). Ammonites ruled the seas for 335 million years before disappearing around 65 million years ago. The abundance of their fossilized remains, along with their great diversity of forms and apparently high rate of evolution, has made them one of the most studied groups of fossil invertebrates.

The most striking characteristic of the ammonite shell beyond its planar-logarithmic spiral form is the regular ribbing that runs parallel to the shell edge. This ornamentation probably stems from the same mechanical conflict that produces spines, yet it is a completely different pattern. The forces are the same, but the magnitude and the geometry on which they operate are not.

The aperture of the ammonite is basically circular. If the mantle radius is larger than the current aperture radius, the mantle will be compressed but not enough to generate the degree of elastic instability needed to produce spines. Rather the compressed mantle pushes outward, and the shell radius at the next increment is larger. But this outward motion is opposed by the calcifying generative zone, which acts as a torque spring trying to maintain the current shell orientation.

We surmised that the effect of these two opposing forces is an oscillatory system: the shell radius increases, reducing compression, but overshoots to a state of tension; the "stretched" mantle then pulls inward to decrease its tensile force, again overshooting to a state of compression. A mathematical description of this "morphomechanical oscillator" confirmed our hypothesis, producing regular ribs with a wavelength and amplitude that increased during the growth and development of the mollusk. These mathematical predictions closely resemble the known forms of ammonites.

Mathematical modeling also predicts that the greater the expansion rate of the growing mollusk—the rate at which the diameter of the shell opening increases—the less pronounced its ribs are. These findings help to explain the observation that increased aperture curvature correlates with increased ribbing pattern, an evolutionary trend that has been noted by paleontologists for more than a century.

This relation between expansion rate and ribbing also provides a simple mechanical and geometric explanation for a long-standing puzzle of mollusk evolution: the shells of the chambered nautilus and its relatives—a group known as the nautilids—have remained essentially smooth since at least 200 million years ago, leading some observers to suggest that the group has apparently not evolved in that time. Indeed, today's few surviving nautilid species are often described as "living fossils." Our biophysical growth model, however, shows that the smoothness of nautilid shells is merely a mechanical consequence of rapid aperture expansion. The nautilids' lineage may have evolved more than their shell morphology suggests, but lacking the distinctive ornamental patterns that paleontologists use to distinguish species, their actual evolution remains largely hidden.

We still have much to learn about how mollusks make their marvelous abodes. A short stroll through any good shell collection reveals a number of patterns scientists have yet to explain. For example, roughly 90 percent of gastropods are "right-handed," building their shells such that they coil in a clockwise direction. Only 10 percent wind to the left. Scientists have only just begun to probe the mechanisms that lead to this prevalence of right-handedness. The origins of some exquisite ornamentations are likewise unknown, such as the fractallike spine pattern found in a number of species in the muricid family of mollusks. Also, although we know that environmental factors influence shell growth rate, the impact of these variables on shell form is less clear.

With these and other mysteries still surrounding seashells—which are model organisms for exploring broader questions about pattern formation in nature—we have our work cut out for us. But an understanding of the physical forces that govern their development only heightens their allure. SA

MORE TO EXPLORE

Mechanical Basis of Morphogenesis and Convergent Evolution of Spiny Seashells. Régis Chirat, Derek E. Moulton and Alain Goriely in *Proceedings of the National Academy of Sciences USA,* Vol. 110, No. 15, pages 6015–6020; April 9, 2013.

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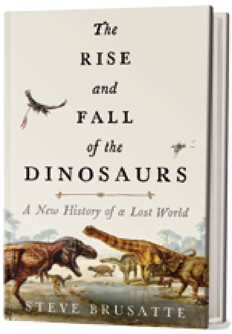
A Multifractal Walk Down Wall Street. Benoit B. Mandelbrot; February 1999.

scientificamerican.com/magazine/sa

By Andrea Gawrylewski

The Rise and Fall of the Dinosaurs: A New History of a Lost World

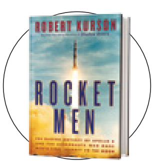
by Steve Brusatte. William Morrow, 2018 ($29.99)



They are film stars, the beloved fascinations of children and adults alike, and the stuff of wild imagination—both terrifying and intoxicating. But despite our cultural obsession with dinosaurs, there is much to their story that has been left untold until now. In this biography of these creatures, paleontologist Brusatte weaves together the origins of dinosaurs, their rise to global dominance and their dramatic demise. He anchors the tale in riveting fossil discoveries from around the globe and his own love affair with these remarkable life-forms. Although theirs is perhaps the best-known mass extinction on Earth, by the author's account, the dinosaurs' reign was a massive success story—they thrived on the planet for more than 150 million years, and their descendants are the more than 10,000 species of birds that occupy almost every corner of the world today.

FEATHERED DROMAEOSAUR *Sinornithosaurus* from Liaoning Province in China.

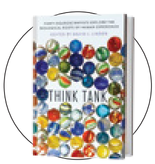
Rocket Men: The Daring Odyssey of *Apollo 8* and the Astronauts Who Made Man's First Journey to the Moon



by Robert Kurson. Random House, 2018 ($28)

Apollo 11 is famous for landing astronauts on the lunar surface in 1969. But the flight of *Apollo 8,* which sent the first crew to orbit the moon seven months earlier, was in some ways even riskier and its success more surprising. Writer Kurson tells this lesser-known tale with suspense, describing how NASA decided to aim for the moon just 16 weeks before launching the mission, at a time when the Soviet Union seemed to be leading the space race. Against the odds, the Americans pulled it off and sent home the first pictures of Earth as a tiny blue marble from the perspective of the moon. The feat was a spark of hope at a time when assassinations, riots and war were ripping the country apart—a contentious era with many similarities to our own. "So far," Kurson writes, "there has been no *Apollo 8* for our time." —*Clara Moskowitz*

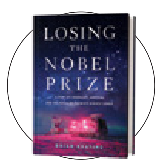
Think Tank: Forty Neuroscientists Explore the Biological Roots of Human Experience



edited by David J. Linden. Yale University Press, 2018 ($25)

How is it that when we drive, our sense of "self" expands to include the car we are driving, allowing us to precisely maneuver into a tight garage without crashing? What phenomenon is responsible for our "gut feelings"? Will it ever be possible to create a computer that can think like a human brain? Linden, a neuroscientist, asked 39 other researchers from around the country what they would most like to tell people about how the brain works. This collection of his and their answers covers the science related to timely topics such as the addictions behind the opioid crisis and why the phrase "time flies when you're having fun" rings true in the brain. Although these essays provide us with glimpses of the scientific underpinnings of thought, they also make us realize that what goes on in our minds is nothing short of magical. —*Yasemin Saplakoglu*

Losing the Nobel Prize: A Story of Cosmology, Ambition, and the Perils of Science's Highest Honor



by Brian Keating. W. W. Norton, 2018 ($27.95)

In 2014 a team of cosmologists using the BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) instrument announced it had glimpsed something spectacular: evidence of cosmic inflation, a long-theorized phenomenon thought to have occurred right after the big bang. Rumors swirled that the BICEP2 team would soon receive a Nobel Prize. Instead the finding crumbled under closer scrutiny, arguably because of "unforced errors" made while scrambling to secure credit for the discovery. Keating, an astrophysicist who formulated the original BICEP experiment, tells the story from his perspective, likening research in this field to "a Stockholm slot machine paying out in Nobel Prizes." The book is an insider's account of a historical cosmological caper and an indictment of the Nobel Prizes themselves for being harmfully out of sync with modern scientific practices and progress. —*Lee Billings*

MICK ELLISON

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His new book is *Heavens on Earth: The Scientific Search for the Afterlife, Immortality, and Utopia.* Follow him on Twitter @michaelshermer

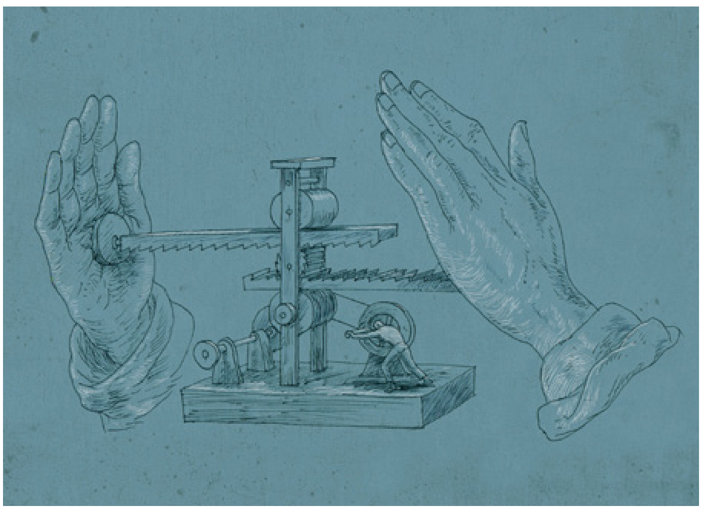
Silent No More

The rise of the atheists

By Michael Shermer

In recent years much has been written about the rise of the "nones"—people who check the box for "none" on surveys of religious affiliation. A 2013 Harris Poll of 2,250 American adults, for example, found that 23 percent of all Americans have forsaken religion altogether. A 2015 Pew Research Center poll reported that 34 to 36 percent of millennials (those born after 1980) are nones and corroborated the 23 percent figure, adding that this was a dramatic increase from 2007, when only 16 percent of Americans said they were affiliated with no religion. In raw numbers, this translates to an increase from 36.6 million to 55.8 million nones. Though lagging far behind the 71 percent of Americans who identified as Christian in the Pew poll, they are still a significant voting block, far larger than Jews (4.7 million), Muslims (2.2 million) and Buddhists (1.7 million) combined (8.6 million) and comparable to politically powerful Christian sects such as Evangelical (25.4 percent) and Catholic (20.8 percent).

This shift away from the dominance of any one religion is good for a secular society whose government is structured to discourage catch basins of power from building up and spilling over into people's private lives. But it is important to note that these nones are not necessarily atheists. Many have moved from mainstream religions into New Age spiritual movements, as evidenced in a 2017 Pew poll that found an increase from 19 percent in 2012 to 27 percent in 2017 of those who reported being "spiritual but not religious." Among this cohort, only 37 percent described their religious identity as atheist, agnostic or "nothing in particular."



Even among atheists and agnostics, belief in things usually associated with religious faith can worm its way through fissures in the materialist dam. A 2014 survey conducted by the Austin Institute for the Study of Family and Culture on 15,738 Americans, for example, found that of the 13.2 percent who called themselves atheist or agnostic, 32 percent answered in the affirmative to the question "Do you think there is life, or some sort of conscious existence, after death?" Huh? Even more incongruent, 6 percent of these atheists and agnostics also said that they believed in the bodily resurrection of the dead. You know, like Jesus.

What's going on here? The surveys didn't ask, but I strongly suspect a lot of these nonbelievers adopt either New Age notions of the continuation of consciousness without brains via some kind of "morphic resonance" or quantum field (or some such) or are holding out hope that science will soon master cloning, cryonics, mind uploading or the transhumanist ability to morph us into cyber-human hybrids. As I explicate in my book *Heavens on Earth,* I'm skeptical of all these ideas, but I understand the pull. And that gravitational well will grow ever deeper as science progresses in these areas—and especially if the number of atheists increases.

In a paper in the January 2018 issue of the journal *Social Psychological and Personality Science* entitled "How Many Atheists Are There?", Will M. Gervais and Maxine B. Najle, both psychologists at the University of Kentucky, contend that there may be far more atheists than pollsters report because "social pressures favoring religiosity, coupled with stigma against religious disbelief…, might cause people who privately disbelieve in God to nonetheless self-present as believers, even in anonymous questionnaires."

To work around this problem of self-reported data, the psychologists employed what is called an unmatched count technique, which has been previously validated for estimating the size of other underreported cohorts, such as the LGBTQ community. They contracted with YouGov to conduct two surveys of 2,000 American adults each, for a total of 4,000 subjects, asking participants to indicate how many innocuous versus sensitive statements on a list were true for them. The researchers then applied a Bayesian probability estimation to compare their results with similar Gallup and Pew polls of 2,000 American adults each. From this analysis, they estimated, with 93 percent certainty, that somewhere between 17 and 35 percent of Americans are atheists, with a "most credible indirect estimate" of 26 percent.

If true, this means that there are more than 64 million American atheists, a staggering number that no politician can afford to ignore. Moreover, if these trends continue, we should be thinking about the deeper implications for how people will find meaning as the traditional source of it wanes in influence. And we should continue working on grounding our morals and values on viable secular sources such as reason and science. SA

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Illustration by Izhar Cohen

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

Problem People

A look at follies, foibles and fumbles

By Steve Mirsky

A long, long time ago I dropped an American history course after the professor answered a student's question with, "In some cases, people were as much a part of the problem as anyone else." At the time, I doubted this guy had much to teach me. But recent events have made me reconsider his pedagogical prowess. I now believe people may indeed be as much a part of the problem as anyone else.

For example, it's been known for years that Volkswagen doctored its emissions tests to meet pollution standards. But only in late January did we learn about the monkeys. From the *New York Times:* "In 2014 … scientists in an Albuquerque laboratory conducted an unusual experiment: Ten monkeys squatted in airtight chambers, watching cartoons for entertainment as they inhaled fumes from a diesel Volkswagen Beetle."

Rest assured, no monkeys were harmed. By the cartoons. The fumes may have been harmful but less so than usual. Because the test of the Volkswagen was a dodge: the diesel Beetle in question had been modified to put out relatively clean exhaust.

The chicanery outraged PETA, People for the Ethical Treatment of Animals, which issued a statement noting that lab monkeys are deprived of fresh air and sunshine. I love monkeys—they're some of my closest evolutionary relatives—but they weren't the only victims. The totality of the VW pollution-standards fakery resulted in years of additional pollution, which deprived all primates (including you, pal) of fresh air and sunshine. Anyway, I'm awarding a point to my history prof: the monkeys were unwitting pawns, and it was, in fact, people who were arguably the biggest part of the VW Bug problem.

Then we have Saudi Arabia's camel contest. Reports broke in late January that some entrants in the King Abdulaziz Camel Festival's beauty contest had been disqualified because they'd received Botox injections. The botulinum toxin helps to inflate facial features such as the lips and nose, thus allowing a given camel to live up to local standards of dromedary attractiveness.

Owners are no doubt driven by pride, although the millions of dollars in prize money may also be a motivating factor. (The idea of injecting Botox into a camel is laughable in the U.S., where the neurotoxin is used properly. That is, to transform human lips into a virtual bill and thus imbue the recipient with that much sought after duck face.) Another point for my prof: innocent ungulates are surely not to blame; once again, it is people who make up the lion's share of the camel problem.

There's also the January case of the woman who was not allowed to board a plane with what press reports called "her emotional support peacock." I'm less taken aback by her attempt to fly with a peacock than with the assertion that the humongous bird offers someone succor. Peacocks are allowed to roam free at the Bronx Zoo, and confronting one on a walking path always triggers my fight-or-flight response. Maybe seeing me activates the bird's fight-or-flight as well. It would have the advantage as far as flight. Just not commercial flight. Problem: people, not peacocks.

Finally, congratulations to Philadelphia. The city's most famous figure, Benjamin Franklin, is reputed to have said, "Games lubricate the body and the mind," and there was much lubrication to be found following the Super Bowl win by the Philadelphia Eagles. Media outlets reported that before the game, Philly officials coated the lampposts lining downtown streets with hydraulic fluid. To keep ebullient Eagles enthusiasts (themselves possibly lubricated, if you know what I mean) from climbing the posts, as is local custom following athletic achievement.

Still, and despite their low coefficient of friction, the posts became festooned with fans, all of whom would be classified by taxonomists as people. Who, as is now established, are as much a part of the problem as anyone else. Because, as Franklin also purportedly said, "Wise men don't need advice. Fools won't take it." SA

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Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

APRIL

1968 Origin of the Continents

"As recently as five years ago the hypothesis that the continents had drifted apart was regarded with considerable skepticism, particularly among American investigators. Since then, as a result of a variety of new findings, the hypothesis has gained so much support that its critics may now be said to be on the defensive. The slow acceptance of what is actually a very old idea provides a good example of the intensive scrutiny to which scientific theories are subjected, particularly in the earth sciences, where the evidence is often conflicting and where experimental demonstrations are usually not possible. Geologists have a new game of chess to play, using a spherical board and strange new rules."

Oxygen in Steelmaking

"The making of steel, one of man's oldest arts, has been advanced by many important refinements since Sir Henry Bessemer inaugurated its modern technology more than a century ago, but it is certain that none of those improvements has had a more dramatic impact on the industry than one that is now being introduced in steel mills the world over. It involves the use of gaseous oxygen in the treating of iron to convert it into steel. The injection of oxygen speeds up every steelmaking process, reduces the cost of steelmaking and improves the quality of the steel. A new process based on the use of oxygen, introduced on a broad scale within the past 16 years, is replacing the open-hearth method."

1918 Plowing by Electric Light

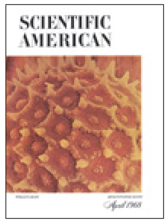
"The only way in which food production in England can be saved from total confusion is by the keenest sort of central administration. So Great Britain has organized a plowing army. Tractors and drivers have been mobilized for the most intensive sort of a drive against the vacant land of the United Kingdom. The machines themselves are in most cases Government property, a large part of them being of a well-known small American make. They are sent in groups to a given district and are used on a schedule of 24 hours per day, in three shifts. This, of course, means night plowing by artificial light, as shown in our illustration. The majority of the drivers and mechanics are women. A thousand drivers have had to be recruited recently."

Fake Lakes

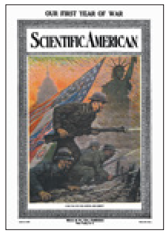
"At intervals during the past four years, Prof. H. C. Cowles, of the University of Chicago, and Mr. E. W. Shaw, of the U.S. Geological Survey, have made an investigation of certain apparently mythical 'lakes' which have been shown on maps of northeastern Arkansas for the past 75 years. Both geological and ecological evidence prove that no such lakes could have existed within the past century, at least. How they came to be charted on the early land survey maps is a mystery. Later cartographers have simply copied the old maps without verification."

1918: Fighting food shortages in Britain. Women drivers till the soil day and night with American tractors.

SCIENTIFIC AMERICAN, VOL. CXVIII, NO. 15; APRIL 13, 1918



1968



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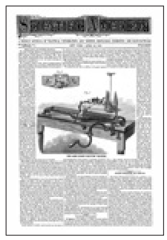


1868

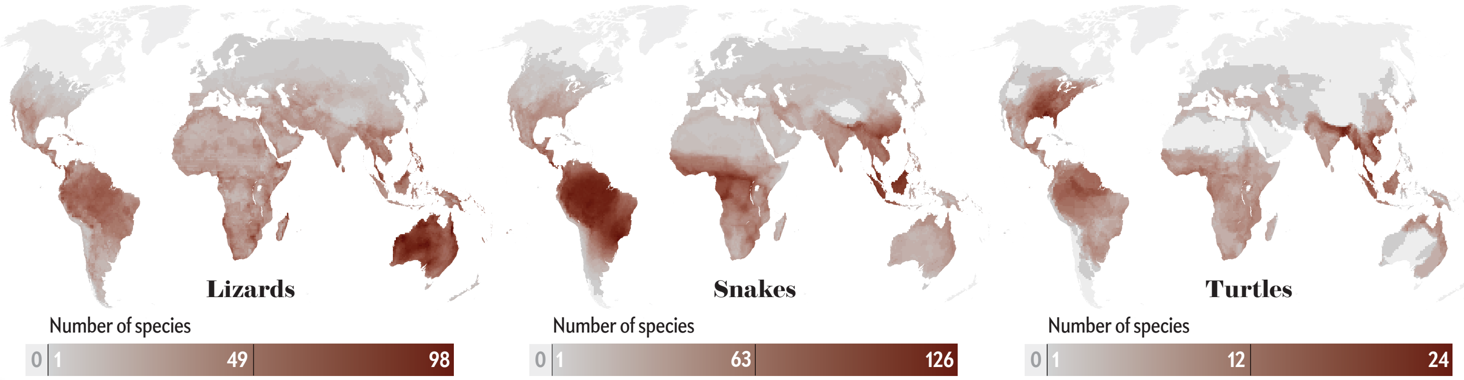
1868 Earth's Origin

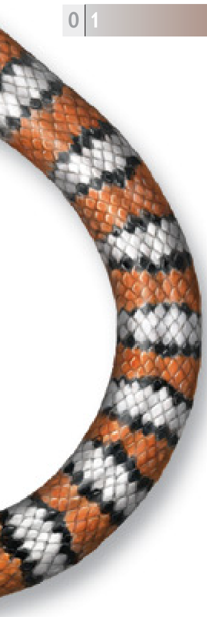
"Speculations concerning the origin of the world have of late years become the favorite theme of theorists. But there is one fact to which we will call attention. The labors of the alchymist laid the foundations of modern chemistry; the search for the square of the circle promoted mathematical science; and to the failure in securing perpetual motion we owe the spread of clearer notions of mechanical principles. But what, we ask, is the benefit that shall accrue to mankind from the vain attempt to lift the veil from the mysteries of the first creation? It would only be a barren acquisition to our theoretical knowledge, from which not a single useful result could be expected."

A Sweet Change

"Sweets of all kinds used to be denounced by tender mothers as 'trash and messes.' Now there is no attempt to taboo that which delighteth the juvenile palate most. In moderation, there is nothing more wholesome than sugar; and it is withal nourishing and warming, in consequence of the large amount of carbon contained in it. All the higher class of sweets came from France and Italy, where for ages they have been famous for these delicacies. But the introduction of steam into their fabrication has given to England the lead in manufactured sugar articles, which are now made on the largest scale, and are vastly cheapened since the days when we used to spend our halfpence in toffy."

Text by Mark Fischetti | Maps by Mapping Specialists, Illustration by Rachel Ivanyi

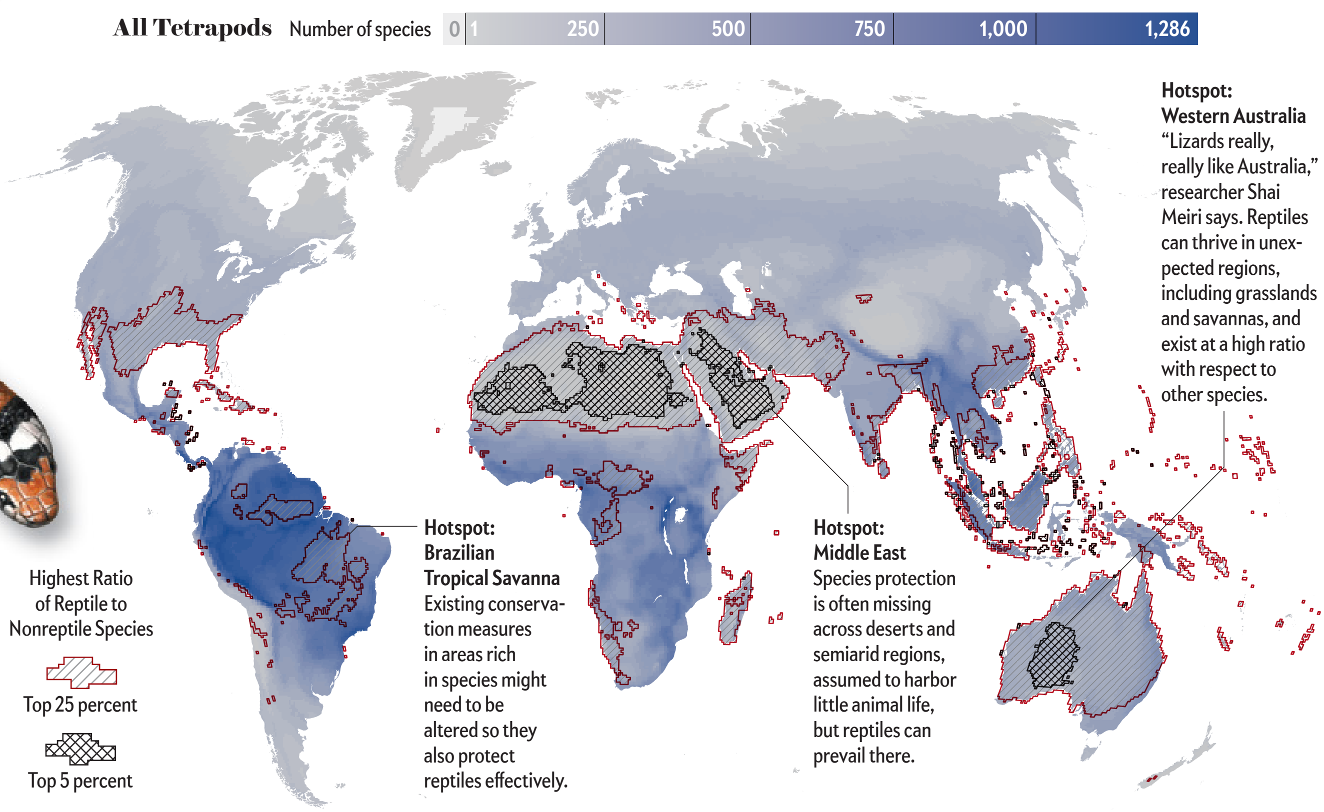




Where the Reptiles Are

Lizards, snakes and turtles are concentrated in largely unprotected areas

The number of mammal and bird species varies from place to place, but these groups of vertebrates still span much of the world. Reptiles do not. New research shows they are highly concentrated in hotspots and are largely absent across the rest of the earth (*blue map*). This highly uneven dispersion (*brown maps*) is a surprise. Scientists had diagrammed the somewhat smooth distributions of other tetrapods—vertebrates descended from the earliest four-limbed creatures. Those populations are typically large in extended regions and gradually tail off in many directions. The experts assumed that reptiles followed a similar pattern and designed conservation measures on the same false assumption. Now that investigators actually know where the world's 10,000 reptile species are, says Shai Meiri of Tel Aviv University, a member of the study team, "we can better model the threats to these species, so we know where to invest, to best protect all of nature."



SOURCE: "THE GLOBAL DISTRIBUTION OF TETRAPODS REVEALS A NEED FOR TARGETED REPTILE CONSERVATION," BY URI ROLL ET AL., IN *NATURE ECOLOGY & EVOLUTION*, VOL. 1; NOVEMBER 2017

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