SPECIAL REPORT **HOW CITIES CAN SAVE US ALL** A vision for a zero-waste, driver-free, energy-positive urban future PAGE 44

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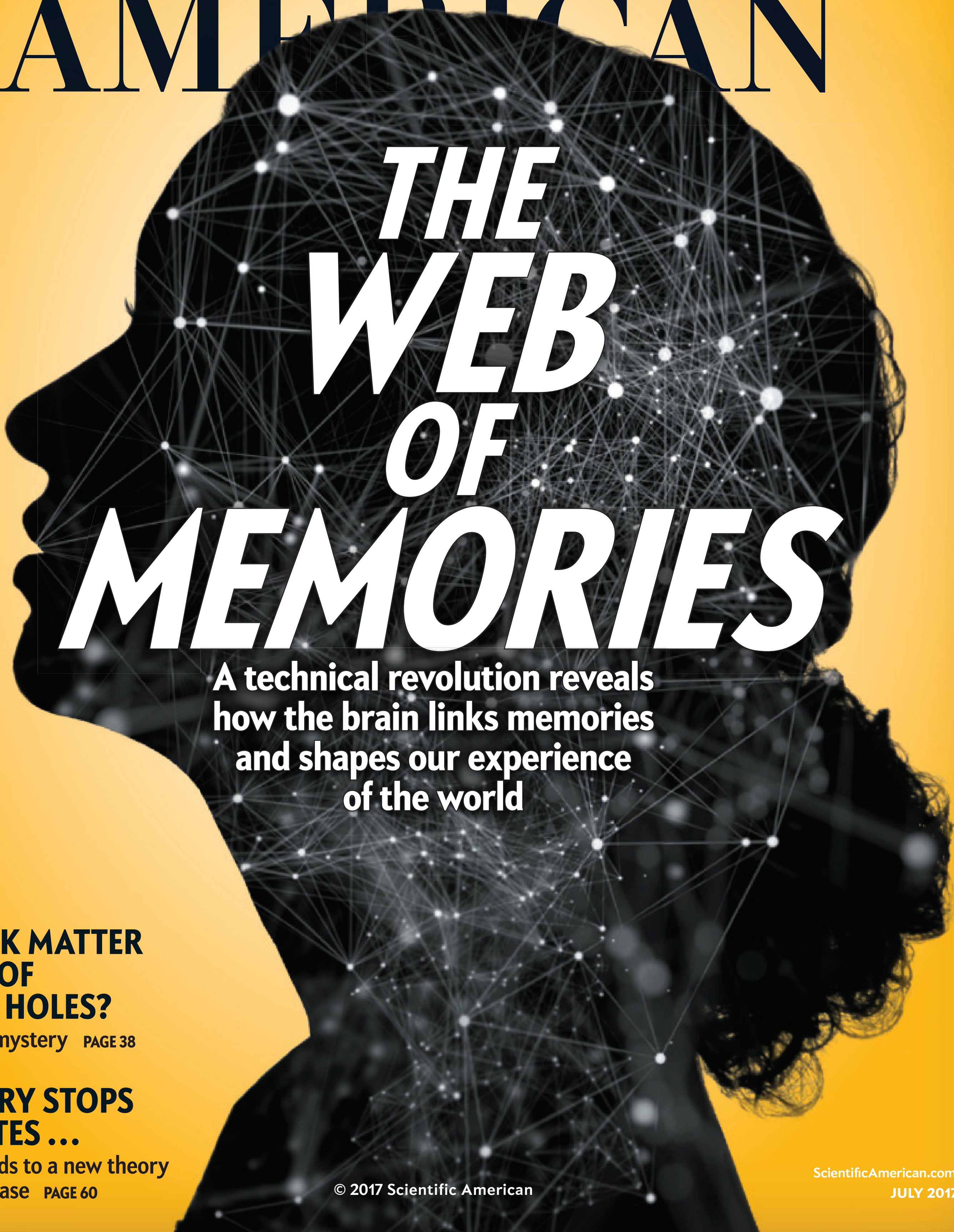

THE WEB OF MEMORIES

A technical revolution reveals how the brain links memories and shapes our experience of the world

PLUS

IS DARK MATTER MADE OF BLACK HOLES?

A cosmic mystery PAGE 38

SURGERY STOPS DIABETES ...

... and leads to a new theory of the disease PAGE 60

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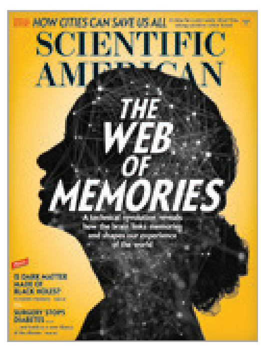

ON THE COVER

New technologies have begun to reveal how one memory links to another—critical for integrating sights, sounds and sensations to form the texture of experience. Disruptions in weaving together these conscious threads often occur in psychiatric disorders and during the cognitive decline of aging.

COVER: GETTY IMAGES (*head and web pattern*); THIS PAGE: GETTY IMAGES (*dancers*)

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ON THE WEB

Tuning Up the Immune System
Video of *Scientific American*'s Immune System Orchestra shows what happens when an allergen changes the music.
Go to www.ScientificAmerican.com/jul2017/allergies

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

Designing the City of Tomorrow Today

As I write this essay, I feel myself being drawn inexorably toward one of the world's great destinations: New York City. Okay, I'm actually riding a commuter train. But this daily journey always feels compelling to me. I'm headed toward a place of great energy, where I work and find collaborative opportunities, meet up with friends, enjoy cultural activities and often find myself spontaneously marveling at the surrounding man-made wonders.

Many other people clearly are equally captivated by the opportunities they find in cities. That is why more than half of humanity lives in these centers of enterprise and innovation, with that number rising quickly. An estimated five billion will be dwelling in cities by 2030—and half of them will be moving into homes and workplaces that do not yet exist. How we create and reshape our urban landscapes and systems will have a powerful effect on the future of our world: "As cities go, so goes the planet," writes architect William McDonough in "How Cities Could Save Us." Beginning on page 44, this article is part of a special report that takes a look at sustainable cities. One key, McDonough says, is to think in terms of living systems: circular systems, rather than linear. As he puts it, "Cities are designed, but they are also organisms." Following the theme, energy researcher Michael E. Webber explores "Tapping the Trash" (*page 48*). He describes how urban centers can help us reduce and reuse waste heat, water and materials, creating revenue and lowering costs. The third part of our report looks at how we get around: Carlo Ratti and Assaf Biderman, both at the Massachusetts Institute of Technology, consider a turning point for transportation enabled by webs of sensor-laden vehicles and smart intersections in their feature, "From Parking Lot to Paradise" (*page 54*).

CURITIBA in Brazil is among the cities developing resource-smart programs.

We each carry within ourselves a different kind of city: an inner hub of energetic neural activity that creates our mind. In the cover story, "Memory's Intricate Web," starting on page 30, neuroscientist Alcino J. Silva describes nothing less than a revolution in memory research wrought by new technologies that can image the activity of individual neurons—even switching the cells on and off as directed. Learning more about how specific cells store a given memory is giving us insights into how we mentally construct the world around us, which for me feels resonant in an issue in which we are discussing how we are shaping the planet. As ever, we welcome your comments. SA

GETTY IMAGES

Illustration by Nick Higgins

February 2017

A COSMIC CONTROVERSY

The origins of space and time are among the most mysterious and contentious topics in science. Our February 2017 article "Pop Goes the Universe" argues against the dominant idea that the early cosmos underwent an extremely rapid expansion called inflation. Its authors instead advocate for another scenario—that our universe began not with a bang but with a bounce from a previously contracting cosmos. In the letter below, a group of 33 physicists who study inflationary cosmology respond to that article. It is followed by a reply from the authors.

In "Pop Goes the Universe," by Anna Ijjas, Paul J. Steinhardt and Abraham Loeb, the authors (hereafter "IS&L") make the case for a bouncing cosmology, as was proposed by Steinhardt and others in 2001. They close by making the extraordinary claim that inflationary cosmology "cannot be evaluated using the scientific method" and go on to assert that some scientists who accept inflation have proposed "discarding one of [science's] defining properties: empirical testability," thereby "promoting the idea of some kind of nonempirical science." We have no idea what scientists they are referring to. We disagree with a number of statements in their article, but in this letter, we will focus on our categorical disagreement with these statements about the testability of inflation.

There is no disputing the fact that inflation has become the dominant paradigm in cosmology. Many scientists from around the world have been hard at work for years investigating models of cosmic inflation and comparing these predictions with empirical observations. According to the high-energy physics database INSPIRE, there are now more than 14,000 papers in the scientific literature, written by over 9,000 distinct scientists, that use the word "inflation" or "inflationary" in their titles or abstracts. By claiming that inflationary cosmology lies outside the scientific method, IS&L are dismissing the research of not only all the authors of this letter but also that of a substantial contingent of the scientific community. Moreover, as the work of several major international collaborations has made clear, inflation is not only testable, but it has been subjected to a significant number of tests and so far has passed every one.

Inflation is not a unique theory but rather a class of models based on similar principles. Of course, nobody believes that all these models are correct, so the relevant question is whether there exists at least one model of inflation that seems well motivated, in terms of the underlying particle physics assumptions, and that correctly describes the measurable properties of our universe. This is very similar to the early steps in the development of the Standard Model of particle physics, when a variety of quantum field theory models were explored in search of one that fit all the experiments.

Although there is in principle a wide space of inflationary models to examine, there is a very simple class of inflationary models (technically, "single-field slow-roll" models) that all give very similar predictions for most observable quantities—predictions that were clearly enunciated decades ago. These "standard" inflationary models form a well-defined class that has been studied extensively. (IS&L have expressed strong opinions about what they consider to be the simplest models within this class, but simplicity is subjective, and we see no reason to restrict attention to such a narrow subclass.) Some of the standard inflationary models have now been ruled out by precise empirical data, and this is part of the desirable process of using observation to thin out the set of viable models. But many models in this class continue to be very successful empirically.

The standard inflationary models predict that the universe should have a critical mass density (that is, it should be geometrically flat), and they also predict the statistical properties of the faint ripples that we detect in the cosmic microwave background (CMB). First, the ripples should be nearly "scale-invariant," meaning that they have nearly the same intensity at all angular scales. Second, the ripples should be "adiabatic," meaning that the perturbations are the same in all components: the ordinary matter, radiation and dark matter all fluctuate together. Third, they should be "Gaussian," which is a statement about the statistical patterns of relatively bright and dark regions. Fourth and finally, the models also make predictions for the patterns of polarization in the CMB, which can be divided into two classes, called E-modes and B-modes. The predictions for the E-modes are very similar for all standard inflationary models, whereas the levels of B-modes, which are a measure of gravitational radiation in the early universe, vary significantly within the class of standard models.

The remarkable fact is that, starting with the results of the Cosmic Background Explorer (COBE) satellite in 1992, numerous experiments have confirmed that these predictions (along with several others too technical to discuss here) accurately describe our universe. The average mass density of the universe has now been measured to an accuracy of about half of a percent, and it agrees perfectly with the prediction of inflation. (When inflation was first proposed, the average mass density was uncertain by at least a factor of three, so this is an impressive success.) The ripples of the CMB have been measured carefully by two more satellite experiments, the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite, as well as many ground- and balloon-based experiments—all confirming that the primordial fluctuations are indeed nearly scale-invariant and very accurately adiabatic and Gaussian, precisely as predicted (ahead of time) by standard models of inflation. The B-modes of polarization have not yet been seen, which is consistent with many, though not all, of the standard models, and the E-modes are found to agree with the predictions. In 2016 the Planck satellite team (a collaboration of about 260 authors) summarized its conclusions by saying that "the *Planck* results offer powerful evidence in favour of simple inflationary models." So if inflation is untestable, as IS&L would have us believe, why have there been so many tests of it and with such remarkable success?

While the successes of inflationary models are unmistakable, IS&L nonetheless make the claim that inflation is untestable. (We are bewildered by IS&L's assertion that the dramatic observational successes of inflation should be discounted while they accuse the advocates of inflation of abandoning empirical science!) They contend, for example, that inflation is untestable because its predictions can be changed by varying the shape of the inflationary energy density curve or the initial conditions. But the testability of a theory in no way requires that all its predictions be independent of the choice of parameters. If such parameter independence were required, then we would also have to question the status of the Standard Model, with its empirically determined particle content and 19 or more empirically determined parameters.

An important point is that standard inflationary models *could have failed any of the empirical tests described above, but they did not.* IS&L write about how "a failing theory gets increasingly immunized against experiment by attempts to patch it," insinuating that this has something to do with inflation. But despite IS&L's rhetoric, it is standard practice in empirical science to modify a theory as new data come to light, as, for example, the Standard Model has been modified to account for newly discovered quarks and leptons. For inflationary cosmology, meanwhile, there has so far been no need to go beyond the class of standard inflationary models.

IS&L also assert that inflation is untestable because it leads to eternal inflation and a multiverse. Yet although the possibility of a multiverse is an active area of study, this possibility in no way interferes with the empirical testability of inflation. If the multiverse picture is valid, then the Standard Model would be properly understood as a description of the physics in our visible universe, and similarly the models of inflation that are being refined by current observations would describe the ways inflation can happen in our particular part of the universe. Both theories would remain squarely within the domain of empirical science. Scientists would still be able to compare newly obtained data—from astrophysical observations and particle physics experiments—with precise, quantitative predictions of specific inflationary and particle physics models. Note that this issue is separate from the loftier goal of developing a theoretical framework that can predict, without the use of observational data, the specific models of particle physics and inflation that should be expected to describe our visible universe.

Like any scientific theory, inflation need not address *all* conceivable questions. Inflationary models, like all scientific theories, rest on a set of assumptions, and to understand those assumptions we might need to appeal to some deeper theory. This, however, does not undermine the success of inflationary models. The situation is similar to the standard hot big bang cosmology: the fact that it left several questions unresolved, such as the near-critical mass density and the origin of structure (which are solved elegantly by inflation), does not undermine its many successful predictions, including its prediction of the relative abundances of light chemical elements. The fact that our knowledge of the universe is still incomplete is absolutely no reason to ignore the impressive *empirical* success of the standard inflationary models.

During the more than 35 years of its existence, inflationary theory has gradually become the main cosmological paradigm describing the early stages of the evolution of the universe and the formation of its large-scale structure. No one claims that inflation has become certain; scientific theories don't get proved the way mathematical theorems do, but as time passes, the successful ones become better and better established by improved experimental tests and theoretical advances. This has happened with inflation. Progress continues, supported by the enthusiastic efforts of many scientists who have chosen to participate in this vibrant branch of cosmology.

Empirical science is alive and well!

Alan H. Guth *Massachusetts Institute of Technology*

David I. Kaiser *M.I.T.*

Andrei D. Linde *Stanford University*

Yasunori Nomura *University of California, Berkeley*

Charles L. Bennett *Johns Hopkins University, Wilkinson Microwave Anisotropy Probe (WMAP) mission and Cosmic Background Explorer (COBE) mission*

J. Richard Bond *University of Toronto, Canadian Institute for Advanced Research, Canadian Institute for Theoretical Astrophysics and Planck collaboration*

François Bouchet *Institut d'Astrophysique de Paris, CNRS and UPMC, Sorbonne Universités, Planck satellite, HFI (High Frequency Instrument) consortium and Planck Science Team*

Sean Carroll *California Institute of Technology*

George Efstathiou *University of Cambridge and Planck Science Team*

Stephen Hawking *University of Cambridge*

Renata Kallosh *Stanford University*

Eiichiro Komatsu *Max Planck Institute for Astrophysics and WMAP collaboration*

Lawrence M. Krauss *Arizona State University*

David H. Lyth *Lancaster University*

Juan Maldacena *Institute for Advanced Study*

John C. Mather *NASA Goddard Space Flight Center and COBE mission*

Hiranya Peiris *University College London, Oskar Klein Center for Cosmoparticle Physics, WMAP collaboration and Planck collaboration*

Malcolm Perry *University of Cambridge*

Lisa Randall *Harvard University*
Martin Rees *University of Cambridge*
Misao Sasaki *Kyoto University*
Leonardo Senatore *Stanford University*
Eva Silverstein *Stanford University*
George F. Smoot III *University of California, Berkeley, and COBE mission*
Alexei Starobinsky *Landau Institute for Theoretical Physics, Russian Academy of Sciences*
Leonard Susskind *Stanford University*
Michael S. Turner *University of Chicago*
Alexander Vilenkin *Tufts University*
Steven Weinberg *University of Texas at Austin*
Rainer Weiss *M.I.T., COBE mission and Laser Interferometer Gravitational-Wave Observatory (LIGO)*
Frank Wilczek *M.I.T.*
Edward Witten *Institute for Advanced Study*
Matias Zaldarriaga *Institute for Advanced Study*

THE AUTHORS REPLY: We have great respect for the scientists who signed the rebuttal to our article, but we are disappointed by their response, which misses our key point: the differences between the inflationary theory once thought to be possible and the theory as understood today. The claim that inflation has been confirmed refers to the outdated theory before we understood its fundamental problems. We firmly believe that in a healthy scientific community, respectful disagreement is possible and hence reject the suggestion that by pointing out problems, we are discarding the work of all of those who developed the theory of inflation and enabled precise measurements of the universe.

Historically, the thinking about inflation was based on a series of misunderstandings. It was not understood that the outcome of inflation is highly sensitive to initial conditions. And it was not understood that inflation generically leads to eternal inflation and, consequently, a multiverse—an infinite diversity of outcomes. Papers claiming that inflation predicts this or that ignore these problems.

Our point is that we should be talking about the contemporary version of inflation, warts and all, not some defunct relic. Logically, if the outcome of inflation is highly sensitive to initial conditions that are not yet understood, as the respondents concede, the outcome cannot be determined. And if inflation produces a multiverse in which, to quote a previous statement from one of the responding authors (Guth), "anything that can happen will happen"—it makes no sense whatsoever to talk about predictions. Unlike the Standard Model, even after fixing all the parameters, any inflationary model gives an infinite diversity of outcomes with none preferred over any other. This makes inflation immune from any observational test. For more details, see our 2014 paper "Inflationary Schism" (preprint available at https://arxiv.org/abs/1402.6980).

We are three independent thinkers representing different generations of scientists. Our article was not intended to revisit old debates but to discuss the implications of recent observations and to point out unresolved issues that present opportunities for a new generation of young cosmologists to make a lasting impact. We hope readers will go back and review our article's concluding paragraphs. We advocated against invoking authority and for open recognition of the shortcomings of current concepts, a reinvigorated effort to resolve these problems and an open-minded exploration of diverse ideas that avoid them altogether. We stand by these principles.

March 2017

GENE JOB

"Should Babies Be Sequenced?" by Bonnie Rochman, discusses how we can now sequence newborns' genomes to screen for genetic risks not included in standard tests and the potential issues with doing so.

Widespread DNA sequencing is incompatible with the U.S.'s largely employer-provided health care system. If a hiring manager compares two otherwise equal candidates, one of whom has a genetic predisposition that doubles the chance of developing a rare disease, that candidate probably won't get the job.

John Schmitt *via e-mail*

TURING PLANS

In discussing the flaws of the Turing test, in which a machine tries to convince an interrogator it is human, in "Am I Human?" Gary Marcus notes that "one can 'win' simply by being deceptive or feigning ignorance." By applying that insight to the Washington Beltway, we may well find that the U.S. is governed by robots. And we humans may indeed get "tired of winning."

John Leydon *Aldie, Va.*

I applaud the effort to devise more rigorous tests of human-level artificial intelligence, as described by Marcus and by John Pavlus in "The New Turing Tests." But what if someone creates a machine that truly passes the old Turing test, not through trickery but genuine intelligence? Will we say to it, "Sorry, because you cannot summarize a video (as in the I-Athlon test) or build a house out of blocks (as in the Physically Embodied Turing Test), we cannot recognize your intelligence?" Could Helen Keller summarize a video? Can Stephen Hawking build a house out of blocks?

Bill Freese *Department of Education, Montana State University*

STARTING STARSHOT

In "Near-Light-Speed Mission to Alpha Centauri," Ann Finkbeiner reports on the Breakthrough Starshot project to use directed energy, in the form of lasers, and wafer-scale spacecraft to enable humanity's first interstellar missions. She also describes my involvement as a member of the project.

While the article is excellent, it lacks clarity regarding the genesis of Breakthrough Starshot: The NASA program now referred to as Starlight, of which I am the director, is directly responsible for beginning Starshot. The program started in 2009 at the University of California, Santa Barbara, with published papers commencing in 2013. The 2014 proposal for its first phase was funded in early 2015. The second phase was funded in 2016 and is still ongoing. NASA's initiative to develop directed-energy-driven spacecraft for an interstellar mission was introduced in spring 2016 as part of the congressional record for fiscal year 2017 that called for the agency to study such a mission to coincide with the 100th anniversary of the first moon landing in 2069. (The report mentions our work as one option.) Proper credit should be attributed to NASA's effort in this area.

My paper "Roadmap to Interstellar Flight," which Finkbeiner notes started the Starshot project in earnest, summarized our NASA program and outlined the path ahead required to achieve interstellar capability using directed energy. That paper and more than four dozen technical papers on our directed-energy program at U.C.S.B. are available on our Web site: www.deepspace.ucsb.edu/projects.

PHILIP LUBIN *University of California, Santa Barbara*

POPULAR FRANCHISE

In "Our Elections Are Not Secure" [Forum], David Dill asserts that in the U.S., "technically sophisticated individuals could steal an election by hacking voting machines in key counties in just a few states."

The best way to prevent such hacking is to elect the president by popular vote. Hackers would then be faced with the impossible task of attacking most of the voting places in the country to change the results of an election.

GORDON MOORE *via e-mail*

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We Can't Avoid Future Disease Outbreaks

But the U.S. can minimize the danger with a robust health emergency fund

By the Editors

Public health emergencies are a fact of life in a world as interconnected as ours. In just the past five years we have witnessed unexpected outbreaks of devastating diseases—Ebola, chikungunya, yellow fever and Zika—each of which has spread far beyond its historical geographical range. No one can say what the next large-scale emergency will be, whom it will affect or when it will strike, but we do know that it is inevitable. Yet the U.S. is woefully unprepared to meet this threat because it does not set aside money to beat back an outbreak before it can spread.

The U.S. used to have a robust national public health emergency fund, first created by Congress in the 1980s, but its balance has since dwindled to a paltry $57,000—enough to buy a few thousand first aid kits but not much else. What we need is more on the order of several hundred million to $1 billion in new funding that is always and immediately available and is replenished whenever it becomes depleted.

A mechanism is already in place to deal with natural disasters such as earthquakes and floods. The Federal Emergency Management Agency is preauthorized to disburse hundreds of millions of dollars to pay for debris removal, for example, when state or local budgets become overwhelmed by a weather emergency.

Creating a similar "rainy day" fund—and providing the Centers for Disease Control and Prevention with permission to use it in advance—could save lives and money, both at home and overseas. There have been some moves in this direction. President Donald Trump's general budget proposal for 2018 includes such a fund. But it does not give any dollar figures, and the health care bill passed by the House of Representatives in May cuts at least $1 billion from annual public health funding.

The idea behind an emergency fund is not to displace efforts to combat infectious disease but to ramp them up to meet a crushing temporary need. During an outbreak the CDC can call on many doctors and nurses to work without pay, but the costs of transportation, medical supplies and protective equipment still have to be covered. The surge in patients typically increases the need for laboratory testing or surveillance of insects, rodents or other carriers of illness—extra requirements that can be met by short-term contracts with commercial companies.

Thomas Frieden, former director of the CDC, estimates that 90 percent of the Ebola deaths that occurred in West Africa in 2014 and 2015 could have been prevented if the agency had been able to unleash a massive effort right away. In July 2014 he estimates that an additional 300 beds to treat Ebola patients would have been enough to stop the illness from spreading. But July was also approaching the end of the fiscal year for the U.S. government, and there was not enough flexibility in the CDC's budget to finance the necessary response. By November, after Congress made further money available, more than 3,000 beds were needed to treat everyone who had become sick.

When Zika hit the southern U.S. and Puerto Rico in 2016, health officials had to go back to Congress to ask for funds for the new emergency. Months went by without action as some legislators wrangled over the role Planned Parenthood might play in the endeavor, among other things. Local health officials reportedly put other critical programs on hold to deal with the new threat.

Legislators from both the Democratic and Republican parties have recognized the problem and are trying to do something about it. Senator Bill Cassidy of Louisiana, a Republican, introduced the Public Health Emergency Response and Accountability Act last year and again in January 2017 to create a more robust national health emergency fund that would tie current funding to amounts spent on previous public health emergencies. In 2016 Representative Rosa DeLauro of Connecticut, a Democrat, called for a one-time appropriation of $5 billion for emergency health and is planning to do so again this year. But introducing legislation (or making a vague promise in the president's budget) does not help if Congress fails to pass it. Lawmakers need to follow through by approving one or both of the proposed measures for the president to sign to ensure that the money will be there when the next public health emergency strikes.

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Illustration by Cat O'Neil

Kunmi Sobowale is a psychiatry resident at the Yale School of Medicine. He has explored increasing access to mental health care in East and Southeast Asia and for low-income populations in the U.S.

Raise Alcohol Taxes, Reduce Violence

It's an effective way to curtail assaults and suicides

By Kunmi Sobowale

The woman disappeared. She had been coming to our group therapy sessions for months, and suddenly she stopped. Other group members told me why: she had been beaten so badly by her husband that she ended up in the hospital. The assault happened while her husband was, to use a too dainty phrase, "under the influence" of alcohol. I wish this were an isolated incident, but alcohol is a common instigator of violence against others, as well as harm to oneself.

This link between alcohol and violence has been shown in multiple countries. In 1998 the Bureau of Justice Statistics reported that in the U.S., two thirds of violent attacks on intimate partners occurred in the context of alcohol abuse. Drinking increases the perpetration of physical and sexual violence. Alcohol use also reportedly increases the severity of violent assaults. Although drinking alcohol does not always lead to violence and is not a prerequisite for violence to occur, the link between alcohol and violence is undeniable.

The victims are overwhelmingly women. But children are also harmed. Parents who drink heavily are more likely to physically abuse their child. Youngsters who live in neighborhoods with more bars or liquor stores are more likely to be maltreated. In fact, one of out every 10 instances of child abuse reported to child protective service agencies in the U.S. involves alcohol use.

Violent, drunken men fall victim, too. They are as likely to die from alcohol-related firearm incidents as drunk-driving accidents. For all the effort put into preventing drunk driving, we have utterly failed to appreciate that being intoxicated while in possession of a firearm is an equally dangerous situation. Nevertheless, many states permit customers to carry firearms into establishments that serve alcohol.

As a mental health care provider, I also commonly see patients under the influence who contemplate or try suicide. Suicide attempts are often impulsive acts. When sober, many patients regret these efforts to take their own life. Unfortunately, alcohol intoxication increases the risk that people will attempt suicide with a firearm, and because guns are the most lethal suicide method in the U.S., it is often too late for regrets.

How do we break this deadly connection? As doctors, we should always ask about alcohol use, violence and access to firearms, simply to raise awareness among our patients. But there is another strategy that would be highly effective: raise alcohol taxes. Yes, alcohol is taxed, but the taxes have not kept up with inflation, making drinking more affordable than it has been in decades. Evidence shows that driving the price up would lower drinking's tragic human cost.

An analysis incorporating results from 112 different studies found that raising the price of alcohol decreases alcohol consumption. People living in states with higher alcohol taxes are less likely to binge drink. In 2011 Maryland increased their alcohol sales tax by 50 percent. The tax was associated with a decrease in the purchase of alcohol in the state. Compared with other U.S. states, there was much less drinking. Further, there were additional benefits, such as fewer cases of gonorrhea in the state. Similar results were found in Illinois. Indeed, the effect of increased alcohol taxes on curtailing violence has been shown in many studies.

Compared with other approaches to violence prevention, higher taxes on alcohol seem more politically feasible—certainly they will get more support than gun-control measures. Taxes are more effective than most other alcohol-consumption interventions, and they garner revenue for local governments. States can use that money to support programs that aid victims of violence. Taxation also drives down youth drinking, which, in turn, lowers the chance that young people will grow into heavy drinkers. One common argument against taxing alcohol is that it disproportionately affects poor people—but a recent study in the journal *Preventing Chronic Disease* suggests that is not true. Moreover, in general, evidence suggests that less alcohol access does not lead people to use other drugs.

If policy makers are serious about violence prevention—to say nothing of reducing car and other accidents—they need to reduce alcohol use. Taxation is a simple and powerful way to do so. SA

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Illustration by Christina Chung

ADVANCES

The Javari River in Peru and Brazil is one of the Amazon River's tributaries. Millions of years ago the Amazon basin was likely flooded by seawater.

INSIDE

- Pinpointing the brain's dreaming "hot zone"
- Do plants have a sense of hearing?
- Missing airplane hunt brings seafloor into focus
- Robots learn social skills to help care for the elderly

GEOLOGY

Amazon Atlantis

Sedimentary evidence suggests the vast river basin had a wet, salty past

For decades scientists have grappled with one of our planet's greatest biogeographical mysteries: how the geologic history of the Amazon River basin has shaped its magnificent ecosystem. Now new research describes sedimentary evidence from eastern Colombia and northwestern Brazil that suggests the enormous basin was covered by ocean water at least twice in the past. The Amazon is famous for its river, which only started flowing around nine million years ago. Ideas about the structure of the preriver landscape include a flooded rain forest, a huge freshwater lake and a fan-shaped, continent-spanning network of streams. Understanding the shape of this ancient landscape is crucial to learning what spawned the staggering biodiversity of the Amazon rain forest.

One theory posits that marine waters inundated western Amazonia during the Miocene epoch, 23 million to five million years ago, possibly creating an environment where hosts of new species could evolve. Scientists agree that sections of the Amazon have been underwater in the past, but there is no consensus as to the mechanism or extent of the flooding.

A study published earlier this year in *Science Advances* indicates that the Amazon flooded during two separate intervals in the early and mid-Miocene (roughly 18 million and 14 million years ago, respectively). Study co-authors Carlos Jaramillo, a pollen expert at the Smithsonian Tropical Research Institute in Panama, and Jaime Escobar, a paleoclimatologist at the University of the North in Colombia, and their colleagues contend that the Caribbean Sea breached the South American coast by way of Venezuela and Colombia, covering massive tracts of ancient Amazonia with a tongue of saltwater that reached into the continent. As the water advanced, it lost depth and became a marine/brackish ecosystem, then a watery transitional zone, which finally gave way to dry land. Distinct layers in the sediment cores show that in Colombia, the flooding events lasted for 900,000 and 3.7 million years, respectively, while in western Amazonia, which is farthest inland, they endured for 200,000 and 400,000 years.

The researchers also describe how sediment cores have yielded fossil evidence supporting the occurrence of these marine inundations. The most interesting macrofossils found in the several-centimeter-wide core from Colombia's Saltarin region are a shark tooth, possibly from a blacktip or a hammerhead, and a mantis shrimp, a marine organism that burrows into the sandy and muddy bottom of tropical seas. "Finding a shark tooth in such a narrow core means there have to be many more, and that points to the extent of these saltwater incursions," Jaramillo says. "The Amazon rain forest is a very dynamic system and not as old as previously thought. Today it covers an area as large as the continental U.S., but nearly 14 million years ago it was an ocean."

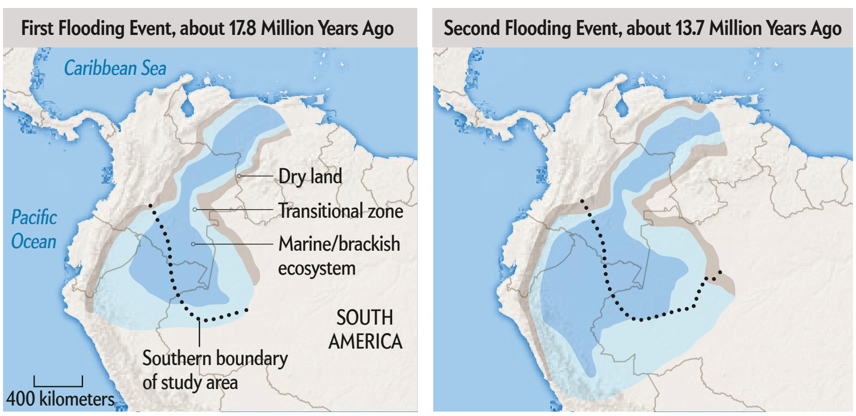
The new findings agree with previous research led by geologist and pollen expert Carina Hoorn of the University of Amsterdam and Amazon Regional University IKIAM in Ecuador. Hoorn recently determined the age of the river but was not involved in the *Science Advances* study. "Taken together, the evidence for marine incursions into Amazonia is really overwhelming" and paves the way for further research on how this marine environment may have influenced the evolution of the region's biodiversity, she says.

But others are more cautious. "This paper provides important, though not absolutely conclusive, evidence of marine incursions," says evolutionary biologist Christopher Dick of the University of Michigan, who studies plant diversification in several parts of the Amazon. "But most of the other scenarios are still possible, even with these new data."

Jaramillo and his co-authors do not go so far as to say that the Miocene saltwater incursions alone are the reason for the Amazon's biodiversity, but they think several of the existing plant genres in today's rain forest could trace their lineages to species living in forests that were permanently flooded. Dick disagrees, however. From a terrestrial botanical perspective, he says, it would be hard to prove that any extant species diversity could be attributed to these floods.

It appears that the detective work in this mighty river and the forest it nurtures will stretch well into the future.

—Angela Posada-Swafford



Researchers reconstructed the historical marine flooding of the Amazon rain forest using sediment cores gathered from eastern Colombia and northwestern Brazil. These maps show the maximum extent of floods during two separate periods. The region was flooded between 18.1 million and 17.2 million years ago and between 16.1 million and 12.4 million years ago, respectively. In both maps, the reconstruction below the southern boundary of the study area is based on cores gathered during an earlier study in 2010 but does not cover the entire time span included in the cores from above the dotted line.

ANIMAL BEHAVIOR

Boogie Bears

Twisting movements leave smelly messages in the animals' paw prints

For decades bear biologists have known that bears engage in a delightful ramble variously dubbed "sumo strutting," "cowboy walking" or, simply, the "bear dance." Many researchers have guessed at the reason, but a recent study finally offers solid clues.

As they walk, the bears vigorously twist their feet into the ground. Sometimes they step into footprints left behind by other bears after giving the prints a good sniff. Some have referred to these collective tracks as bear highways because they become well traveled over time.

"Everyone suspected that there was something in [the footprints]," says Agnieszka Sergiel, a biologist at the Polish Academy of Sciences' Institute of Nature Conservation and a co-author of the study, which was published recently in *Scientific Reports.* "But no one really investigated." She and her colleagues wondered whether the bears deposit their scent through glands on their paws as a means of communication.

Sergiel's team examined a pair of brown bears and determined that the animals' paws contain sweat glands, suggesting that the prints leave behind a scent. The researchers also identified 26 different volatile compounds—six of them unique to males—in paw sweat, indicating that bears may use aroma to determine the sex of previous ursine travelers.

Sergiel says the bear footprints are akin to mailboxes, although the messages they send remain a mystery.

—Jason G. Goldman

PRECEDING PAGES: INGO ARNDT *Getty Images*; THIS PAGE: SOURCE: "MIOCENE FLOODING EVENTS OF WESTERN AMAZONIA," BY CARLOS JARAMILLO ET AL., IN *SCIENCE ADVANCES*, VOL. 3, NO. 5, ARTICLE NO. E1601693; MAY 3, 2017; ART WOLFE *Getty Images* (bears)

Map by Mapping Specialists

GENETICS

The Mouse Parent Trap

A single gene may be linked to nest building in mice

Nurturing nesters: oldfield mice (*Peromyscus polionotus subgriseus*) make good parents.

Some wild mice are diligent parents, building elaborate grassy nests to keep their young safe and warm. Others are less attentive and construct shoddier homes for their offspring. Researchers recently identified a gene that regulates nest building—one of only a few genes known to affect parental behavior in mammals, including humans.

In a study published in *Nature,* geneticist Andrés Bendesky of Harvard University and his colleagues worked with two kinds of mice that are genetically similar but differ in their pairing behavior: a subspecies of oldfield mice (*Peromyscus polionotus subgriseus*) form monogamous pairs, whereas deer mice *Peromyscus maniculatus*) mate with multiple partners. They also parent differently. Oldfield mice build more elaborate nests than their promiscuous counterparts, and they spend more time grooming and huddling with their pups, as well as retrieving stray ones. In the study, these parenting behaviors did not depend on the care that the mice received as babies—when pups of one species were fostered by parents of the other species, they still grew up to mimic their biological parents' nurturing habits.

In search of a genetic basis for these parental behaviors, Bendesky and his colleagues crossbred the two types of mice twice to yield nearly 800 grandpups. Among the second-generation offspring, one gene linked to nest building stood out—it regulates the hormone vasopressin, which, like oxytocin, has a strong effect on social and bonding behaviors in mammals and birds. The researchers followed up with two experiments: in one, they injected vasopressin into the brains of mouse parents from both of the wild species, and in the other, they genetically manipulated vasopressin neurons in the brains of house mice *Mus musculus*) to excite them. Both sets of mice built lower-quality nests, suggesting that vasopressin and the gene responsible for producing it play a critical role in nest building.

The results surprised Oliver Bosch, a biologist at the University of Regensburg in Germany, who was not involved with the new study. In his own research with rats and voles, vasopressin *promoted* some maternal behaviors. It is possible that the hormone serves different functions before the birth of pups than it does afterward, depending on whether parents are preparing for their babies' arrival or tending to them. "Maybe it's suppressed in the beginning, and then later it kicks in and promotes maternal behavior," he says. It should come as no shock, after all, when the affairs of mice go astray. —*Andrea Marks*

NEUROSCIENCE

The Stuff of Dreams

A "hot zone" in the dreaming brain offers a window into consciousness

"To sleep, perchance to dream"—Shakespeare may not exactly have been talking about our nocturnal journeys to another world, but that does not make the phenomenon of dreams any less mysterious or meaningful. Recent research is expanding our understanding—and yielding insights into consciousness itself.

Sleep provides science with a way to study consciousness in all of its various forms, from vivid dreams to no awareness at all, says neuroscientist Benjamin Baird. When subjects are snoozing, researchers can isolate conscious experiences from the confounding influence of the senses.

In a recent attempt to peek inside the dreaming brain, Baird and leading consciousness expert Giulio Tononi, both at the University of Wisconsin–Madison, and their colleagues used scalp electrodes to record sleepers' brain waves via high-density electroencephalography. They woke people at frequent intervals to ask if they had been dreaming and, if so, what their dreams were about. One of their experiments garnered a total of about 200 such waking accounts from 32 subjects, and a second added some 800 more from a smaller group specially trained in dream reporting.

The team identified a "hot zone" in a posterior cortical region, near the back of the head, where low-frequency brain waves (linked to unconsciousness) decreased and high-frequency activity rose when people said they had been dreaming—regardless of whether or not it was during rapid eye movement (REM) sleep. (Despite common belief, dreaming can occur during both REM and non-REM sleep.) The findings were described in *Nature Neuroscience.*

In a third experiment with seven subjects, the scientists predicted with 87 percent accuracy whether participants were dreaming. Furthermore, brain-wave activity in certain brain regions was linked to specific dream content—including locations, faces and speech. These same areas are activated during waking experience. "We didn't actually try to predict [dream] content in this study," Baird notes, but he says that would be an exciting "potential direction."

This approach represents "a really cool and innovative paradigm," says neuroscientist Christof Koch of the Allen Institute for Brain Science in Seattle, who was not involved in the work and who serves on *Scientific American*'s board of advisers. Finding that dream-related activity was focused toward the back of the brain was surprising, he says, because consciousness is widely thought to arise in frontoparietal regions. One limitation of the study is the delay between a subject waking up and recounting a dream. Ultimately, Koch says, "we want to get closer and closer to the experience itself." —*Tanya Lewis*

COURTESY OF ANDRÉS BENDESKY AND HOPI HOEKSTRA (*mice*); GETTY IMAGES (*sleeping woman*)


MIRAI
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INTRODUCING THE HYDROGEN-FUELED TOYOTA MIRAI. ITS ONLY EMISSION IS WATER.
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PSYCHOLOGY

Secrets and Lies

welling on clandestine information hurts us more than the act of concealing it

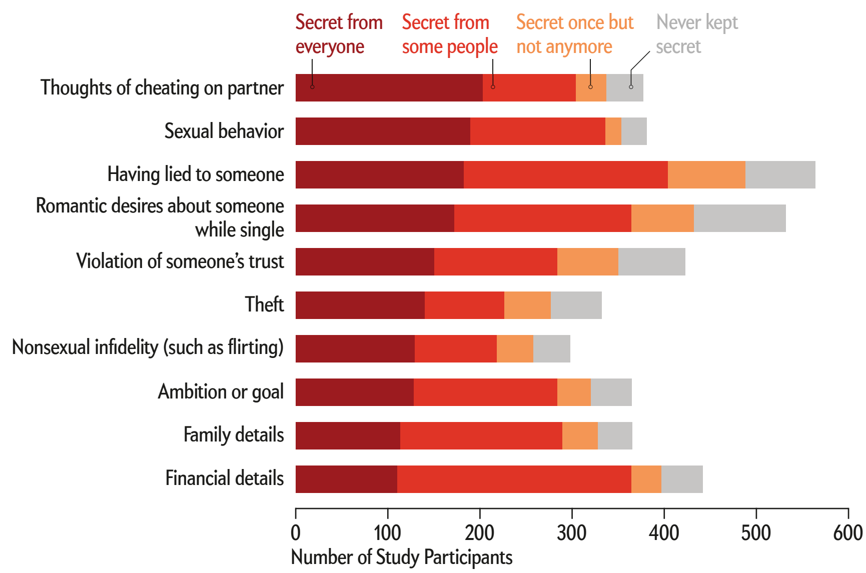
It is no secret that we all have secrets. Maintaining them can be draining, but not for the reason most researchers have long assumed. A new study redefines "secrecy" itself and offers a novel explanation for its known link to depression, anxiety and poor overall health. The researchers suggest that secrecy is primarily the *intention* to conceal information, regardless of any active concealment around others. And that hurts us by making us feel inauthentic, even when we are alone.

Michael Slepian, a psychologist at Columbia Business School, and his colleagues recently reported their findings in a paper published online in the *Journal of Personality and Social Psychology.* In six studies, they queried a total of 1,200 Americans via the Internet—as well as 312 people picnicking in New York City's Central Park—regarding 38 categories of behavior or identity that are often kept secret. For five of these studies, respondents said they were currently hiding information in about 13 of these categories on average (including about five for which they had a secret they were keeping from everyone). The most common secrets were extrarelational thoughts (thinking about having relations with another person while already in a relationship), romantic desire (while being single) and sexual behavior (consumption of pornography, fantasies, and so on). The graphic presents a full breakdown of the most common secrets; additional data are available at www.keepingsecrets.org.

People said that when they were not interacting with anyone, they thought about their secrets about twice as often as they actively concealed them in conversation. The more often their mind wandered to a secret, the more they reported that it damaged their well-being and the less healthy they said they were. Surprisingly, active concealment did not affect well-being at all—in contrast to previous assumptions. Four additional studies, all involving couples and conducted online, produced similar findings.

If you must keep a secret, Slepian suggests avoiding dwelling on it by practicing mindfulness or discussing the forbidden topic in anonymous online forums. *—Matthew Hutson*

The Top 10 Categories of Things We Keep Secret



Over three studies (a subset of 10), researchers surveyed 600 participants about commonly secret behaviors they had experienced and to what degree they had kept each one hidden. The graph shows data for the 10 behaviors most frequently kept totally secret.

SOURCE: "THE EXPERIENCE OF SECRECY," BY MICHAEL L. SLEPIAN ET AL., IN *JOURNAL OF PERSONALITY AND SOCIAL PSYCHOLOGY.* PUBLISHED ONLINE MAY 8, 2017

Graphic by Amanda Montañez

SUSTAINABILITY

Waning Woods

The planet is losing pristine land tracts that are key to healthy ecosystems

We humans have left our mark on the entire planet; not a single ecosystem remains completely untouched. But some landscapes have been affected less than others. And the extent to which the earth can provide habitats for plants and animals, sequester atmospheric carbon and regulate the flow of freshwater depends on the vastness of the least affected regions. These tracts, where human influence is still too weak to easily detect by satellite, are prime targets for conservation. Using satellite imagery, a group of researchers mapped the global decline between 2000 and 2013 of such "intact forest landscapes" (IFLs), defined as forested or naturally treeless ecosystems of 500 square kilometers or more. Around half of the area of the world's IFLs are in the tropics, and a third can be found in the boreal forests of North America and Eurasia. Logging, agriculture, mining and wildfires contributed to the drop, as reported in January in *Science Advances.*

The bright side? Landscapes under formal protection, such as national parks, were more likely to remain intact. —*Jason G. Goldman*

BY THE NUMBERS

12.8 million

square kilometers Global extent of IFLs in 2000, a total area equivalent to a third of the surface of the moon.

Nearly 1 million

square kilometers Approximate area of IFLs lost between 2000 and 2013, about the size of Egypt.

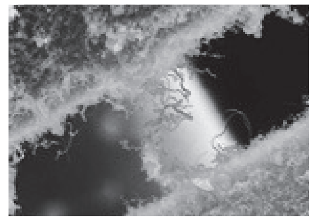
65

Number of countries that were home to at least one IFL in 2000.

19

Number of countries that will be completely devoid of IFLs in 60 years if losses continue at the current rate.

SOURCE: "THE LAST FRONTIERS OF WILDERNESS: TRACKING LOSS OF INTACT FOREST LANDSCAPES FROM 2000 TO 2013," BY PETER POTAPOV, IN *SCIENCE ADVANCES*, VOL. 3, NO. 1, ARTICLE NO. E1600821; JANUARY 4, 2017; GETTY IMAGES (*trees*)



Fuzzy fibers: silicon carbide nanotubes (*inset*) could make rocket engines more heat-resistant.

MATERIALS SCIENCE

Hot Rockets

Velcro-like fibers could help enable hotter engines for Mars-bound spacecraft

The insides of today's rocket engines can reach a blistering 1,600 degrees Celsius—hot enough to melt steel. And tomorrow's engines will need to be even more scorching. Hotter engines are more fuel-efficient, produce more thrust and can carry larger loads—all key for Mars-bound spacecraft and advanced aircraft.

In the quest for rocket materials that can tolerate more heat, engineers have been trying to devise tough, lightweight composites made of silicon carbide fibers, a small fraction of the width of a human hair, embedded in a ceramic material. Silicon carbide can withstand 2,000 degrees C—the temperature of the hoped-for hotter engines. Today's composites are made by layering woven mats of silicon carbide fibers and filling the space between them with a porous ceramic. But existing composites can crack under the high pressures that occur in engines because the fibers slip against one another and pull out of the ceramic.

In a possible breakthrough, scientists at Rice University and the NASA Glenn Research Center have developed "fuzzy" silicon carbide fibers whose surfaces resemble a microscopic version of Velcro. The fibers, described recently in *Applied Materials & Interfaces,* would be less likely to slip or pull out of a surrounding ceramic medium because their fuzzy tangles lock them together.

To make these threads, the researchers first grew curly carbon nanotubes that stick out from the silicon carbide surface like ringlets of hair. Then they dipped the fibers in an ultrafine silicon powder and heated them, which converts the carbon nanotubes into silicon carbide fibers. The team tested the fuzzy fibers' strength by embedding them in a transparent, rubbery polymer—and found these composites to be four times as strong as those made with smooth threads. NASA research engineer and study co-author Janet Hurst says the team now wants to test the new, curly fibers in a ceramic medium. They also want to make fibers with a fuzzy boron nitride nanotube coating because it is strong and shields the fibers from damaging oxygen exposure.

Silicon carbide fibers are strong along their length but can snap across their width under high pressure. Yet the new fibers should resist breakage because their soft fuzz helps to dissipate the strain by distributing it, says Steven Suib, director of the Institute of Materials Science at the University of Connecticut, who was not involved in the new research.

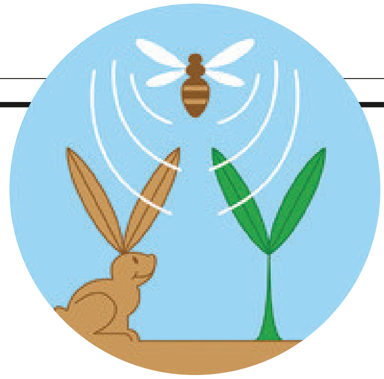
—Prachi Patel

GETTY IMAGES (*space shuttle*); AJAYAN RESEARCH GROUP *Rice University* (*fibers*)

BIOLOGY

Can Plants Hear?

Flora may be able to detect the sounds of flowing water and munching insects



Pseudoscientific claims that music helps plants grow have been made for decades, despite evidence that is shaky at best. Yet new research suggests some flora may be capable of sensing sounds, such as the gurgle of water through a pipe or the buzzing of insects.

In a recent study, Monica Gagliano, an evolutionary biologist at the University of Western Australia, and her colleagues placed pea seedlings in pots shaped like an upside-down Y. One arm of each pot was placed in either a tray of water or a coiled plastic tube through which water flowed; the other arm had dry soil. The roots grew toward the arm of the pipe with the fluid, regardless of whether it was easily accessible or hidden inside the tubing. “They just knew the water was there, even if the only thing to detect was the sound of it flowing inside the pipe,” Gagliano says. Yet when the seedlings were given a choice between the water tube and some moistened soil, their roots favored the latter. She hypothesizes that these plants use sound waves to detect water at a distance but follow moisture gradients to home in on their target when it is closer.

The research, reported earlier this year in *Oecologia,* is not the first to suggest flora can detect and interpret sounds. A 2014 study showed the rock cress *Arabidopsis* can distinguish between caterpillar chewing sounds and wind vibrations—the plant produced more chemical toxins after “hearing” a recording of feeding insects. “We tend to underestimate plants because their responses are usually less visible to us. But leaves turn out to be extremely sensitive vibration detectors,” says lead study author Heidi M. Appel, an environmental scientist now at the University of Toledo.

Another hint that plants can hear comes from the phenomenon of “buzz pollination,” in which a bee buzzing at a particular frequency has been shown to stimulate pollen release.

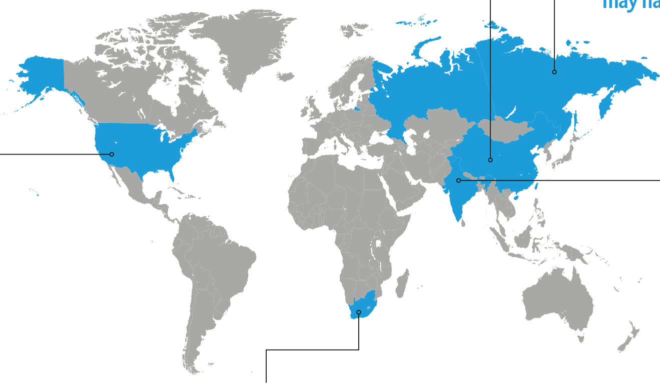
Michael Schöner, a biologist at University of Greifswald in Germany, who was not involved in the new research, believes that plants may have organs that can perceive noises. “Sound vibrations could trigger a response of the plant via mechanoreceptors—these could be very fine, hairy structures, anything that could work like a membrane,” he says.

This research raises questions about whether acoustic pollution affects plants as well as animals, Gagliano observes: “Noise could block information channels between plants, for example, when they need to warn each other of insects.” So next time you turn on a leaf blower or a hedge trimmer in your garden, consider the lilies. —*Marta Zaraska*

Illustration by Thomas Fuchs

IN THE NEWS

Quick Hits



CHINA
Some caterpillar pests have grown resistant to genetically modified (GM) crops designed to be toxic to them. But researchers have developed a hybrid of GM and nonmodified cotton that keeps one species of caterpillar susceptible to the plant's deadly proteins.

RUSSIA
A study of animal bones collected from the Berelyokh site in the Siberian republic of Sakha indicates that mammoths may have suffered from human diseases, including osteoporosis, a possible factor in their extinction. A lack of minerals in their diet may have made the animals susceptible.

U.S.
Researchers modeled noise levels in nearly 500 wilderness and park locations and found that more than half of them were twice as loud as the environment would be without human-generated sounds. This cacophony could inhibit animals' hunting, mating and other survival behaviors.

INDIA
Analyses of scat, blood and tissue show that two populations of endangered Bengal tigers in the Himalaya foothills are not breeding enough to maintain genetic diversity. Researchers say that relocating villages and halting mining could encourage more mingling between those groups.

SOUTH AFRICA
Newly discovered weapon remnants suggest humans were using a delicate, skillful stone-sharpening technique called pressure flaking to finely shape points for spears and other hunting tools as early as 77,000 years ago.

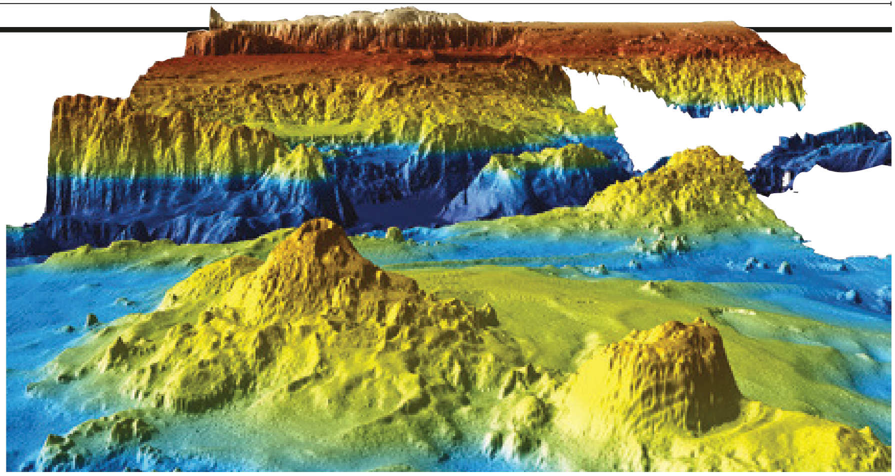
For more details, visit
www.ScientificAmerican.com/jul2017/advances

—Andrea Marks

EARTH SCIENCE

Uncharted Territory

The hunt for the missing flight MH370 plane maps a largely unexplored part of the Indian Ocean's seafloor



The first scientific study to come out of the search effort reveals a detailed underwater terrain marked by steep slopes and pockmarks. Shown here is the Diamantina Escarpment.

COURTESY OF COMMONWEALTH OF AUSTRALIA AND GEOSCIENCE AUSTRALIA, 2017

When a Malaysia Airlines flight vanished from the skies in 2014, initial reports characterized the massive undersea search area as mostly flat. But now the first scientific study to emerge from the hunt has revealed a little-explored region of great topographic complexity in the southeastern Indian Ocean. This area includes the point at which the Indian subcontinent and the Australian and Antarctic continents separated during the breakup of the supercontinent Gondwana. With 500 times the resolution of earlier satellite measurements, new maps have resolved formerly fuzzy pixels into well-defined features—strange ridges and "pockmarks," as well as a vast plateau that ends in a steep escarpment notched with large landslides.

The new geophysical data, acquired using state-of-the-art shipboard sonar and published online earlier this year in *Eos,* span 2,500 kilometers of seabed. "This data set is clearly unprecedented in terms of the magnitude of the area surveyed and because it reveals a part of the deep ocean floor that had been largely unexplored," says lead study author Kim Picard, a marine geoscientist at Geoscience Australia.

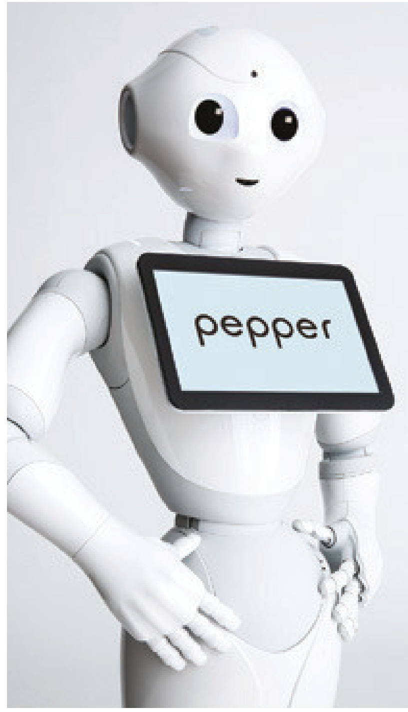
Geoscience Australia plans on releasing the first batch of data this month, with more to follow in mid-2018. Once the maps are made public, they will help researchers address ongoing puzzles in a region with a complex tectonic history. One mystery, says study co-author Millard Coffin, a marine geophysicist at the University of Tasmania, is an enigmatic seafloor texture called a spreading fabric—small, elongated ridges that generally parallel a rift in the seafloor where two plates are moving apart, allowing magma to rise. This phenomenon may have resulted from repeating pulses of volcanism along mid-ocean ridges, which previous research has linked to cycles of ice ages and warming. Investigations of these and other features may elucidate why seafloor spreading has been more complicated in the Indian Ocean than in the Atlantic, Coffin says. The improved resolution will also help scientists better understand many other deep-ocean processes, Picard explains, including landslides and pockmarks, craterlike features possibly caused by the escape of an unknown fluid or gas.

The Malaysia Airlines tragedy was one of the cruelest and most wrenching in aviation history, with 239 people lost and a long international search that has failed to pinpoint clues or causes. But as Coffin notes, "much new knowledge about the deep seafloor is arising from it." *—Terri Cook*

ROBOTICS

Grandma's Robot Helper

Machines that read human social cues show promise in assisting the elderly



SoftBank Robotics' "Pepper" robot (*shown here*) can read and respond to human emotions. An adapted version of the bot is designed to aid the elderly.

COURTESY OF SOFTBANK ROBOTICS

Robots already perform many traditionally human tasks, from vacuuming to surgery—and they could soon help care for the sick and elderly. But until they can convincingly discern and mimic emotions, their caretaker value will be severely limited. In an effort to create "friendlier" machines, researchers are developing robotic helpers that can better read and react to social signals.

In late 2016 IBM and Rice University unveiled the Multi-Purpose Eldercare Robot Assistant (MERA), a customized version of the Pepper robot developed by SoftBank Robotics in Japan. Pepper, an ivory-colored android about the height of a seven-year-old, can detect and respond to human emotions via vocal cues and facial expressions. It has already been deployed as a friendly assistant in Japanese stores and homes. MERA, specifically designed as an at-home companion for the elderly, records and analyzes videos of a person's face and calculates vital signs such as heart and breathing rates.

MERA's speech technology, originally developed for IBM's Watson (the artificial-intelligence system that won *Jeopardy!*), allows it to converse with a patient and answer health questions. "It has everything bundled into one adorable self," says Susann Keohane, founder of IBM's Aging-in-Place Research Lab.

Roboticist Maja Matarić and her colleagues at the University of Southern California are taking a different but complementary approach to developing social machines. They are designing robots that tap into human social dynamics to help seniors help themselves. "What we found is people really need help with motivation" to do necessary tasks, she says. "So we created the field of socially assistive robotics: machines that help people through social, not physical, interaction." For elderly individuals, such assistance comes in various guises—from coaching them in physical therapy to aiding them in socializing with friends and family.

Matarić and her team recently tested Spritebot, a one-foot-tall green owl robot that assists seniors in playing games with their children or grandchildren. The researchers found that people talked to one another more and played games for longer when Spritebot was participating in, and moderating, their interactions.

In an upcoming study, Matarić and her colleagues will pair elderly people with robot companions that encourage them to form healthy habits, such as walking more. She hopes that monitoring how people interact with companion robots over time will inform her team about both habit formation and the dynamics of the human-robot bond.

The need for socially assistive robots may arise from a shortage of human companions for the elderly, but Matarić points out that robots could also offer some benefits over their flesh-and-blood counterparts. "Machines are infinitely patient," she explains. "They have [fewer] biases to begin with, and they have no expectations."

—Catherine Caruso

Probiotics Are No Panacea

Although certain bacteria help treat some gut disorders, they have no known benefits for healthy people

By Ferris Jabr

Walk into any grocery store, and you will likely find more than a few "probiotic" products brimming with so-called beneficial bacteria that are supposed to treat everything from constipation to obesity to depression. In addition to foods traditionally prepared with live bacterial cultures (such as yogurt and other fermented dairy products), consumers can now purchase probiotic capsules and pills, fruit juices, cereals, sausages, cookies, candy, granola bars and pet food. Indeed, the popularity of probiotics has grown so much in recent years that manufacturers have even added the microorganisms to cosmetics and mattresses.

A closer look at the science underlying microbe-based treatments, however, shows that most of the health claims for probiotics are pure hype. The majority of studies to date have failed to reveal any benefits in individuals who are already healthy. The bacteria seem to help only those people suffering from a few specific intestinal disorders. "There is no evidence to suggest that people with normal gastrointestinal tracts can benefit from taking probiotics," says Matthew Ciorba, a gastroenterologist at Washington University in St. Louis. "If you're not in any distress, I would not recommend them." Emma Allen-Vercoe, a microbiologist at the University of Guelph in Ontario, agrees. For the most part, she says, "the claims that are made are enormously inflated."

THE NUMBERS GAME

THIS STORY HAS PLAYED OUT before, most notably with vitamin supplements, which decades of research have revealed to be completely unnecessary for most adults and, in some cases, dangerous, correlating with higher rates of lung, breast and prostate cancers. But that has not stopped marketers from pushing another nutritional craze. According to a National Institutes of Health survey, the number of adults in the U.S. taking probiotics or their cousins, prebiotics (typically nondigestible fibers that favor the development of gut bacteria), more than quadrupled between 2007 and 2012, from 865,000 people to nearly four million. San Francisco–based business consulting firm Grand View Research estimates that the global probiotics market exceeded $35 billion in 2015 and predicts that it will reach $66 billion by 2024.

The popular frenzy surrounding probiotics is fueled in large part by surging scientific and public interest in the human microbiome: the overlapping ecosystems of bacteria and other microorganisms found throughout the body. The human gastrointestinal system contains about 39 trillion bacteria, according to the latest estimate, most of which reside in the large intestine. In the past 15 years researchers have established that many of these commensal microbes are essential for health. Collectively, they crowd out harmful microbial invaders, break down fibrous foods into more digestible components and produce vitamins such as K and B12.

The idea that consuming probiotics can boost the ability of already well-functioning native bacteria to promote general health is dubious for a couple of reasons. Manufacturers of probiotics often select specific bacterial strains for their products because they know how to grow them in large numbers, not because they are adapted to the human gut or known to improve health. The particular strains of *Bifidobacterium* or *Lactobacillus* that are typically found in many yogurts and pills may not be the same kind that can survive the highly acidic environ-

KARI LOUNATMAA *Science Source*

FRIENDLY MICROBES: Bacteria such as these lactobacilli, which are often added to yogurt and probiotic supplements, help to maintain a healthy environment in the intestine.

Ferris Jabr is a contributing writer for *Scientific American.*

ment of the human stomach and from there colonize the gut.

Even if some of the bacteria in a probiotic managed to survive and propagate in the intestine, there would likely be far too few of them to dramatically alter the overall composition of one's internal ecosystem. Whereas the human gut contains tens of trillions of bacteria, there are only between 100 million and a few hundred billion bacteria in a typical serving of yogurt or a microbe-filled pill. Last year a team of scientists at the University of Copenhagen published a review of seven randomized, placebo-controlled trials (the most scientifically rigorous types of studies researchers know how to conduct) investigating whether probiotic supplements—including biscuits, milk-based drinks and capsules—change the diversity of bacteria in fecal samples. Only one study—of 34 healthy volunteers—found a statistically significant change, and there was no indication that it provided a clinical benefit. "A probiotic is still just a drop in a bucket," says Shira Doron, an infectious disease expert at Tufts Medical Center. "The gut always has orders of magnitude more microbes."

REAL BENEFITS

DESPITE A GROWING SENSE that probiotics do not offer anything of substance to individuals who are already healthy, researchers have documented some benefits for people with certain conditions.

In the past five years, for example, several combined analyses of dozens of studies have concluded that probiotics may help prevent some common side effects of treatment with antibiotics. Whenever physicians prescribe these medications, they know they stand a good chance of annihilating entire communities of beneficial bacteria in the intestine, along with whatever problem-causing microbes they are trying to dispel. Normally the body just needs to grab a few bacteria from the environment to reestablish a healthy microbiome. But sometimes the emptied niches get filled up with harmful bacteria that secrete toxins, causing inflammation in the intestine and triggering diarrhea. Adding yogurt or other probiotics—especially the kinds that contain *Lactobacillus*—during and after a course of antibiotics seems to decrease the chances of subsequently developing these opportunistic infections.

A 2014 review by Cochrane—an independent network of experts who serve as rigorous arbiters of medical research—found that probiotics may be particularly useful in a hospital's neonatal intensive care unit. The addition of beneficial bacteria to a nutritional regimen seems to significantly reduce the likelihood of developing necrotizing enterocolitis, which is a devastating, poorly understood and often fatal gut disease that primarily afflicts preterm infants—especially the smallest and most premature among them. Researchers think that many cases of the disease begin with an opportunistic bacterial infection in the not yet fully developed intestine of an infant. As the illness progresses, gut tissue becomes increasingly inflamed and often starts to die, which can, in turn, rupture the intestine and flood the abdominal cavity with pathogenic microbes that proliferate to dangerous levels. Researchers estimate that 12 percent of preterm infants weighing less than 3.3 pounds will develop necrotizing enterocolitis and that 30 percent of them will not survive. Standard treatment involves a combination of antibiotics, feeding via intravenous tubes, and surgery to remove diseased and dead tissue. Probiotics probably prevent the disorder by boosting the numbers of beneficial bacteria, which may deter the harmful ones.

Probiotics also seem to ameliorate irritable bowel syndrome, a chronic disease characterized by abdominal pain, bloating, and frequent diarrhea or constipation (or a mix of the two). A 2014 review of more than 30 studies, published in the *American Journal of Gastroenterology* by an international team of researchers, determined that in some cases, probiotics help to relieve the symptoms of irritable bowel syndrome for reasons that are not entirely clear, although it may be that they impede the growth of harmful microbes. The researchers concluded, however, that they did not have enough data to recommend any particular strains of bacteria. Microbiologists often caution that a promising study on a single strain of a particular species of bacteria should not be taken as proof that all probiotics work equally well. "Bacterial strains are so genetically different from one another, and everybody has a different gut microbiota," Allen-Vercoe says. "There will probably never be a one-size-fits-all probiotic."

But what if investigators could design probiotics to treat specific individuals? Many researchers think personalized probiotics are the most promising path forward for patients with compromised gut microbiomes. Last year Jens Walter of the University of Alberta and his colleagues published a study that gives a glimpse of this potential future. The researchers decided to see what it would take to get the bacteria in a probiotic to successfully colonize the intestines of 23 volunteers. They chose a particular strain of *Bifidobacterium longum* that earlier studies had indicated could survive in the human intestine. In the study, the volunteers consumed either a drink containing 10 billion live *B. longum* bacteria or a placebo in the form of a glucose-based food additive (maltodextrin) each day for two weeks. Periodic fecal samples revealed higher than typical levels of *B. longum* in participants who did not consume the placebo.

In seven people, however, these bacterial levels persisted for more than five months after the treatment ended. "We never expected they would survive more than a few weeks," Walter says. A follow-up analysis determined that these seven people had begun the experiment with lower levels of *B. longum* in the first place. In other words, their gut ecosystems had a vacancy that the probiotic filled. That is exactly the kind of insight that clinicians need to create and recommend more effective probiotics. If a doctor knows that an individual with severe diarrhea has an undersized population of a particular beneficial microbe, for example, then prescribing the missing strain should increase the chance of a successful treatment.

"The key is taking an ecological perspective," Walter says. "We need to think about which microbes have the right adaptations to survive in a particular gut ecosystem." Put another way, treatments for microbe-related disorders are most successful when they work in tandem with the human body's many microscopic citizens, not just against them. SA

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

Computer-Aided Creativity

How much should an artist reveal about letting technology make some choices?

By David Pogue

I'll never forget the first time I saw "piano juggling." It was December 1989, on Johnny Carson's *The Tonight Show*.

Carson's guest played the keys of an oversized piano on the floor—by striking them with bouncing balls. Faster and faster he went, juggling downward. Beethoven's "Für Elise" was amazing enough—but Liszt's rapid-fire Hungarian Rhapsody no. 2? The crowd went crazy. How could anyone nail both the keys and the rhythms with perfect accuracy?

Nobody could. During a close-up, I saw that the "piano" was a single, four-foot-wide touch panel. The "keys" appeared to be just painted on. It didn't matter *where* the balls hit; each triggered the next note in a programmed sequence. He controlled the rhythm, but the rest was automated. Of course, it's not easy to toss balls in rhythm, and the act is still loads of fun. But the audience clearly believed that he was also hitting specific *keys*.

Seeing that audience hoodwinked set me up for a life of wondering: Is an artist obligated to reveal how much of his or her creativity is being assisted by technology?

I loved *Popular Photography* magazine—until it shut down in March, after 80 years. Its aim was to teach readers how to shoot better pictures. To that end, it published, with each image, the settings the photographer had used: "1/400 sec at f/5.6, ISO 1000," for example. That string of numbers always gave me a sense of hopelessness. How could an amateur like me ever learn what combinations of shutter speed, aperture and sensitivity to light (ISO) to dial up for a certain picture?

Eventually a professional photographer told me a little secret: even the pros often let the camera choose some or all of those settings. They might use, for example, shutter-priority mode (in which the camera chooses the aperture), aperture-priority mode (the camera chooses the shutter speed) or even full automatic mode (the camera chooses everything).

Yet even photographs taken in automatic mode were described in the magazine as, you know, "1/400 sec at f/5.6, ISO 1000." Yes, those *were* the settings—but for all the readers knew, the camera chose them, not the person. Those specs misled those of us who aspired to be like the top shooters.

Apple's GarageBand program for Mac computers lets you create fully orchestrated "compositions" just by dragging tiles into a grid. Everything sounds great, whether or not you know anything about rhythm, pitch or harmony. At the time of GarageBand's introduction, its product manager told me that even if the program semiautomates the composition process, it still gives people a taste of the real thing. It could inspire a novice to *learn* music, maybe take up an instrument.

Agreed. But how can we gauge artists' talent without knowing how much of the work was theirs? Should it affect how much we pay for their output? And what about when commercial musicians use GarageBand to produce their tracks—as Oasis and many indie bands have done?

Everyone knows that technology assists almost every creative endeavor these days, from the moment a four-year-old drips paint onto a turntable to make spin art. We also are aware that Hollywood uses computers for its special effects and that most pop songs are Auto-Tuned and pitch-corrected. But in those cases, the audience is in on the fact that machinery has helped out.

It's not the same thing when technology's assistance is concealed from us and is credited to the human. That's why lip-synching at live concerts is still controversial and why athletes are disqualified for secretly using drugs or other performance enhancements. Disclosing when our creative works have come from canned parts isn't just important for intellectual honesty; it would also make a better barometer for the rising tide of robots entering creative fields. (If you hadn't heard, robots are now capable of composing chorales and painting portraits.)

These days even professional musicians, artists and performers can substitute an on/off switch for human talent. Shouldn't the public know which is which? SA

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NEUROSCIENCE

MEMORY'S INTRICATE WEB

A technical revolution provides insight into how the brain links memories, a process critical for understanding and organizing the world around us

By Alcino J. Silva

Alcino J. Silva is a Distinguished Professor and director of the Integrative Center for Learning and Memory at the University of California, Los Angeles. His laboratory (www.silvalab.org) studies memory mechanisms, as well as the causes and treatments for memory disorders.

Our memories

depend on our ability to recall details about the world—a child's face, a goose, a lake. To transform them into actual experiences, though, the brain must somehow merge these individual elements into an integrated whole—the look on that child's face when she sees a flock of geese suddenly take flight from a lakeside stand of reeds.

A cohesive sense of memory relies on other factors, too. Our survival over the millennia has depended on recalling not only the right information—say, a lion or a snake—but also the context. Did we encounter the animal during a surprise confrontation on an isolated stretch of African savanna or as part of an unhurried viewing at the San Diego Zoo?

To steer clear of other kinds of predators in our daily lives, we also need to be able to link memories over time: Judging whether a seemingly attractive investment is worth pursuing depends on the source of a recommendation—the probity, for instance, of the person who suggested it. Failing to connect the two can have disastrous consequences.

The field of neuroscience is starting to grapple with how the brain links memories across space and time. Until now, the vast majority of studies have focused on the way we acquire, store, recall and alter individual memories. Most memories, though, do not exist on their own as single, isolated entities. Instead one recollection summons the next, establishing intricate sequences of memories that help us to better predict and comprehend the world around us.

The fundamental mechanisms the brain uses to create these linked memories are beginning to reveal themselves—after 20 years of research in my laboratory and others. Understanding the physical processes involved in interweaving individual memories will do more than just provide insight into how the brain works. It may help us to prevent memory disorders that disrupt our ability to create and tie together memories.

A HAPPY ACCIDENT

WHEN WE BEGAN our studies of memory linking in the late 1990s, we lacked the tools and basic knowledge we needed to tackle this subject. A key first step in determining how memories are intertwined was our discovery of a concept called memory allocation, the realization that the brain uses specific rules to assign bits of learned information to discrete groups of neurons in regions of the brain involved in forming the memory.

Serendipity played a key role in the discovery of memory allocation. It started with a conversation I had with Michael Davis, a friend and colleague now at Emory University, during a visit to Yale University in 1998. Davis shared with me the findings of studies in which his lab manipulated a gene known as *CREB* to enhance emotional memory in rats—the association, for example, between a tone and an electric shock. Previ-

IN BRIEF

Memory research has undergone a revolution: new technologies image the activity of individual neurons and even turn the cells on and off at precise moments, allowing brain scientists to perform experiments that were thought of as science fiction just a few years ago.

Techniques now available to neuroscientists have shown that memories are not randomly assigned to neurons in brain regions engaged in information processing and storage. Instead specific mechanisms determine which cells go on to store a given memory.

The brain's ability to control which neurons encode which memories is critical for strengthening memories and for connecting them, features that are disrupted in many neuropsychiatric disorders and during cognitive decline in aging.

PRECEDING PAGES: ANDREAS KUEHN *Getty Images (head)*; GETTY IMAGES *(web pattern)* ously, my lab, now at the University of California, Los Angeles, and other researchers had shown that the *CREB* gene was needed to form long-term memories. The *CREB* gene accomplishes this task by encoding a protein that regulates the expression of other genes needed for memory. During learning, some synapses (the cellular structures neurons use to communicate) are built up, or strengthened, so that they can facilitate interaction among cells. The CREB protein acts as a molecular architect of this process. Without its help, most experiences would be forgotten.

What surprised me was that Davis's group was able to improve memory, even though his lab increased CREB levels in only a subset of the overall population of neurons of the amygdala, a brain region critical for emotional memory. The question that lingered with me for months after my visit to Yale was, How did the memory end up in just the few cells where it could take advantage of the higher CREB levels? Could it be that CREB not only orchestrated memory formation but also helped to ensure that cells with CREB were more likely to be involved in memory formation? In our own investigations of CREB, we homed in on its function within specific brain regions we knew were involved with memory: the amygdala and the hippocampus; the latter stores an internal map of one's surroundings.

MICROSCOPE mounted on the head of a live mouse lets researchers inspect the activity of brain cells where memories are stored.

COURTESY OF DENISE J. CAI *Integrative Center for Learning and Memory, University of California, Los Angeles*

Science is just as much about finding questions as it is about answering them. What that conversation with Davis helped me realize is that neuroscientists knew very little about the rules, if, indeed, there were any, of how a given memory is allocated to the neurons in each of the brain regions that process and store our recollections. So we decided to look more closely.

Our first big break came after we recruited neuroscientist Sheena A. Josselyn, who had studied CREB in Davis's lab. In a series of animal experiments that she conducted in my lab and later with colleagues at her own lab at the University of Toronto, Josselyn used a virus to introduce extra copies of CREB into specific neurons within the mouse amygdala. She showed that those neurons were nearly four times more likely to store a fearful memory than neighboring ones.

In 2007, after almost a decade of effort, my lab, in collaboration with Josselyn's team, finally published evidence that emotional memories are not randomly assigned to neurons within the amygdala. Rather the cells tapped to store these memories are those that have more of the CREB protein. Just as important, subsequent experiments showed that CREB has a similar function in other brain regions, including the hippocampus and the cortex, the outermost layer.

SWITCHING MEMORIES ON AND OFF

TO CONFIRM CREB'S ROLE in memory allocation, we turned to newly developed methods that have transformed the study of memory in recent years. These lab techniques make it possible to either activate or switch off neurons—in effect, eliciting or silencing a memory.

As one example, Yu Zhou, then in my lab, genetically modified a small set of mouse amygdala neurons so that they had higher CREB levels and expressed another protein engineered by Edward Callaway's lab at the Salk Institute for Biological Studies in La Jolla, Calif. Callaway's nifty protein allowed us to silence the CREB neurons at a time of our choosing. When we shut off the neurons that had high CREB, leaving their counterparts with lower levels of the protein still active, emotional memory was suppressed, a result that provides evidence that neurons with higher levels of CREB are more likely to be involved in memory storage.

We knew that higher levels of CREB could determine which cells stored a given memory, but we did not know how this happened. Robert Malenka of Stanford University and his colleagues had discovered that increasing CREB in certain neurons meant they were more easily activated. Could this increase in excitability be the reason why neurons with higher CREB levels were picked for memory storage?

To address that question, Zhou modified amygdala neurons to produce more CREB. Using tiny microelectrodes, she determined how easily these neurons are activated, a measure of excitability. The results confirmed that the modified neurons were more easily switched on, compared with their unaltered counterparts. The elevated excitability (an enhanced readiness to receive and pass on electrical impulses that carry information between neurons) suggested that the cells may have been better prepared to initiate the set of processes needed for laying down a memory.

To test that idea, Zhou also looked at synaptic connections involving the neurons with more CREB. A considerable body of evidence has shown that increases in the strength of synaptic connections are critical for memory formation. After training the mice on a task that subsequently evoked emotional memories, she tested the strength of synaptic connections of the amygdala neurons with higher CREB levels to see whether they had stronger connections, compared with cells that had not been altered to produce more CREB.

To do this, she stimulated the synapses of these cells with a small electric current and recorded their responses with tiny electrodes embedded within the cells. As expected, the amygdala neurons with higher CREB had stronger synapses than other cells, a result consistent with the idea that they were more likely to have stored the emotional memory.

In still more recent work, Josselyn's lab demonstrated that a memory of a fearful experience could be stored in a predetermined set of amygdala neurons by genetically engineering them with a specific type of ion channel that increases the excitability of these neurons. Ion channels form pores on the surface of the cells, and the particular ones that Josselyn chose allowed these cells to be more easily activated. Similarly, neuroscientist Albert Lee's lab at the Howard Hughes Medical Institute's Janelia Research Campus in Ashburn, Va., reported that artificially increasing the excitability of hippocampal neurons in a specific place while animals ran around a track made those neurons more likely to respond to that location in the track, a result consistent with our findings that excitability has a critical role in determining which cells are engaged in storing a given memory.

Finally, our group, as well as Josselyn's, took advantage of a groundbreaking technology called optogenetics that uses light to either activate or inhibit neurons. We used the technique to switch on specific neurons that had higher CREB levels. Thomas Rogerson and Balaji Jayaprakash, both then in my lab, began by engineering amygdala neurons to produce more CREB and channelrhodopsin 2 (ChR2), an ion channel activated by blue light. We then showed that we could artificially trigger recall of a fear memory in mice when we used the light to turn on amygdala neurons with higher CREB but not ones with lesser levels of the protein, confirming that the memory was stored in those neurons.

LINKING UP

IN 2009 I WAS ASKED to write an article on our memory research, and I took that opportunity to introduce our ideas on how memories are linked over time. CREB's ability to regulate which cells form a given memory—in other words, memory allocation—led me to the hypothesis that this process may be key to the ability to connect separate memories, what my lab now calls the "allocate to link" hypothesis. Because memory allocation occurs in a subset of neurons having higher CREB that are more easily activated, this process primes these neurons to readily store another memory. When two memories share many of the same neurons, they are formally linked.

Consequently, activation of those neurons during recall of one of the two memories triggers recall of the other. Key to this idea was the prediction that two memories formed closer in time—both within a day—are more likely to be linked than when they are separated by longer periods. With intervals much longer than a day, the second memory no longer benefits from the excitability triggered by the first memory and so is stored in a different population of neurons. The time-limited nature of memory linking makes sense because events that occur within the span of a day are far more likely to be relevant to one another than those separated by, say, a week.

Writing the article and outlining these ideas drew me even more to the challenge of how we might test them. The allocate-to-link hypothesis was straightforward, but it was not at all clear how we would confirm its legitimacy. Testing had to wait for the right time.

The situation changed when Denise J. Cai and Justin Shobe, both then in my lab, joined the project. Cai came up with a clever idea. Together with Shobe, she exposed mice to two chambers during the same day within an interval of five hours, hoping that the memories of the two chambers would be linked. Later she gave them a mild paw shock in the second chamber. As expected, when she subsequently placed the mice in the chamber where they received the shock, they froze, presumably because they remembered that they had received a shock there. Mice freeze as a natural reaction to fear because most predators notice prey better when they move.

The critical result emerged when Cai and Shobe placed the mice in the neutral chamber. We reasoned that if the memories from both chambers were linked, the mice in the neutral space would be reminded of being shocked in the other chamber and thus would freeze in anticipation—and that is exactly what we found.

We also guessed that the two memories would be less likely to be linked if they were separated by a seven-day interval. And indeed, reexposing the animals to the neutral chamber after the longer time span did not remind them of the shock chamber, and they did not freeze. In general, with time intervals much longer than a day, memories remain unlinked.

These behavioral findings were exciting, but they did not test a key prediction of the hypothesis—that discrete memories formed at closely spaced intervals are stored in the same brain area in overlapping populations of neurons. This physical overlap links the two memories, so that the recall of one brings to mind the other.

A key prediction of our hypothesis was that discrete memories formed at closely spaced intervals are stored in the same brain area in overlapping populations of neurons.

VISUALIZING MEMORIES

TO REALLY TEST the allocate-to-link hypothesis would require nothing short of being able to see memories in the brain as they were being created. Techniques for imaging neurons in live mice are already in use, but they all required that the heads of the mice be fixed to large microscopes, a setup not conducive to the behavioral experiments needed to test the hypothesis.

I find it amazing, though, how many times in my career the right technique has come along just when we need it the most. I happened to attend a seminar at U.C.L.A., given by Mark Schnitzer of Stanford, that described a tiny microscope his lab had just invented that could visualize the activity of neurons in freely moving mice. This two- to three-gram microscope can be mounted like a hat on an animal's head. The instrument was what our group needed to track the neurons activated by a given memory. It allowed us to determine if these same neurons become active a few hours later during the creation of another memory, an essential prediction of the allocate-to-link hypothesis.

We were so excited by the promise of this wonderful invention that we decided to engineer our own version of the microscope. We teamed up with Peyman Golshani's and Baljit Khakh's labs, both at U.C.L.A., and together we hired a talented postdoctoral fellow, Daniel Aharoni, who went on to engineer what we came to call the U.C.L.A. miniscopes. Similar to the Schnitzer microscopes, our miniscopes are equipped with a lens that could be embedded near the brain cells we wanted to record from. The device is snapped onto a base plate secured to the animal's skull, holding it stable during training tasks and memory testing. Just as we borrowed techniques from other researchers, we were also glad to share. We are avid supporters of the open-source movement in science and have made our designs and software for the U.C.L.A. miniscopes available to hundreds of other groups worldwide.

To visualize the activity of neurons with the miniscopes, Cai and her colleague Tristan Shuman took advantage of an imaging technique that genetically engineers neurons in an animal so that they fluoresce when calcium levels in the cells rise—it is known as a genetically encoded calcium indicator.

We decided to focus on the CA1 region of the hippocampus because of its role in learning and remembering places, such as the chambers that we had used in our behavioral experiments. The mice wearing their miniscope hats were placed in the two chambers. We wanted to know whether the time interval between exposures to the different chambers affected which neurons were activated.

The results were more than we had expected! Essentially our miniscope and behavioral experiments showed that when the mice linked the memories of the two chambers, many of the CA1 neurons that became active when the animals visited the first chamber were also switched on when they explored in the second chamber. If the interval between visits was about five hours, the mice formed two memories in a similar cluster of neurons. When the time lapse increased to seven days, this overlapping pattern of activation did not appear.

We were delighted by this finding because it confirmed a basic premise of the allocate-to-link hypothesis: memories couple when they are stored in overlapping populations of neurons. If you later reactivate an ensemble of neurons formed for either of two memories, it stimulates the other one and facilitates its recall.

TAGGING MEMORIES

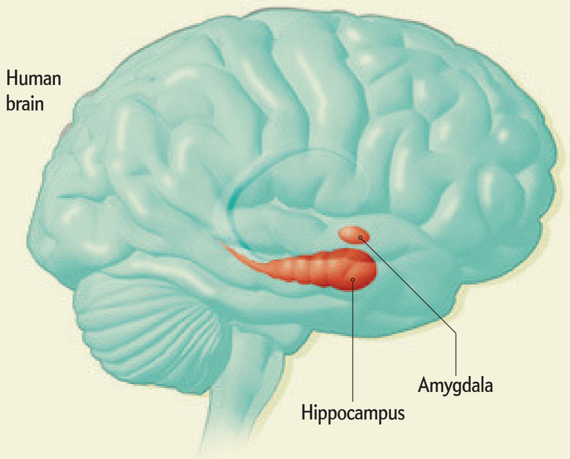
TO FURTHER VALIDATE the miniscope results, Cai turned to another method developed by neuroscientist Mark Mayford, now at the University of California, San Diego. This experiment involved Mayford's technique, called the TetTag system (for *tet*racycline *tag*). When a memory is formed during a transgenic mouse's visit to a chamber, TetTag marks activated neurons with a fluorescent marker that remains intact for weeks.

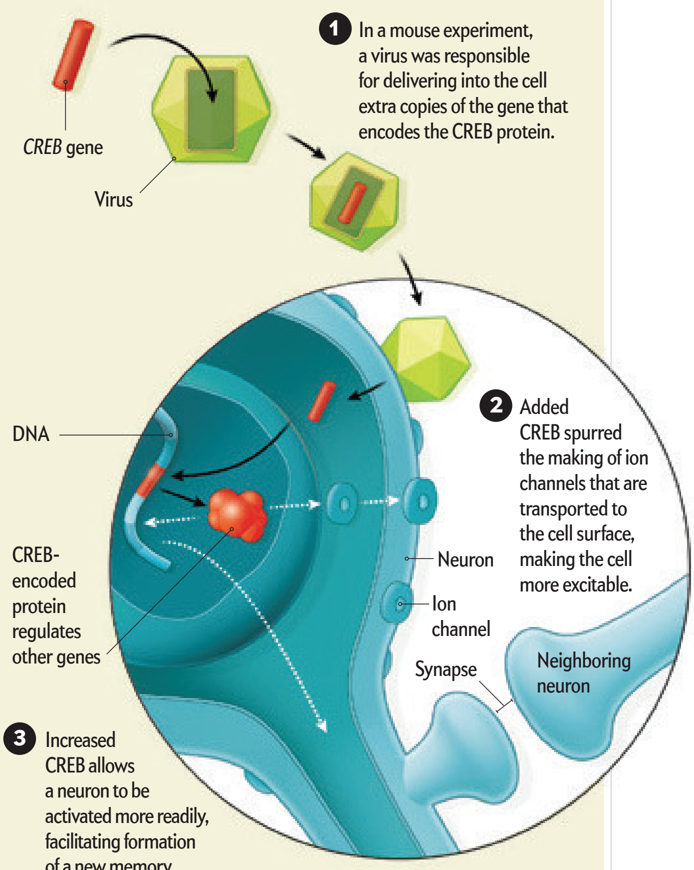
Postmortem studies of the animals can then compare the recently activated neurons—tagged by genes that are expressed immediately after memory formation—with those marked by the long-lasting tag. This step identifies not only neurons switched on by one event—in which case a neuron features a single fluorescing tag—but also those activated by two occurrences: the glowing of both tags.

Using the same experimental setup as before, Cai and her team showed that during a short, five-hour interval, the overlap between the neurons encoding each of two memories with double tags was significantly greater than would be expected by

Memory Makers

Key brain regions play a role in forming memories. The amygdala is essential for memories with emotional content, and the hippocampus is involved in creating memories of experiences. My laboratory performed a mouse experiment that showed that cells in which my team increased the levels of a protein called CREB were more likely to encode a memory. —*A.J.S.*

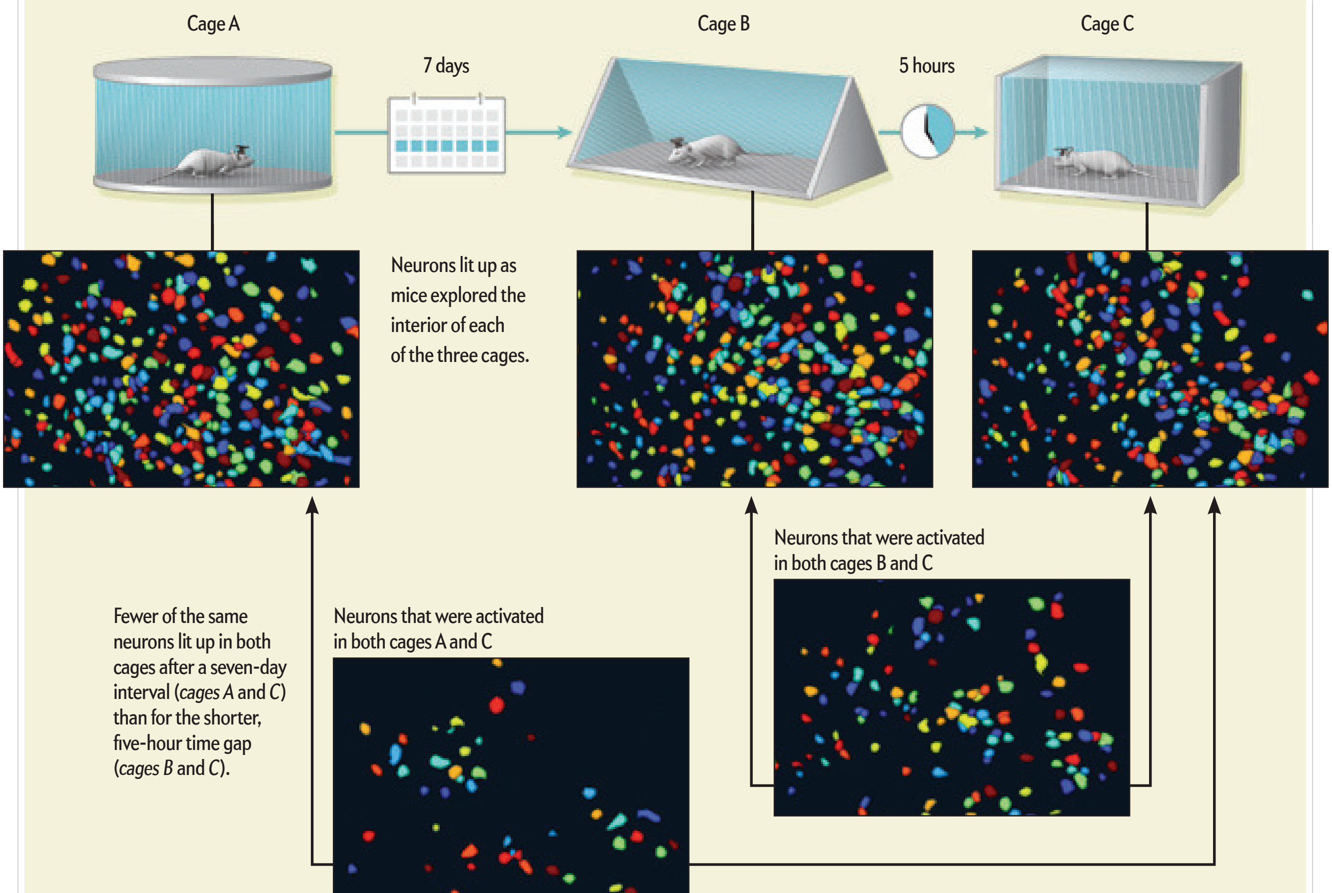




Illustrations by Tami Tolpa

Remembrance of (Linked) Things Past

The “Proustian moment”—when one recollection leads to the next—has now gained a solid footing in the brain sciences. Experiments have shown that a mouse exposed to two chambers—say, B and C—links the two together in its memory if exposed to the two enclosures at an interval of five hours. But a mouse does not remember cages A and C together if the time period is separated by seven days. The linked recall of cages B and C takes place because many of the same neurons used to store the memories of the two cages turn on at the same time, unlike those for cages A and C.



FROM “A SHARED NEURAL ENSEMBLE LINKS DISTINCT CONTEXTUAL MEMORIES ENCODED CLOSE IN TIME,” BY DENISE J. CAI ET AL., IN *NATURE*, VOL. 534; JUNE 2, 2016 (*neuron images*)

chance. For a seven-day interval, the overlap between two experiences was not significantly above the level of chance.

Other experiments by Josselyn’s Toronto team provided still more evidence of the validity of our memory-linking hypothesis. Not only did her group carry out a different version of the neuronal tagging experiment, the scientists also found independent behavioral evidence for memory linking. The Toronto researchers reasoned that if populations of neurons encoding two memories overlapped, increases in CREB levels triggered by the first memory would also strengthen a second memory. But instead of exposing the mice to different places, as in our work, Josselyn’s team trained the animals to learn to recognize two different tones. Training on the first tone strengthened the memory of a second tone if the two training sessions occurred within six hours but not from six to 24 hours.

Recently Kaoru Inokuchi and his colleagues at the University of Toyama in Japan took this analysis a step further. They used optogenetics to inactivate the group of cells that was shared by two different emotional memories while leaving other cells undisturbed, including those that were unique to each of the two memories. The investigators showed that by inactivating the shared cells, they were able to disrupt the linking between the two memories without affecting recall of each individual memory. This elegant experiment provided direct evidence that the neurons shared by two memories are key for memory linking. It also added to the number of labs that provided independent evidence for our fledgling allocate-to-link hypothesis.

IMPROVING MEMORY IN AGING

NEXT, WE DECIDED TO STUDY memory linking in older mice. Compared with young mice, older mice have lower levels of CREB in the brain, including in neurons in the CA1 area of the hippocampus, and consequently lower excitability. Knowing that, we predicted that aging mice should run into difficulties in linking memories. So Cai and her colleagues set about repeating many of the same experiments we had already completed in older animals. The results surprised us. Experienced scientists know that hypotheses are just tools. We do not expect them to be necessarily right. Inevitable failures help us to reshape our ideas along the way. But this time, our hunches proved correct.

I still remember when Cai burst into my office, slightly out of breath. She told me that the middle-aged mice, despite remembering each individual chamber, indeed had problems linking the memories, even when they were exposed to them five hours apart, an interval that presented no difficulty for younger mice. Compared with the young adult mice, the miniscope imaging of the older animals revealed a lack of overlap between stored memories.

Understanding how memories become intertwined with one another may help develop treatments for memory problems common to many psychiatric disorders.

We were both excited but also skeptical, so we went right back and repeated the experiments. The second time around, the results became only more convincing. The neurons in middle-aged mice with lower CREB levels did not link memories as easily as those in young mice.

These results emboldened us to broaden the scope of our investigation. Could we increase artificially the excitability of a subset of CA1 neurons just when the older mice explored the two chambers, ensuring that some of the CA1 neurons activated in one chamber were also switched on when the animals moved to the second?

To accomplish this, we took advantage of a groundbreaking technique that genetically engineers receptors onto the surface of a cell, which allows control over the cell's function. The technique bears the memorable techie acronym DREADD (for *d*esigner *r*eceptors *e*xclusively *a*ctivated by *d*esigner *d*rugs). Activating the DREADD receptors allowed us to turn on the same subset of CA1 neurons while the animals explored both chambers, thereby forging a link between their memories of the two enclosures.

I must confess that at first the idea for this experiment sounded preposterous. There are any number of reasons why it could have failed. For one thing, memories for places involve many millions of neurons spread throughout multiple interconnected brain regions, not just the CA1 region. Aging could have affected memory-linking processes in many, if not all, of these areas. Thus, even if we were successful in increasing excitability in a subset of CA1 neurons, these cells may not have been the right ones. What is more, we may not have triggered the right levels of excitability.

But the experiment worked. The key for this type of Hail Mary trial is to balance investment in time and money with the potential payoff that may be forthcoming. Nevertheless, in this case, I can safely say that luck was on our side. By restoring increases in excitability in a specific subset of CA1 neurons of middle-aged mice, we were able to allocate the two memories to many of the same CA1 neurons and thus restore memory linking in these middle-aged mice.

Research from other labs in both rodents and humans has also elucidated how one memory can be intertwined with another. Neuroscientist Howard Eichenbaum of Boston University demonstrated that rats are capable of finding connections between memories that share content. Neuroscientist Alison Preston of the University of Texas at Austin and her colleagues showed that when memories share content, humans can link them more easily. Recalling one will likely bring back the other.

The growing arsenal of tools at our disposal to measure and control neural activity is beginning to unravel the mechanisms our brain uses to organize information. Our team is now trying to extend this work in new ways. Together with computational neuroscientist Panayiota Poirazi of the Institute of Molecular Biology and Biotechnology at the Foundation for Research and Technology–Hellas in Greece, we are building computer models to simulate how and when memories link up. We are also trying to figure out the mechanisms that control the time intervals needed for memory linking in different brain structures.

So far a number of broad-ranging experiments carried out by multiple labs all strongly support the allocate-to-link hypothesis. We hope that an understanding of how memories become entangled may help us to develop treatments for memory problems that are common across a wide swath of psychiatric conditions, from age-related cognitive decline to schizophrenia, depression and bipolar disorder. Beyond clinical implications, the studies we have described reflect an exciting new era in memory research in which the experiments we do are no longer limited by the techniques we have at our disposal but by the reaches of our imagination.

MORE TO EXPLORE

Synaptic Tagging during Memory Allocation. Thomas Rogerson et al. in *Nature Reviews Neuroscience,* Vol. 15, No. 3, pages 157–169; March 2014.

Memory Integration: Neural Mechanisms and Implications for Behavior. Margaret L. Schlichting and Alison R. Preston in *Current Opinion in Behavioral Sciences,* Vol. 1, pages 1–8; February 2015.

Finding the Engram. Sheena A. Josselyn et al. in *Nature Reviews Neuroscience,* Vol. 16, No. 9, pages 521–534; September 2015.

A Shared Neural Ensemble Links Distinct Contextual Memories Encoded Close in Time. Denise J. Cai et al. in *Nature,* Vol. 534, pages 115–118; June 2, 2016.

Competition between Engrams Influences Fear Memory Formation and Recall. Asim J. Rashid et al. in *Science,* Vol. 353, pages 383–387; July 22, 2016.

FROM OUR ARCHIVES

Making Memories Stick. R. Douglas Fields; February 2005.

scientificamerican.com/magazine/sa

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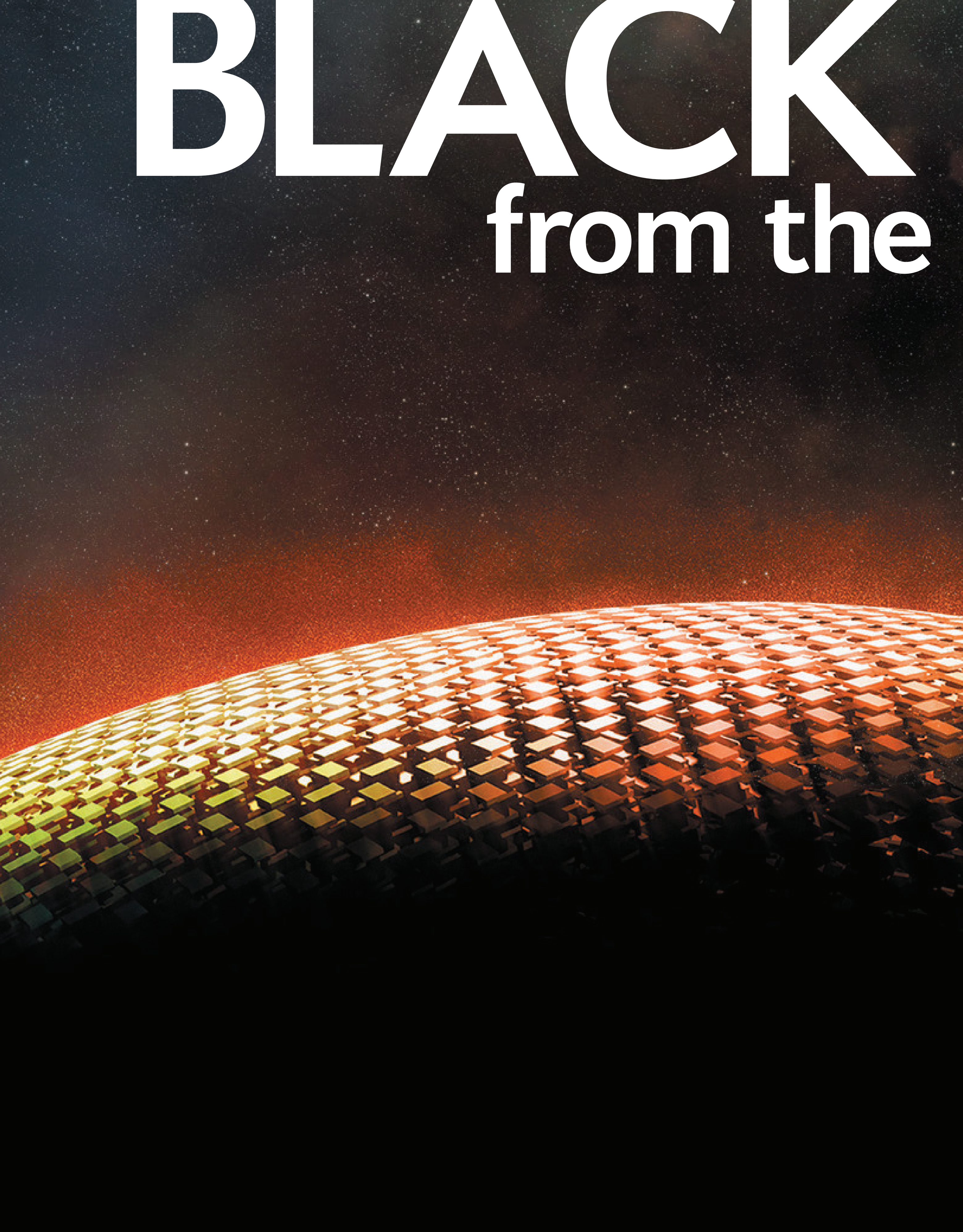


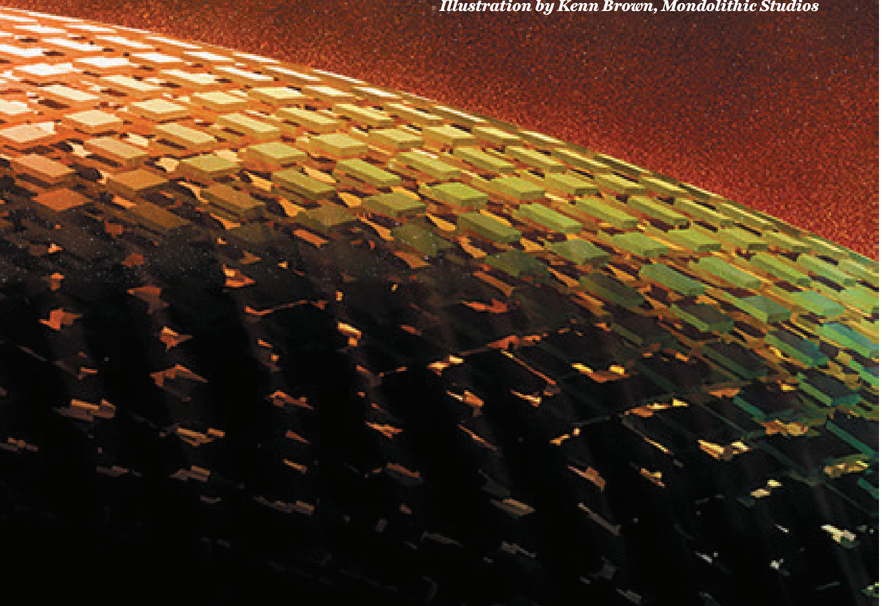
HOLES Beginning of Time

COSMOLOGY

A hidden population of black holes born less than one second after the big bang could solve the mystery of dark matter

By Juan García-Bellido and Sébastien Clesse

Illustration by Kenn Brown, Mondolithic Studios



IN BRIEF

The nature of dark matter—the invisible material that holds galaxies together by its gravity—is a deep cosmic enigma.

Many researchers suspect dark matter is made of weakly interacting massive particles and have been seeking them in experiments. But to date, no such "WIMPs" have been found.

"Primordial" black holes that may have formed shortly after the big bang are an alternative candidate for dark matter. Yet these, too, have so far eluded detection.

More evidence for primordial black holes may emerge in new data from gravitational-wave detectors and other observatories. If confirmed to exist, these objects could solve the mystery of dark matter and several other cosmic conundrums.

More than a billion years ago two black holes in the distant universe spiraled around each other in a deathly dance until they merged. This spiraling collision was so violent that it shook the fabric of spacetime, sending perturbations—gravitational waves—rippling outward through the cosmos at the speed of light. In September 2015, after traveling more than a billion light-years, those ripples washed over our planet, registering as a "chirp" in the sensors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

This was the first direct detection of gravitational waves, and the observation confirmed Albert Einstein's century-old prediction of their existence. Yet the chirp revealed that each of the merger's progenitor black holes was 30 times heavier than the sun. That is, their masses were two to three times larger than ordinary black holes born from supernova explosions of massive stars. These black holes were so heavy, it is hard to explain how they formed from stars at all. Furthermore, even if two such black holes did independently form from the deaths of very massive stars, they would have then had to find each other and merge—an event with an exceedingly low probability of occurring within the current age of the universe. It is thus reasonable to suspect that these massive black holes formed via some other, more exotic pathway that might not involve stars at all. Beyond its detection of gravitational waves, it may be that LIGO has unveiled something even more extraordinary: black holes that predate the formation of the stars themselves.

Although such "primordial" black holes have never before been seen, some theoretical models suggest they could have formed in astronomical numbers from the hot, dense plasma that filled the cosmos less than one second after the big bang. This hidden population could solve several outstanding mysteries in modern cosmology. In particular, primordial black holes could constitute some, if not all, of dark matter—the invisible 85 percent of the matter in the universe that acts as gravitational glue to hold galaxies and galaxy clusters together. Further studies with LIGO and other facilities will soon test these ideas, potentially unleashing a new revolution in our understanding of the cosmos.

Juan García-Bellido is a theoretical physicist and professor at the Institute for Theoretical Physics in Madrid. His research interests are the early universe, dark energy, black holes and quantum gravity. García-Bellido is an active member of the Dark Energy Survey and the European Space Agency missions Euclid and Laser Interferometer Space Antenna (LISA).

Sébastien Clesse is a Belgian cosmologist and postdoctoral researcher at RWTH Aachen University in Germany. His work covers cosmic inflation, modified gravity and primordial black holes. Clesse is an active member of the Euclid mission and of the Square Kilometer Array collaboration.

THE FALL OF MACHOS, THE RISE OF WIMPS

BLACK HOLES would initially seem to be ideal candidates for dark matter because they emit no light. Indeed, along with other dark objects such as planets and brown dwarfs, they make up one long-proposed solution to the dark matter problem: MACHOs, short for *ma*ssive *c*ompact *h*alo *o*bjects. Found both in spherical halos surrounding each galaxy and near each galaxy's luminous center, MACHOs would create the gravitational pull responsible for the otherwise anomalous motions of stars and gas that astronomers observe in the outskirts of galaxies. Simply put, galaxies seem to be rotating too fast to be held together by the visible mass in stars that we observe. Dark matter provides the extra pull to prevent spinning galaxies from flinging off their stars.

If MACHOs make up most of the universe's dark matter, they must also account for other observations. Whatever dark matter is, it shapes the universe's largest structures, determining the origin and growth of galaxies as well as clusters and superclusters of galaxies. These objects coalesce from the gravitational collapse of clumps of gas inside dark matter halos. Cosmologists have precisely mapped the spatial distribution of these clumps through deep and wide galaxy surveys and correlated them with tiny temperature fluctuations present in the cosmic microwave background (CMB), the big bang's all-sky afterglow. The diffuse mass of dark matter in large galaxies and clusters also bends space to distort the light from far distant background objects—a phenomenon known as gravitational lensing.

The MACHO hypothesis, however, fell from favor a decade ago when MACHOs did not turn up in tentative, indirect searches for their existence. Most notably, astronomers looked for them via microlensing, a variety of gravitational lensing in which a black hole, a brown dwarf or even a planet passes in front of a background star and temporarily magnifies the star's light. Several multiyear microlensing surveys of millions of stars in the Large and Small Magellanic Clouds, the main satellite galaxies of the Milky Way, found no evidence that MACHOs made up the entirety of our galactic halo. These results were conclusive enough to rule out MACHOs up to around 10 solar masses as the primary constituent of dark matter. As these surveys took place, theorists built the case for an alternative hypothesis—WIMPs, or weakly interacting massive particles.

WIMPs are predicted by certain extensions of the Standard Model of particle physics, but they remain at least as elusive as MACHOs. To date, no evidence of their existence has been found despite decades of searches using particle accelerators, underground detectors and space telescopes. As null results piled up in the search for WIMPs, some researchers began reconsidering the MACHO hypothesis, focusing particularly on primordial black holes. But what process could have seeded these strange objects throughout the observable universe, and how could they have eluded detection for so long?

BLACK HOLES FROM THE BIG BANG

PHYSICISTS BERNARD CARR AND STEPHEN HAWKING proposed the idea of primordial black holes in the 1970s, although they considered only black holes with masses smaller than that of a mountain. Such minuscule black holes would have already evaporated and vanished within the age of our nearly 14-billion-year-old universe, via a quantum-mechanical process discovered by Hawking and appropriately called Hawking radiation. Consequently, Carr and Hawking's primordial black holes would have a negligible contribution to the universe's current amount of dark matter.

The possibility that massive primordial black holes could actually be most or even all of the dark matter hinges on an idea known as cosmic inflation, first proposed by physicist Alan Guth in the early 1980s. Inflation is a hypothetical phase of prodigious expansion immediately after the big bang. In 10^{-35} second, two points separated by less than an atomic radius would have become separated by four light-years, a distance comparable to that of the closest stars. Moreover, during inflation tiny quantum fluctuations are magnified to macroscopic scales by the rapid expansion, seeding the growing universe with underdense and overdense regions of matter and energy from which all cosmic structures subsequently emerge. As bizarre as it may seem, the theory of inflation is strongly supported by observations of such density fluctuations in the CMB.

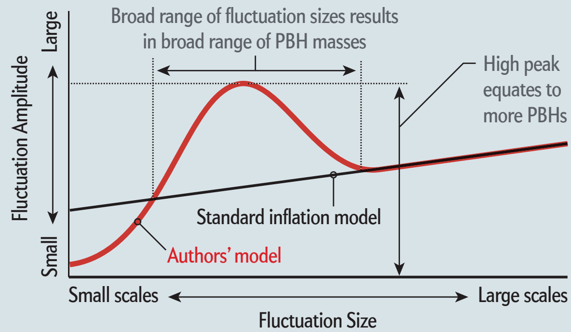
In 1996 one of us (García-Bellido), together with Andrei Linde of Stanford University and David Wands of the University of Portsmouth in England, discovered a way for inflation to form sharp peaks in the spectrum of density fluctuations in the early universe [*see box on opposite page*]. That is, we showed how quantum fluctuations enormously magnified by inflation would naturally produce particularly dense regions that would collapse to form a population of black holes less than one second after inflation ends. Such black holes would then behave as dark matter and would dominate the matter content of the present-day universe.

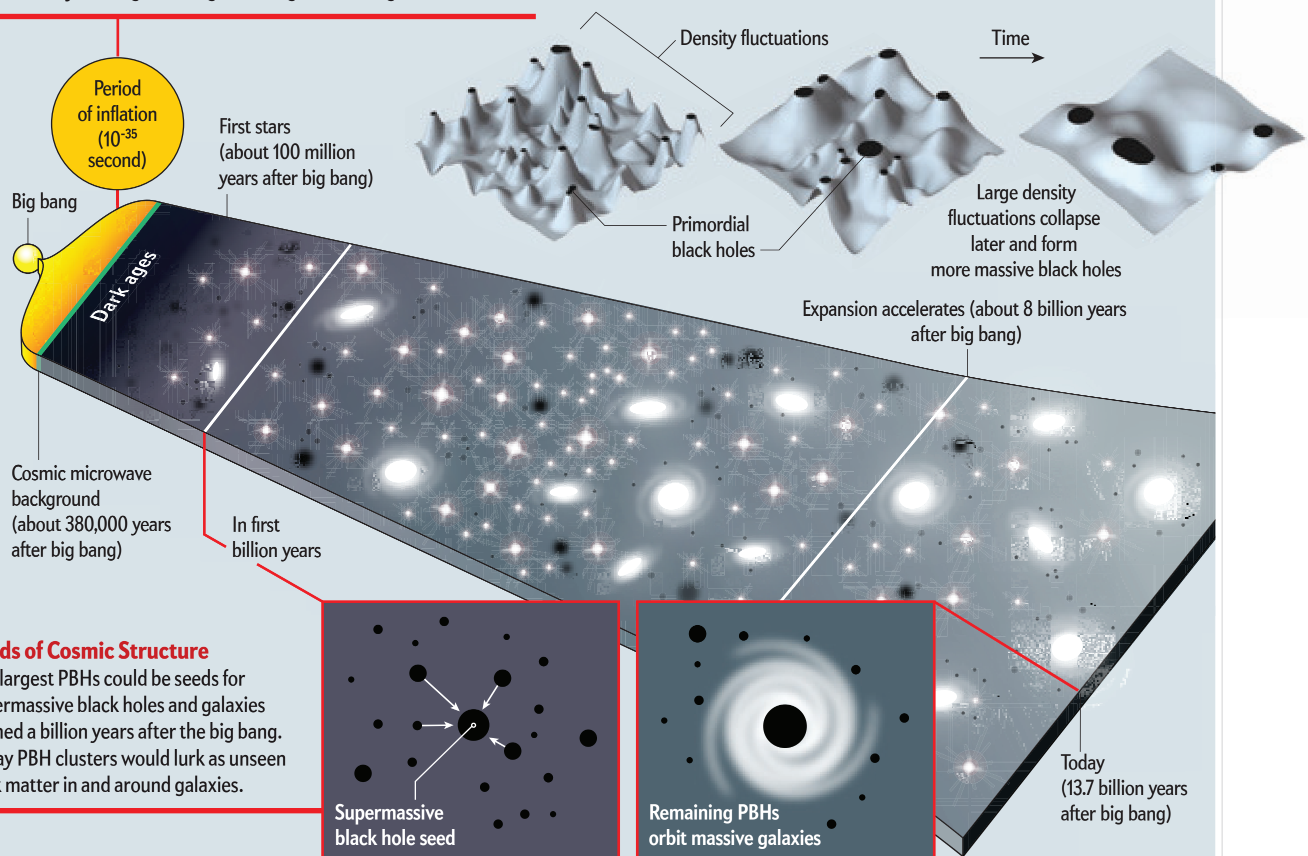
Black Holes Birthed by the Big Bang

The universe's first black holes may have been born in the earliest moments of cosmic time, when all was a seething, thick fog of fundamental particles. In the 1970s theorists realized that dense regions of that fog could collapse under their own gravity just a second after the big bang, forming so-called primordial black holes (PBHs) that would then shape the structure of the evolving, expanding universe. Emitting no light, PBHs would be a natural—albeit difficult to detect—candidate for dark matter.

Primordial Black Holes Form in Clusters

Inflation—a proposed acceleration to the universe's expansion less than a second after the big bang—would form PBHs by magnifying quantum fluctuations to immense scales. As inflation ended, these fluctuations would create density perturbations that then form PBHs. Larger, more powerful fluctuations would create more massive and numerous PBHs. The authors' inflationary model predicts a broad peak of magnified fluctuations and a range of density perturbations, producing PBHs in clusters, with each PBH ranging from one 100th to 10,000 times the mass of our sun. Half a million years after the big bang, a cluster might span hundreds of light-years and contain millions of PBHs. As the PBHs within such clusters merged together, scattered apart, and fed on ordinary gas and dust, they would guide the growth of galaxies and galactic clusters.





Seeds of Cosmic Structure

The largest PBHs could be seeds for supermassive black holes and galaxies formed a billion years after the big bang. Today PBH clusters would lurk as unseen dark matter in and around galaxies.

This model generated a population of black holes with the same mass, determined by the amount of energy within the collapsing region. Many other groups then started exploring these ideas within different models of inflation.

In 2015 the two of us (Clesse and García-Bellido) proposed a scenario, similar to that of 1996, in which these primordial fluctuations exhibit a broad peak in their energy densities and spatial sizes, giving rise to primordial black holes with a wide range of masses. A key consequence of this scenario is the fact that large density fluctuations collapse in close spatial proximity to one another, generating clusters of black holes of different masses—from one 100th to 10,000 times the mass of our sun. Within half a million years of

Illustration by Jen Christiansen and George Retseck (density-fluctuation panels) the big bang, each growing, evolving cluster could contain millions of primordial black holes in a volume just hundreds of light-years across.

Such clusters of primordial black holes would be sufficiently dense to explain LIGO's mysterious black hole mergers, which one would not otherwise expect to occur with regularity. From time to time, the trajectories of two primordial black holes within a cluster can cross, so that both objects become gravitationally bound to each other. They would then spiral closer together for up to millions of years, radiating gravitational waves until they merge. In January 2015 we actually predicted that LIGO would detect gravitational waves from such massive mergers—waves identical to those LIGO then detected later that year. Our estimates for the rate of merger events within primordial black hole clusters fit perfectly within the limits set by LIGO. If LIGO and other similar facilities detect many more mergers within the next few years, it may be possible to determine the range of masses and spins for all the progenitor black holes. Such a statistical analysis of black hole mergers would provide crucial information for testing their potentially primordial origins.

A key aspect of this scenario is that it evades the constraints on MACHOs previously set by gravitational microlensing experiments—constraints that ruled out black holes of up to about 10 solar masses as the main constituent of dark matter. If primordial black holes exist and possess a wide range of masses, only a small fraction would be visible to these microlensing experiments, with the bulk remaining invisible. And if primordial black holes are grouped in clusters, this arrangement suggests a probability of less than one in 1,000 that a cluster would happen to be along the line of sight of the stars in the nearby satellite galaxies monitored for microlensing events.

To avoid this effect, one could search for microlensing events elsewhere in the sky, looking for the magnified light from stars in the Milky Way's neighboring Andromeda galaxy or even from quasars in far distant galaxies. In this way, one could probe a much larger volume of galactic halos for signs of MACHOs—that is, for primordial black holes. Recent observations suggest that whereas MACHOs of up to 10 solar masses may not make up the entirety of an average galaxy's halo, MACHOs between one tenth and a few solar masses could easily account for about 20 percent of the mass in a typical galactic halo. This value is consistent with our broad-mass primordial black hole scenario.

Simply put, we cannot yet rule out the possibility that dark matter is mostly made up of primordial black holes. Indeed, this proposed scenario could decipher several other cosmic mysteries related to dark matter and galaxy formation.

Is Dark Matter Made of Primordial Black Holes?

These observations will make the difference:

1. Detecting more gravitational waves
Gravitational-wave detectors such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) in the U.S. and Advanced Virgo in Italy should detect more black hole mergers. The detection of an unexpectedly large number of massive black hole mergers would be a hint for a primordial origin but would not by itself prove that primordial black holes constitute dark matter. Such proof will have to emerge from corroboration via other observations. Ultimately, detecting a black hole with a mass lower than the so-called Chandrasekhar limit (1.45 solar masses), below which stars cannot produce a black hole, would be the undeniable sign of a primordial origin. Fortunately, LIGO may very soon reach the sensitivity to detect such a black hole if its companion is more massive (greater than 10 solar masses). Finally, on cosmological scales, abundant black hole binaries should induce a diffuse background of gravitational waves, which could be detected by the future space-based Laser Interferometer Space Antenna (LISA) and by ground-based pulsar timing arrays.

2. Discovering more ultrafaint dwarf galaxies
In 2015 astronomers using data from the Dark Energy Survey collaboration discovered dozens of ultrafaint dwarf galaxies in the galactic halo, a finding that suggests hundreds of such dark matter–dominated dwarf galaxies could orbit around the Milky Way. If dark matter is made of primordial black holes, most of them should reside in such dwarf galaxies, a large number of which could be detected with future space-based facilities such as the European Space Agency's Euclid mission and NASA's Wide-Field Infrared Survey Telescope (WFIRST).

3. Measuring variations in the position of stars
The ESA's ongoing Gaia mission is measuring the positions and velocities of about one billion stars in the Milky Way with unprecedented precision. These measurements may reveal the presence of numerous isolated massive black holes via the tiny variations those objects have on the motions of neighboring stars.

4. Mapping neutral cosmic hydrogen
Before and during the formation of the first stars, the universe was mostly composed of neutral hydrogen, which emits characteristic radiation at a radio wavelength of 21 centimeters. As early as 2020, the Square Kilometer Array (SKA), planned to be the largest radio telescope ever built, will begin making an all-sky map of this 21-centimeter signal. The accretion of matter by primordial black holes creates intense x-ray radiation, ionizing the surrounding neutral hydrogen and imprinting signatures on this 21-centimeter all-sky map. SKA should thus detect the presence of massive primordial black holes if they account for the dark matter.

5. Probing distortions of the cosmic microwave background
X-rays from primordial black holes gorging on gas and dust in the early universe should also induce distortions on the spectrum of the cosmic microwave background. The importance of this effect is still controversial, in particular in models where primordial black holes are grouped in dense clusters. Nevertheless, NASA's Primordial Inflation Explorer (PIXIE) mission concept has been proposed to accurately measure such distortions, which should strongly constrain models of primordial black hole dark matter.

MANY PROBLEMS, ONE SOLUTION

CLUSTERS OF PRIMORDIAL BLACK HOLES could clear up the so-called missing satellite problem—the apparent lack of "dwarf" satellite galaxies that should form around massive galaxies such as our Milky Way. Current simulations modeling the cosmic distribution of dark matter accurately replicate the universe's observed large-scale structure, in which halos of dark matter pull galaxy clusters into giant filaments and sheets surrounding great voids of lower density. On smaller scales, however, these simulations predict the existence of numerous subhalos of dark matter orbiting around massive galaxies. Each of these subhalos should host a dwarf galaxy, and hundreds should surround the Milky Way. Yet astronomers have found far fewer dwarf galaxies than predicted.

Many potential explanations for the missing satellite problem exist, mainly the notion that simulations fail to fully account for the influence of ordinary matter (hydrogen and helium in stars) on the formation and behavior of the predicted dwarf galaxies. Our scenario suggests that if clustered primordial black holes made up most dark matter, they would dominate the subhalos surrounding the Milky Way, absorbing a fraction of ordinary matter and reducing the rate of star formation in the subhalos. Moreover, even if these subhalos vigorously formed stars, these stars could easily be ejected by close encounters with massive primordial black holes. Both effects would greatly reduce the brightness of the satellites, making them very hard to detect without wide-field cameras of exquisite sensitivity. Fortunately, such cameras now exist, and astronomers have already used them to discover dozens of ultrafaint dwarf galaxies surrounding the Milky Way. These objects appear to host up to hundreds of times more dark matter than luminous stars, and our model predicts that thousands more should orbit our galaxy.

Simulations also predict a population of galaxies intermediate in size between dwarf galaxies and massive galaxies. Such objects are said to be too big to fail because they would be sufficiently large to readily form stars and be easily seen. Still, they have not turned up in astronomers' searches of the Milky Way's vicinity. This too-big-to-fail problem has a solution similar to that of the missing satellite problem: massive primordial black holes in the cores of intermediate-sized galaxies could eject stars and star-forming gas from these objects, rendering them effectively invisible to most surveys.

Primordial black holes could also resolve the origin of supermassive black holes (SMBHs). These monsters weigh from millions to billions of solar masses and are observed at the centers of quasars and massive galaxies very early in the universe's history. Yet if these SMBHs formed and grew from the gravitational collapse of the universe's first stars, they should not have acquired such gigantic masses in such a relatively short time—less than a billion years after the big bang.

In our scenario, although most primordial black holes have just tens of solar masses, a very small fraction will be far heavier, ranging from hundreds to tens of thousands of solar masses. Born less than a second after the big bang, these monstrous objects would then act as giant seeds for the formation of the first galaxies and quasars, which would rapidly develop SMBHs at their centers. Such seeds could also account for the existence of intermediate-mass black holes possessing 1,000 to a million solar masses observed orbiting SMBHs and at the centers of globular clusters of stars. In short, primordial black holes may be the missing link between conventional stellar-mass black holes and SMBHs. The observational case for this scenario is building rapidly: recent detections of unexpectedly abundant x-ray sources in the early universe are most easily explained by large numbers of primordial black holes producing x-rays as they gorge on gas less than one billion years after the big bang.

SEEING IN THE DARK

EVEN THOUGH massive primordial black holes could solve the mystery of dark matter, as well as many other long-standing problems of cosmology, the game is not yet over. Other models and explanations are still possible, and future observations should allow us to distinguish among the alternatives. Indeed, within the next few years several observations could test the primordial black hole scenario [*see box on opposite page*]. They include the detection of ultrafaint dwarf galaxies, the influence of massive primordial black holes on the positions of stars in the Milky Way, the mapping of neutral hydrogen during the first epoch of star formation and the study of distortions in the cosmic microwave background.

Beyond these experiments, we also now possess a completely new tool to unravel the mysteries of the universe in the form of Advanced LIGO and other gravitational-wave detectors. If indeed LIGO has detected merging members of a hidden population of massive primordial black holes, we should expect many more to be detected in coming years. In June 2016 Advanced LIGO scientists presented to the community a second detection of gravitational waves, emitted during the merging of two black holes, of 14 and eight solar masses, respectively, as well as a tentative hint of another merger of black holes of 23 and 13 solar masses. As we finalized this article, they claimed to have detected six additional merging events. These detections suggest that binary black holes are much more frequent than expected and that they are broadly distributed in mass, in agreement with our scenario of massive primordial black holes.

Taken together these new experiments and observations could confirm the existence of primordial black holes and their possible linkage to the universe's missing matter. Soon we may no longer be in the dark about dark matter. SA

MORE TO EXPLORE

Density Perturbations and Black Hole Formation in Hybrid Inflation. Juan García-Bellido, Andrei Linde and David Wands in *Physical Review D,* Vol. 54, No. 10, pages 6040–6058; November 15, 1996.

Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the Seeds of Galaxies. Sébastien Clesse and Juan García-Bellido in *Physical Review D,* Vol. 92, No. 2, Article No. 023524; July 15, 2015.

Did LIGO Detect Dark Matter? Simeon Bird et al. in *Physical Review Letters,* Vol. 116, No. 20, Article No. 201301; May 20, 2016.

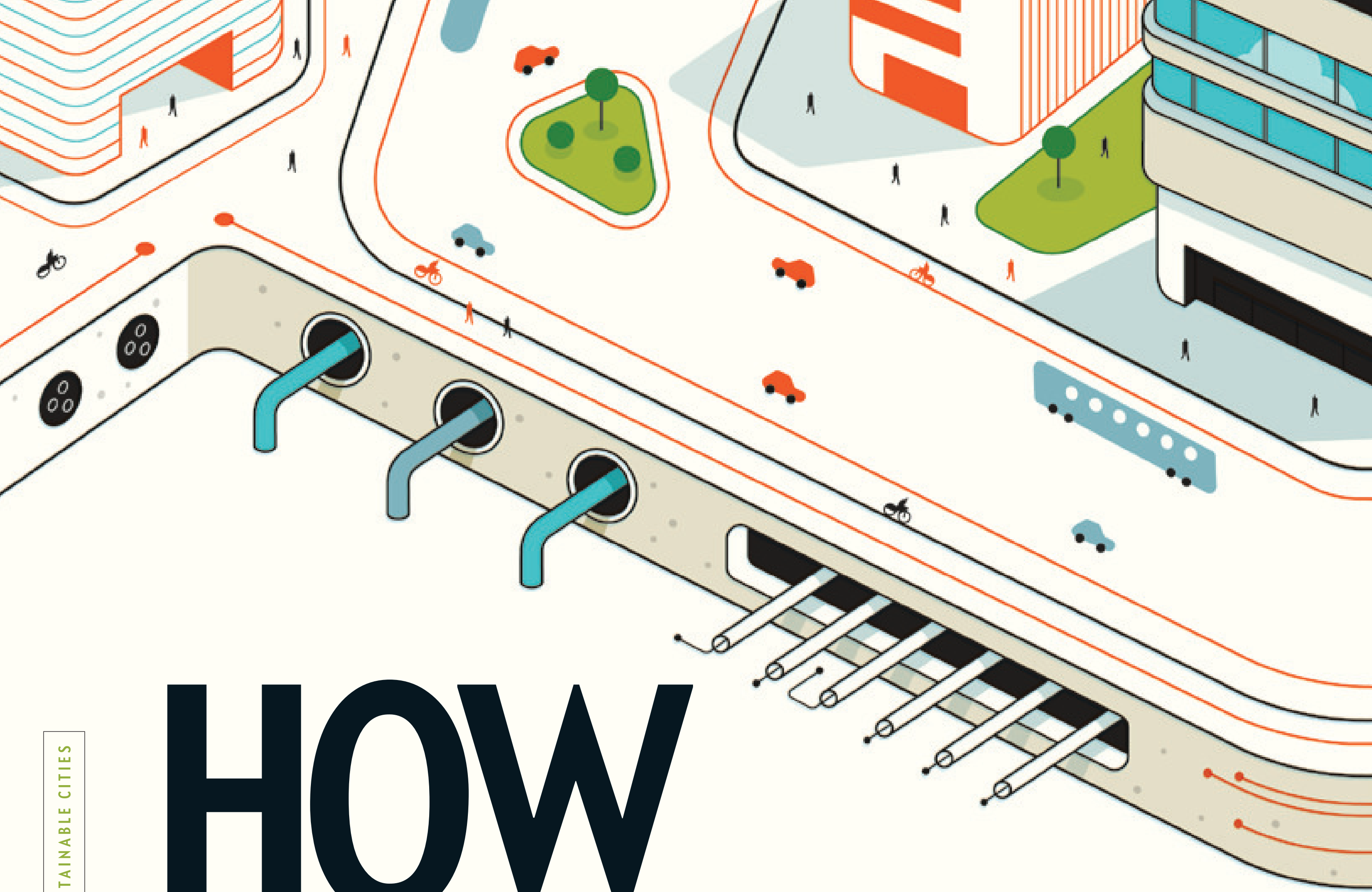
LIGO Gravitational Wave Detection, Primordial Black Holes, and the Near-IR Cosmic Infrared Background Anisotropies. A. Kashlinsky in *Astrophysical Journal Letters,* Vol. 823, No. 2, Article No. L25; June 1, 2016.

The Clustering of Massive Primordial Black Holes as Dark Matter: Measuring Their Mass Distribution with Advanced LIGO. Sébastien Clesse and Juan García-Bellido in *Physics of the Dark Universe,* Vol. 15, pages 142–147; March 2017.

FROM OUR ARCHIVES

Mystery of the Hidden Cosmos. Bogdan A. Dobrescu and Don Lincoln; July 2015.

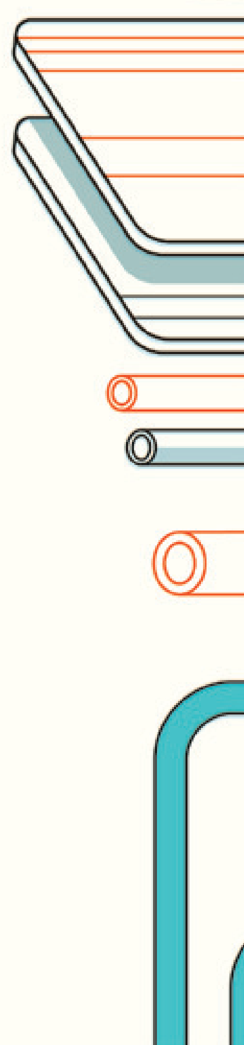
scientificamerican.com/magazine/sa



HOW CITIES COULD SAVE US

Urban areas can improve the planet as well as people's lives if we design them to be much more resourceful with energy, water, food and minerals

By William McDonough



IN BRIEF

To be sustainable, cities should be designed according to the circular principles of nature, including making maximum use of solar radiation and treating waste as a resource.

Newly designed facilities are pioneering these principles, including Park 20|20 in the Netherlands and NASA's Sustainability Base in California.

"Positive cities" allow people to live and work in the same neighborhoods, creating great efficiencies and promoting safe, dignified and creative lives.

Illustrations by Harry Campbell

CITIES ARE HOME TO MORE THAN HALF THE WORLD'S population, and they exert increasing stress on the earth. They produce up to 70 percent of global carbon dioxide emissions, use up vast quantities of water, degrade water quality and produce mountains of waste. As cities go, so goes the planet. And cities are growing—fast. By 2030, according to the latest United Nations estimates, five billion people will live in cities, nearly half of them conducting their lives in homes, schools, workplaces and parks that do not yet exist.

The challenges in making cities as sustainable as possible are enormous. But they are also inspiring because cities can play an outsized role in creating solutions for a more sustainable world. Cities are engines of innovation and entrepreneurial energy. As networks of city leaders are showing, municipalities are also powerful actors, pooling their strengths, setting environmental agendas and exercising global leadership. From megacities to towns, mayors and city councils, investors, economists and planners are responding to the urgent need to redesign the basic elements of fast-growing cities from the ground up. How they reimagine the urban landscape and how they design growth will profoundly influence the future of all life on earth.

William McDonough is an architect who has pioneered design for sustainable development. He is founder of William McDonough + Partners and McDonough Innovation and co-founder of the Cradle to Cradle Products Innovation Institute.

Many cities are taking important steps to reduce air and water pollution. They are being "less bad." Efficiency in itself, however, is insufficient to move us to a positive future. If cities can also be effective and do "more good," for example, by converting waste back into nutrients for food production, cities can propel us toward a future we want, not just reduce the impacts we do not want. More good, not just less bad.

A clear vision for reimagining the city and its relationship to its surrounding countryside can be found in replicating the operating system of the natural world. In essence, natural systems operate on the free energy of the sun, which interacts with the geochemistry of the earth to sustain productive, regenerative biological systems. Human systems, including cities, that operate by the same laws can approach the effectiveness of living systems.

These laws can be distilled into three key principles: equate waste with food; maximize use of solar income; and celebrate diversity.

Waste does not exist in nature, because each organism contributes to the health of the whole. A fruit tree's blossoms fall to the ground and decompose into food for other living things. Bacteria and fungi feed on the organic waste of both the tree and the animals that eat its fruit, depositing nutrients in the soil that the tree can take up and convert into growth. One organism's waste becomes food for another. Nutrients flow perpetually in regenerative, cradle to cradle cycles of birth, decay and rebirth. Waste equals food.

OUR CITIES are currently designed for linear flow. Biological nutrients (such as food and wood) and technical nutrients (such as metals and plastics) enter at one end and are used, then discarded. After waste is sifted for valuable recyclables such as metals, paper and certain plastics, it flows out the other end, headed for landfills or incinerators. The process is "take, make, waste." But just as we have redesigned certain consumer products to be disassembled, recycled or reused, we can design cities in a similar, circular fashion: take, make, retake, remake, restore.

In the circular city, wastes become resources. Consider sewage. In a linear city, wastewater-treatment plants process food residues and human waste—including the valuable minerals they contain, such as phosphate—and release the effluent into rivers as pollution. Farmers then buy more phosphate from Morocco or other distant lands to make new fertilizer to grow more food in soils that have lost those minerals. In the circular city, sewage-treatment plants become fertilizer factories. The carbon, phosphate and nitrogen flowing out of the facility are seen as potential assets for soil, not as liabilities for the nearest river. Circular cities mine the wastewater for phosphate and turn it into fertilizer for parks and vegetable gardens on city rooftops and for farms and forests surrounding the city. This process eliminates the need to buy more phosphate from faraway sources and transport it to the U.S. It also avoids the energy and carbon emissions involved in mining and transport. Ostara Nutrient Recovery Technologies in Vancouver is one of several companies pioneering the collection of the phosphate mineral struvite for fertilizer from sewage sludge.

Eliminating the concept of waste extends to all systems, so circular cities design incoming materials for "next use" instead of "end of life." For example, new technologies allow cell-phone circuit boards to be profitably processed in a clean facility, where all the rare earth minerals and precious metals are recovered for reuse in new electronic products.

A second key principle of nature, and what we might call positive cities, is that everything is powered by the sun—and sometimes, as in the Iceland city of Reykjavík, by geothermal power. Trees and plants manufacture food from sunlight—an elegant, effective system that uses the earth's only perpetual source of energy income. Buildings can tap into solar income by directly converting the sun to energy and by passively collecting the solar radiation for heat and natural lighting. Winds—thermal flows fueled by sunlight—can also be harnessed. Together solar, wind and geothermal energy can generate enough power cost-effectively to meet the needs of entire cities and regions, even nations. Cities such as San Francisco are already making significant progress toward meeting their commitments to run 100 percent on renewable energy in the next 15 years.

The third key principle—diversity—is found in all healthy ecosystems. Each organism has a unique response to its surroundings that works in concert with other organisms to sustain the system. Each organism fits in its place, and in each system the most fitting thrive.

Urban designers aiming for what fits attend carefully to local ecologies. They as-

BIG DATA

World population living in cities: **55%**

5 Billion

People living in cities by 2030

U.S. cities committed to 100% renewable energy: **27**

Residents who use the bus in Curitiba, Brazil: **85%**

SOURCES: *THE WORLD'S CITIES IN 2016: DATA BOOKLET*. UNITED NATIONS, 2016 (*population in cities now and in 2030*); SIERRA CLUB (*U.S. cities committed to renewable energy*); *LOW CARBON GREEN GROWTH ROADMAP FOR ASIA AND THE PACIFIC*. UNITED NATIONS ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC. U.N., 2012 (*bus use in Curitiba, Brazil*)

sess the geology, hydrology, vegetation and climate. They incorporate natural and cultural history. By combining this rich "essay of clues," designers discover appropriate patterns for the development of the landscape. By doing so, they create possibilities for positive growth that supports life.

Ultimately, what we want is a city designed to allow people to live and work in the same neighborhood. If residents can decompose cell phones at a clean factory that fits within a city's ecosystem, there is no need to relegate the factory to special zones of bad behavior at the outskirts of town. A positive city eliminates the need for zoning driven by concern about unsafe or unhealthy activities. Factories can be in the middle of clean residential neighborhoods, providing jobs so people can live within walking or biking distance. That opportunity, in turn, greatly reduces the need for commuting and transportation—a huge waste of resources and of people's time. And if fresh, healthy food is grown on rooftops across the city, as Method Products' new South Side Soapbox factory in Chicago is doing, not only can local organic waste be a resource for food-growing systems, but people working at the rooftop farms can live locally as well.

Imagine everything we make as a gesture that supports life, inspires delight and finds harmony with nature. Buildings operate like trees; they sequester carbon, make oxygen, distill water, provide habitat for thousands of species, and convert solar income into all the thermal and electrical energy they need—and sell excess power to the neighbors. Buildings with on-site wetlands and botanical gardens recover nutrients from wastewater and clean what remains for on-site kitchens and bathrooms. Fresh air, flowering plants and daylight are everywhere. Buildings and communities function as life-support systems.

With this vision in mind, we can imagine food and materials produced in the surrounding countryside, created with tools and technology made in the city. The city returns waste as a raw material that replenishes the system, putting the "re" back into resources. Everything moves in regenerative cycles, from city to country, country to city, in natural and cultural networks that circulate biological and technical nutrition—the hardware and software of the 21st century. The metabolism of a living, positive city allows human settlements and the natural world to flourish together. If we are to make our cities truly sustaining and beneficial for all, we need to take this as a literal, strategic truth that informs all our designs.

It is compelling to lay out principles for a utopian future. But can existing cities actually put them into practice today? Some recent industrial facilities are demonstrating how.

The renovation and expansion of the Ford Rouge Center in Dearborn, Mich., transformed the massive, historic car- and truck-manufacturing complex into a model of industrial sustainability. The master plan incorporated a 10-acre green roof—the heart of a system of wetland gardens, porous paving, hedgerows and bioswales. The project turned a 100-year-old industrial brownfield site into a thriving storm-water ecosystem that captures, cleanses and slowly releases water to the adjacent Rouge River in ways that support watershed health. Native killdeer returned to nest a week after construction was completed.

Another model is Sustainability Base, NASA's new center for science and computing at its Ames Research Center in Moffett Field, Calif. The facility has the potential to provide all its heating, cooling and energy needs—and even an energy surplus—from solar and geothermal sources and a fuel cell with advanced energy-management controls. Wastewater is treated on-site.

The award-winning Park 20|20 development in Hoofddorp, the Netherlands, is another model. It is a diverse set of buildings and open spaces now being completed across 28 acres. People can access the park easily by air, rail, bus and bicycle. Green zones, plazas, public gardens and canal boardwalks provide a connection to the larger community. Each building's size, structure and orientation are optimized to capture the sun's energy and light. Buildings across the park integrate energy, water and waste-management systems, acting as a single organism.

CAN WE EXPAND these successes to entire cities? Inspiration comes from some intriguing places. One of them is Curitiba, Brazil.

Curitiba began transforming in the 1970s, under legendary architect and urban planner Jaime Lerner, who was mayor three different times from the 1970s to the 1990s. During his first term Lerner realized that the poor town of several hundred thousand inhabitants needed better public transportation. Because a subway or heavy rail system would cost far too much, he instead asked Volvo to make 270 Swedish articulated buses, done within the city, which gave residents jobs. The city hired locals to build aboveground, street-side bus shelters, or *tubos,* from which people could travel anywhere for a flat fare. Instead of riders paying with a token as they boarded a bus, a slow process, Lerner had them prepay when entering the *tubo* platform, so when the bus arrived, they could get on quickly, reducing loading time and making the entire system efficient.

As a result of Curitiba's rapid population growth, garbage was piling up in narrow alleyways where trucks could not retrieve it. Lerner created a program to instruct children how to separate trash, then sent them home to teach their families. In exchange for the sorted garbage, people were paid in bus tokens or fresh food;

Lerner paid them in a currency for mobility. Suddenly, everyone was using mass transit. Today 85 percent of Curitiba citizens use the bus, and 90 percent recycle. Curitiba recycles 70 percent of its refuse—one of the highest rates in the world.

This innovative thinking went on and on. Instead of building a big central library downtown, the city created a network of 50 small "Lighthouses of Knowledge" throughout the neighborhoods so that every child was within walking distance of a library. Local builders, of course, constructed the brightly colored buildings. The libraries work with municipal schools and offer thousands of books and free Internet for citizens ages three to 80. These and other steps transformed the city to a live-work design.

Now imagine if Manhattan had this same kind of vision—with local food growing on the rooftops of hundreds of schools and hospitals, providing nutrition as well as local jobs. Kids could use their optical sensors known as eyeballs to sort trash, pull out the plastics, bring them to recycling centers so they do not end up in the ocean and then get paid in toys. Clean factories would reformulate the plastics into monomers that can be used again. Everything is powered by the sun, and materials flow in continuous cycles of biological and technical nutrition.

What we are after, for all people, is something I would call the "good life"—a life that is safe, dignified and creative. Positive cities are the places where that can happen. If they are designed and run on this principle, everything gets better. We have to insist on the rights of humanity and nature to coexist, to bring together the city and its surrounding countryside.

Cities are designed, but they are also organisms. As the late French anthropologist Claude Lévi-Strauss pointed out years ago, cities are "something lived and something dreamed." As makers of living places, we cannot help projecting ourselves onto the landscape. But as we dream of our ideal cities, as we conjure the human weft on the geologic warp of the land, we can begin to see more clearly the true character of the place we inhabit, its spirit. Then, as we shape the nature of our cities, we will be making places that celebrate both human creativity and a rich, harmonious relationship with the living earth. We will be forging a new geography of hope. SA

TAPPING THE TRASH

Transforming costly wastes into valuable resources can make cities highly efficient

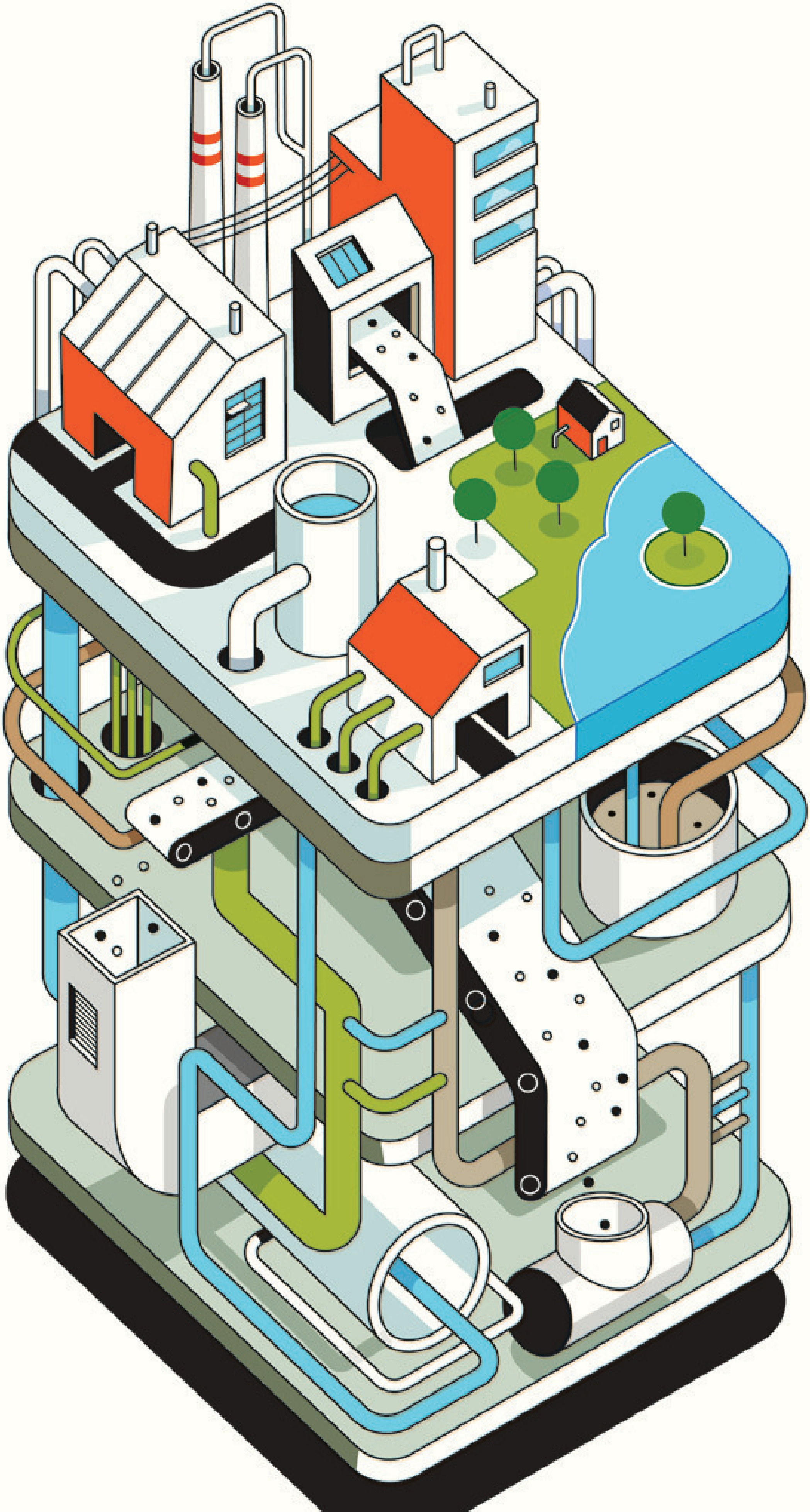
By Michael E. Webber

ON DECEMBER 20, 2015, A MOUNTAIN OF URBAN REFUSE COLLAPSED in Shenzhen, China, killing at least 69 people and destroying dozens of buildings. The disaster brought to life the towers of waste depicted in the 2008 dystopian children's movie *WALL-E,* which portrayed the horrible yet real idea that our trash could pile up uncontrollably, squeezing us out of our habitat. A powerful way to transform an existing city into a sustainable one—a city that preserves the earth rather than ruining it—is to reduce all the waste streams and then use what remains as a resource. Waste from one process becomes raw material for another.

Many people continue to migrate to urban centers worldwide, which puts cities in a prime position to solve global resource problems. Mayors are taking more responsibility for designing solutions simply because they have to, especially in countries where national enthusiasm for tackling environmental issues has cooled off. International climate agreements forged in Paris in December 2015 also acknowledged a central role for cities. More than 1,000 mayors flocked to the French capital during the talks to share their pledges to reduce emissions. Changing building codes and investing in energy efficiency are just two starting points that many city leaders said they could initiate much more quickly than national governments.

Michael E. Webber is deputy director of the Energy Institute, co-director of the Clean Energy Incubator and a professor of energy resources at the University of Texas at Austin. His latest book is *Thirst for Power: Energy, Water, and Human Survival* (Yale University Press, 2016).

It makes sense for cities to step up. Some of them—New York City, Mexico



MACHINES dig through rubble in Shenzhen, China, after a mountain of refuse collapsed, burying dozens of buildings.

GETTY IMAGES

City, Beijing—house more people than entire countries do. And urban landscapes are where the challenges of managing our lives come crashing together in concentrated form. Cities can lead because they can quickly scale up solutions and because they are living laboratories for improving quality of life without using up the earth's resources, polluting its air and water, and harming human health in the process.

Cities are rife with wasted energy, wasted carbon dioxide, wasted food, wasted water, wasted space and wasted time. Reducing each waste stream and managing it as a resource—rather than a cost—can solve multiple problems simultaneously, creating a more sustainable future for billions of people.

POLLUTION AS SOLUTION

LESSONS ABOUT WASTE abound in history. John Snow, a London doctor, deduced that terrible cholera outbreaks struck London in 1848 and 1854 because public water wells were contaminated by sewage. Building sewers was an obvious solution, but political leaders rejected Snow's findings because his ideas did not fit prevailing ideologies and because the actions were deemed too expensive. Similar rejection is offered for today's climate scientists, who tell us that our waste is killing us, though in a much slower and less direct fashion, and that fixing the problem will require significant investments in new infrastructure. Snow was later vindicated as a hero (perhaps the same fate awaits our present-day scientists) after new leaders created ambitious public works projects to cram 1,200 miles of sewers into a crowded city of three million people, ending the cholera problem. The work also created the lovely river embankments that still stand as a key piece of London's urban environs and along which many people stroll.

Today just flushing the waste away is not enough, however. After we reduce it, we should close the loop and use the remainder again. First, limit waste, then put it to work.

This new thinking begins by redefining our concept of pollution. Raj Bhattarai, a well-known engineer at the municipal water utility in Austin, Tex., taught me a new definition for pollution: resources out of place. Substances are harmful if they are in the wrong place: our bodies, the air, the water. But in the right place, they are useful. For example, instead of our sending solid waste to a landfill and paying the bill, it can be incinerated to generate electricity. And the sewage for a million-person community can be mined for millions of dollars of gold and other precious metals annually for use in local manufacturing.

This idea fits with the larger concept of the so-called circular economy—where society's different actions and processes feed into one another beneficially. Simply put, waste is what you have when you run out of imagination.

LESS IS MORE

ONE OBVIOUS PLACE to start reducing waste is leaky water pipes. A staggering 10 to 40 percent of a city's water is typically lost in pipes. And because the municipality has cleaned that water and powered pumps to move it, the leaks throw away energy, too.

Energy consumption itself is incredibly wasteful. More than half the energy a city consumes is released as waste heat from smokestacks, tailpipes, and the backs of heaters, air conditioners and appliances. Making all that equipment more efficient reduces how much energy we need to produce, distribute and clean up.

Refuse is another waste stream to consolidate. The U.S. generates more than four pounds of solid waste per person every day. Despite efforts to compost, recycle or incinerate some of it, a little more than half is still dumped in landfills. Reducing packaging is one way to lessen this volume while also generating other benefits. Big retailers such as Walmart, for example, have found that reducing packaging results in fewer trucks needed for shipping and more shelf space to display goods.

Wasted food is its own heart-wrenching issue. Despite famine and food scarcity in many places globally, Americans throw away 25 to 50 percent of their edible food. Food requires vast amounts of energy, land and water to grow, produce, store, prepare, cook and dispose—so wasted food leaves a significant imprint. Initiatives that have popped up in the U.S., such as the I Value Food campaign, and in the U.K. are a start toward solving this vital issue.

PUTTING WASTE TO WORK

ONCE CITIES REDUCE waste streams, they should use waste from one urban process as a resource for another. This arrangement is rare, but compelling projects are rising. Modern waste-to-energy systems, such as one in Zurich, burn trash cleanly, and some, including one in Palm Beach, Fla., recover more than 95 percent of the metals in the gritty ash that is left by the combustion. Rural villages, such as Jühnde in Germany, create enough biogas from cattle and pig manure to heat or power a large portion of their homes. My research group at the University of Texas at Austin has demonstrated that a cement plant in New Braunfels, Tex., can burn fuel pellets made of unrecyclable plastics rather than coal, avoiding carbon dioxide emissions and impacts from coal mining.

Even trash that is put in landfills can provide some value. Cities can collect methane that rises as the waste decomposes, which is an obvious improvement over flaring (burning off) the gas or simply letting the methane waft up into the atmosphere, where it traps much more heat than the equivalent amount of carbon dioxide. Power generators can convert the collected gas into electricity. Vancouver's landfills extract the methane and burn it to heat nearby greenhouses that grow tomatoes.

Even then, landfills are still leaky. That inspired Vancouver, which has pledged to become the greenest city on earth, to give residents separate bins for trash and organic matter (food scraps, yard clippings and tree trimmings). Officials expect citizens to use them properly and deploy city inspectors to check that waste haulers are dumping refuse that is separated correctly. The city produces methane from the organic waste while generating solids known as amendments that can make soil more fertile. These solutions solve multiple problems at once—saving money for energy that would otherwise have been purchased, reducing the need for expensive landfilling and avoiding unnecessary use and damage of land—while improving agriculture.

COURTESY OF VILLAGE FARMS

VANCOUVER burns methane collected at landfills to produce heat that warms tomato greenhouses run by Village Farms.

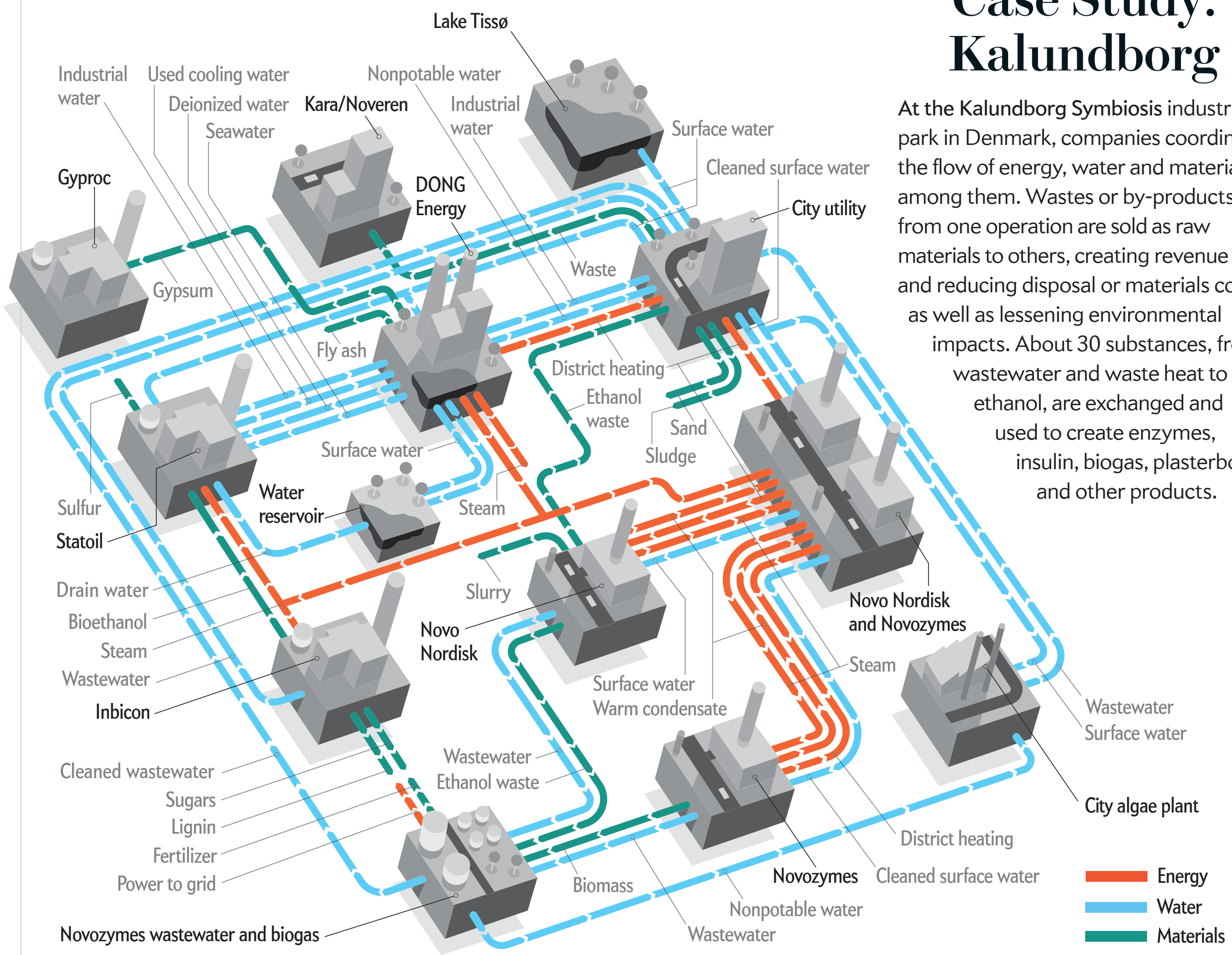
Austin does something similar with its wastewater sludge, passing it through anaerobic digesters to make biogas it sells or uses on-site for generating heat. It converts the remaining solids into a popular soil amendment known as Dillo Dirt (a reference to the armadillo, one of its local creatures). The city earns money by selling the Dillo Dirt, offsetting some of the cost of treating wastewater. Although composting is a growing and popular trend among residents—and one worth pursuing—doing it poorly can actually lead to more methane emissions. For Austin, it makes more sense for residents to put food scraps down the drain and through a grinder so that the city's industrial-scale harvesters at the wastewater plant can do the work of the composter but with greater efficiency.

Waste heat is another big opportunity. Harvesting it is difficult because low temperatures are hard to convert into electricity. NASA developed thermoelectric generators to do this on its spacecraft, but the technology is expensive and inefficient. Nevertheless, advanced materials that can more effectively convert heat to electricity are coming. A place to start is the hot wastewater that goes down the drain when we wash our clothes, dishes or bodies. Sandvika, a suburb of Oslo, has massive heat exchangers along city waste pipes that extract heat to warm dozens of nearby buildings or defrost sidewalks and roadways. By turning on heat pumps in the summer, it can use some of the heat to cool those same buildings. Vancouver liked the idea so much that it repeated the concept, using wastewater to heat hundreds of buildings and the Olympic Village.

Taking that idea further is the Kalundborg Symbiosis in Denmark, a leading example of closed-loop thinking. The industrial park has seven companies plus municipal facilities—centered on electric, water, wastewater and solid-waste facilities—that are interconnected such that the waste from one is an input for another. Pipes, wires and ducts move steam, gas, electricity, water and wastes back and forth to improve overall efficiency and reduce total wastes, including CO_2 emissions. For example, wastewater from the oil refinery flows to the power plant, where it is used to clean and stabilize fly ash from coal combustion. The refinery also sends waste steam to Novo Nordisk, which puts the heat to work for growing about half the world's supply of insulin with bacteria and yeast [*see box on next page*]. The entire park looks like a living, industrial organism. And it has demonstrated economic growth with flatlined or reduced emissions.

Case Study: Kalundborg

At the Kalundborg Symbiosis industrial park in Denmark, companies coordinate the flow of energy, water and materials among them. Wastes or by-products from one operation are sold as raw materials to others, creating revenue and reducing disposal or materials costs, as well as lessening environmental impacts. About 30 substances, from wastewater and waste heat to ethanol, are exchanged and used to create enzymes, insulin, biogas, plasterboard and other products.



SUSTAINABLE CITIES

SPECIAL REPORT

SOURCE: SYMBIOSIS CENTER DENMARK www.symbiosecenter.dk

DATA-DRIVEN DECISIONS

CAN THE KALUNDBORG SYMBIOSIS model be replicated on a larger scale, for cities worldwide? Yes, but only if we make cities smart. An industrial park is flexible because it has only a few tenants and decision makers, but a city has many individuals and organizations making independent decisions about energy, water and waste every day. Integrating them requires a cultural shift toward cooperation, boosted by advances in smart technologies. "Smart cities" will depend on ubiquitous sensing and cheap computing, compounded by machine learning and artificial intelligence. This combination can identify inefficiencies and optimize operations, reducing wastes and costs while operating all kinds of equipment automatically.

Thankfully, making cities smart is an alluring objective for planners who want to accommodate higher densities of people without diminishing quality of life. For example, in India, where population and public health problems are severe, Prime Minister Narendra Modi has announced his intention to convert 100 small and medium-sized municipalities into smart cities as a possible solution.

The "smart" moniker itself is an accusation that most cities are dumb. That accusation sticks because municipalities rife with waste seem to be operating blind. The U.S. National Science Foundation has just launched a major research initiative called Smart & Connected Communities to help cities make better use of data. That name, by the way, indicates that intelligence is not enough—interconnections among systems and people matter, too.

Smart cities rely heavily on big data gathered from widespread sensor networks and advanced algorithms to quickly gain insights, draw conclusions and make decisions on those data. Connected networks then communicate those analyses to equipment all across the city. Smart meters for closely tracking electricity, natural gas and water use by time of day, household and industrial appliance are an obvious place to start. Real-time traffic sensors, air-quality monitors and leak detectors are also at hand. The Pecan Street consortium in Austin is collecting data from hundreds of homes to learn how access to such data streams might help consumers change their behaviors in ways that reduce consumption while saving costs. Cities such as Phoenix and military bases such as Fort Carson in Colorado have pledged to

Illustration by Harry Campbell

become self-sufficient users of energy and water and net-zero producers of waste. Achieving those ambitious goals will require a lot of interconnected data.

Better transportation may give urbanites their first glimpse of a smart city's benefits by cutting wasted time. Reducing the footprint of transportation means cleaning up the fuels, making the vehicles more efficient, reducing trip distances and duration, increasing vehicle occupancy and cutting back on the number of trips. If people live close to their work, they can walk or bike or use mass transit. Studies show that building protected bicycle lanes leads to dramatically increased ridership, and because bicycles require so little space, compared with cars, they can reduce congestion on the roads.

A driverless city will also free up wasted space and time associated with parking. With shared or autonomous cars in constant motion instead of private cars that are parked at home and work, the number of parking spaces can be restricted dramatically, opening up wasted space and easing congestion further. Researchers at the Center for Transportation Research at the University of Texas at Austin used sophisticated models to determine that shared, autonomous vehicles would lessen the number of cars needed in a city by an order of magnitude and would cut emissions, despite causing a slight increase in total miles traveled because the vehicles would stay in motion. Instead of wasting their time driving, commuters can rest, read e-mails, place phone calls or conduct other business. That work can create economic value—and trim a person's office hours so he or she can get home earlier for dinner.

Making our infrastructure smarter is certainly the key to solving basic problems such as leaky water pipes. Identifying leaks should be easy if meters are distributed throughout a water system to track flows and readily pinpoint the amount and location of those leaks. Researchers in Birmingham, England, developed a system with tiny pressure sensors that use a small amount of power to frequently check for and detect leaks in water networks, a big improvement over the old technique of waiting for someone to call and complain that water is shooting like a geyser out of the road. And someday we might send smart robots down the pipes to repair the problems.

PIPES in Kalundborg, Denmark, carry waste steam from the DONG Energy power plant to companies that use it for manufacturing.

COURTESY OF KALUNDBORG SYMBIOSIS

Instead of our sending waste to a landfill, it can be incinerated to generate electricity. Sewage can be mined for gold and other precious metals for local manufacturing.

High-performance sensors will also let us find and predict natural gas leaks before accidents happen. Gas leaks are not only bad for the environment and a waste of resources but dangerous, as we see in headline-grabbing explosions in urban areas with aging infrastructure.

It is hard to know where smart, waste-conscious cities may arise. I imagine a likely candidate will be a Midwestern town with a million people or more that needs to reinvent itself because its economy was gutted decades ago. Indianapolis comes to mind, in part because it needs to rebuild water, wastewater and sewer systems based on bad decisions a century ago. The city has been investing in its downtown and is on the rise. Pittsburgh is leveraging its existing assets—a vibrant urban core, city pride, forward-looking leadership from Mayor William Peduto, the strength of Carnegie Mellon University and other hotbeds of innovation—to go from being defined by its smokestacks to being defined by its brainpower. Indeed, Uber launched its autonomous-vehicle service there. Columbus, Ohio, which is the state capital and home to a major university, is another place to look for cutting-edge experiments in becoming smart. The U.S. Department of Transportation recently awarded Columbus a $40-million grant to reinvent its approach to mobility.

GETTING FROM HERE TO THERE

TURNING PROFLIGATE CITIES into places that reduce waste and reuse what is left will not be easy. Integrated R&D investments from the federal government have to be combined with practical policies from all levels of government. Unfortunately, R&D funding is in recent decline, and in the U.S., it may drop further under the Trump administration.

Investment has to be socially savvy as well. Studies show that R&D for smart cities has focused more on technology than what the citizenry needs. Done the wrong way, the benefits of a smart city might accrue to those who already have Internet connectivity and access to advanced technologies, which would only widen the technology gap on top of other socioeconomic divides.

Municipalities also need to help residents become smarter citizens because each individual makes resource decisions every time he or she buys a product or flips a switch. Access to education and data will be paramount. Connecting those citizens also requires collaboration and neighborly interactions: parks, playgrounds, shared spaces, schools, and religious and community centers–all of which were central tenets of centuries-old designs for thriving cities. The more modern and smart our cities become, the more we might need these old-world elements to keep us together. SA

FROM PARKING LOT TO PARADISE

Carlo Ratti is director of the Senseable City Lab at the Massachusetts Institute of Technology and founder of the Carlo Ratti Associati design studio.

Assaf Biderman is an inventor, associate director of the Senseable City Lab and founder of Superpedestrian, a company focused on developing robotic vehicles for single and double occupancy.

SPECIAL REPORT

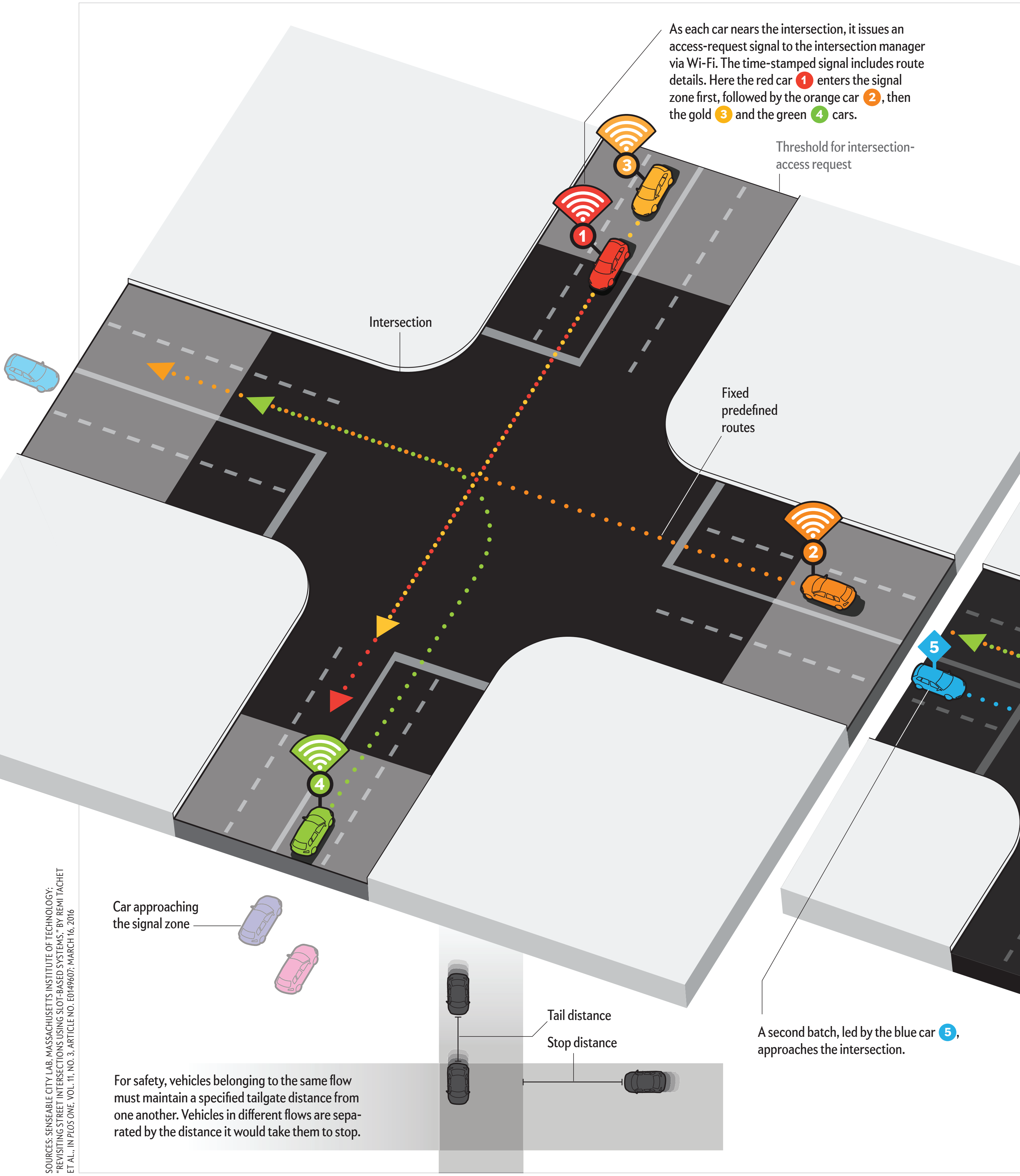
SUSTAINABLE CITIES

A moving web of sensor-laden vehicles and smart intersections will transform how we get around town

By Carlo Ratti and Assaf Biderman

CARS AND CITIES HAVE A COMPLICATED relationship. Today, plagued with swelling road congestion and rising air pollution, we tend to think of the two as increasingly incompatible. But during the 20th century the automobile left one of the most durable marks on city planning. As Swiss-born architect Le Corbusier declared in his seminal 1925 book *The City of To-morrow and Its Planning,* "The motor-car … has completely overturned all our old ideas of town planning."

Almost 100 years later we are at a similar turning point. First, demand for urban transportation is expected to more than double by 2050, which means that we will need to more than double capacity on the roads just to keep congestion at the (often unacceptable) levels we experience now. Second, thanks to the rapid convergence of information and communication technologies, robotics and artificial intelligence, our mobility systems—cars, buses and other forms of transportation—are undergoing massive transformations. Once again,



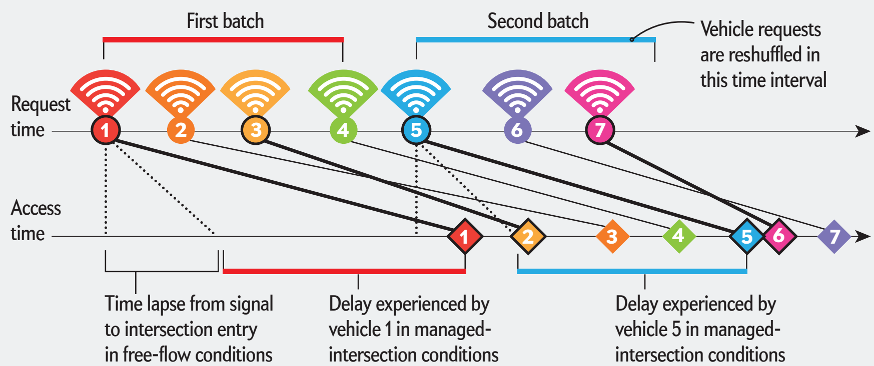
SOURCES: SENSEABLE CITY LAB, MASSACHUSETTS INSTITUTE OF TECHNOLOGY; "REVISITING STREET INTERSECTIONS USING SLOT-BASED SYSTEMS," BY REMI TACHET ET AL., IN *PLOS ONE*, VOL. 11, NO. 3, ARTICLE NO. E0149607; MARCH 16, 2016

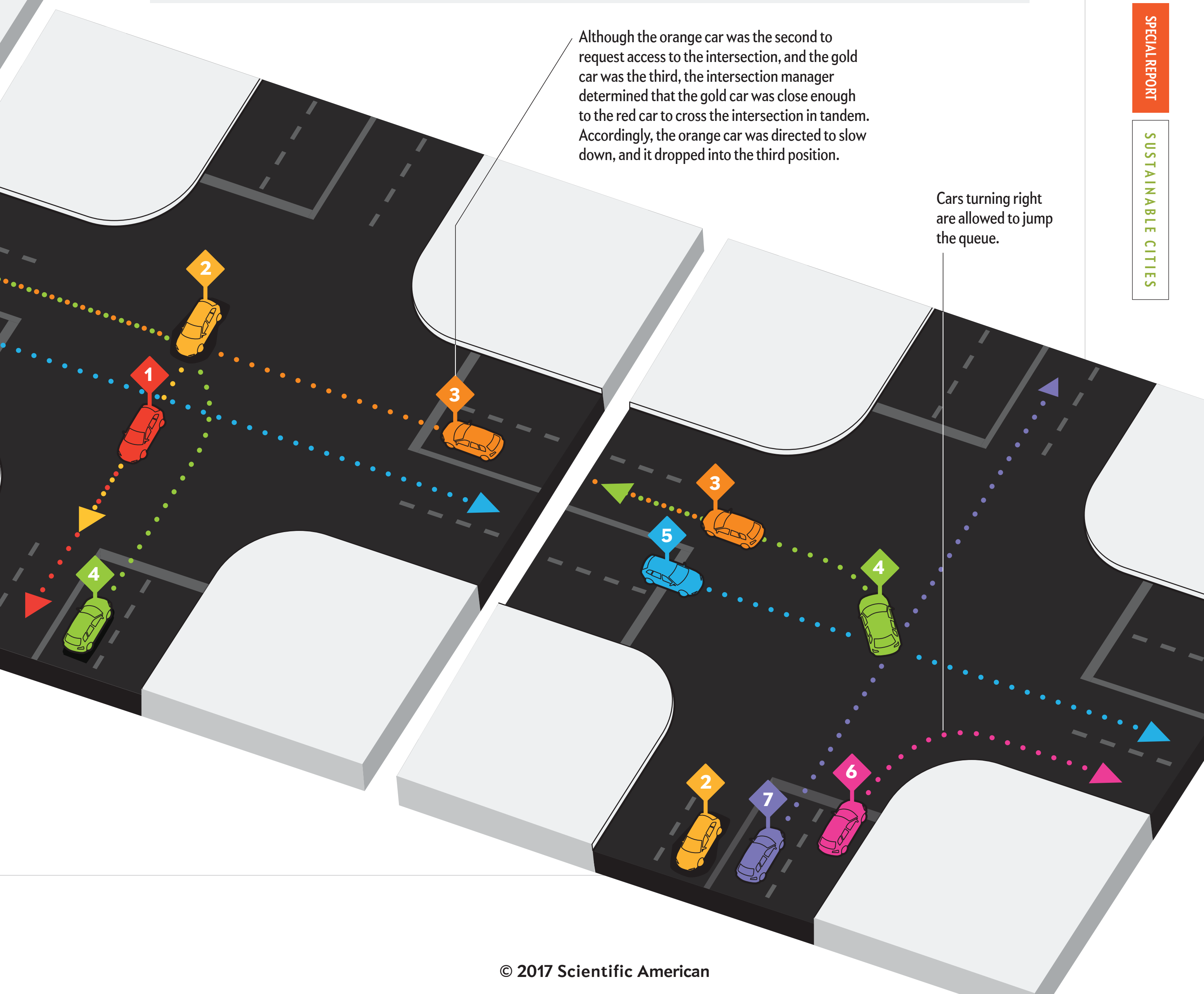
Illustration by Jen Christiansen

Traffic Control

Self-driving vehicles would enable city planners to replace traffic lights with slot intersections, in which each vehicle approaching an intersection is assigned a time "slot" when it can pass through. Research suggests that slot intersections could allow twice as many vehicles to pass through an intersection in a given amount of time, compared with traffic lights.

Slot intersections are most efficient when vehicles are grouped together in batches, allowing the automated-intersection manager to reshuffle car order within one group of vehicles at a time. This arrangement prevents a string of cars on a more heavily traveled road from dominating the system at the expense of cars headed in the other direction.





they stand poised to radically reshape the urban landscape.

Self-driving (or autonomous) vehicles are leading the charge. In recent decades cars have shifted from the kinds of mechanical systems Henry Ford might have recognized to veritable computers on wheels. The average car is now equipped with an array of sensors that collect internal and external data to help it run safely and efficiently. Companies such as Waymo (spun out of Google), Cruise (acquired by General Motors), Otto (acquired by Uber), Zoox and nuTonomy, for example, are experimenting with additional sensors that can "see" a street much in the way our eyes do. Once you feed that information into an onboard artificial-intelligence system, you get a fully autonomous vehicle, capable of navigating on busy traffic grids without any human input.

Autonomous cars will free up much of the time we spend every day driving, and they will make our roads safer. They are going to be game changers for our cities—but in ways that are far from decided. On one hand, we can imagine that more people will begin to share these vehicles so that the machines can give lifts to one passenger after the other, all day long. In that case, our cities might run using a small fraction of the vehicles currently in service. On the other hand, we might have more dystopian scenarios. Robin Chase, co-founder and former CEO of the car-sharing service Zipcar, has written of "zombie cars—those with no one in them—clogging our cities and our roads." Her vision foresees unemployment for professional drivers, lost revenue from our transportation infrastructure, and "a nightmare of pollution, congestion, and social unrest."

Technological nirvana or urban dystopia? To tackle this question, we need to delve into the ways autonomous vehicles could alter our cityscapes and the ways we move through them.

THE SHARING ECONOMY

ON AVERAGE, cars sit idle *96* percent of the time. That makes them ideal candidates for the sharing economy. The potential to reduce congestion is enormous. A handful of car-sharing systems—such as Zipcar and car2go—are already having a major impact on the total number of vehicles in our cities. Scholars have estimated that every shared vehicle removes nine to 13 privately owned cars from the streets.

The benefits will grow exponentially as autonomous vehicles, currently available in experimental forms, gain a notable portion of the market, blurring the distinction between private and public modes of transportation. "Your" car could give you a lift to work in the morning and then, rather than sitting in a parking lot, give a lift to someone else in your family—or to anyone else in your neighborhood or social media community.

As a result, a single vehicle could go from one to 24 hours of use a day. A recent paper by our colleagues at the Massachusetts Institute of Technology reports that, under such conditions, the mobility demand of a city like Singapore—host to one of the world's first publicly accessible fleets of self-driving cars—could be met with only 30 percent of its existing vehicles. In addition to vehicle sharing, autonomy could open up a new wave of ride sharing. Already applications such as Via , uberPOOL and Lyft Line allow different people to share the same ride, cutting operating costs and individual fares. Autonomy could boost ride sharing even more because all trips could be managed online. In cities, the potential for ride sharing is significant, based on analyses by our Senseable City Lab at M.I.T.

New York City, for example, is eminently shareable. Our lab's HubCab project gathered data from 170 million taxi trips involving 13,500 Medallion taxis in the city—specifically, the GPS coordinates for all pickup and drop-off points and corresponding times between the two. We then developed a mathematical model to determine the potential effect of ride sharing applied to those journeys. The project introduced the concept of "shareability networks," making it possible to optimize the trip-sharing opportunities. Our quantitative results revealed how taxi sharing could reduce the aggregate number of cars by 40 percent with only minimal delays for passengers. Further work showed that places such as San Francisco, Vienna and Singapore could benefit in similar measure.

Combine car sharing *and* ride sharing, and a city might get by with just 20 percent the number of cars now in use, with its residents traveling on-demand. Of course, such reductions are theoretical. In real life, they would depend on how willing people are to share rides and adopt self-driving technology. But any drop in the number of vehicles could lower the costs and energy associated with building and maintaining our mobility infrastructure. Fewer cars might also mean shorter travel times, less congestion and a smaller environmental impact.

NO PARKING, NO TRAFFIC LIGHTS

AUTONOMOUS CARS will not require additional urban infrastructure—specially designed roads, for example—but they will lead to other significant changes. Consider parking. In the U.S., parking infrastructure covers around 8,000 square miles, an area nearly as large as New Jersey. If more vehicles were shared, we would need dramatically fewer parking spaces. What would the consequences be?

Vast areas of urban land could be redeveloped to support social functions.

Over time, vast areas of valuable urban land, currently occupied by parking lots, could be redeveloped to support a whole new spectrum of social functions. Park(ing) Day, an annual event first held in San Francisco in 2005, offers some preliminary ideas. Every year the event challenges artists, designers and citizens to transform metered parking spots into temporary public places. In the past, participants have rolled out sod and placed trees and benches along the curbside.

On a much larger scale and on a permanent basis, vacant parking lots could be converted to offer shared public amenities such as playgrounds, cafés, fitness trails and bike lanes.

Other common sights along our city streets might vanish. Take traffic lights, a 150-year-old technology originally conceived to help horse carriages avoid collisions. Sensor-laden self-driving vehicles, which can communicate with one another to maintain safe distances, will need less assistance at road crossings. As a result, slot-based intersections, modeled after air traffic control systems, could replace traffic lights. On approaching an intersection, a vehicle would automatically contact a traffic-management system to request access. It would then be assigned an individualized time, or "slot," to pass through the intersection.

Slot-based intersections could significantly reduce queues and delays, as our Light Traffic project has demonstrated. Analyses show that systems assigning slots in real time could allow twice as many vehicles to cross an intersection in the same amount of time as traffic lights usually do. This arrangement could have a major impact on the road network of any given city. Travel and waiting times would drop; fuel consumption would go down; and less stop-and-go traffic would mean less air pollution. As an added bonus, slot-based intersections are flexible enough to accommodate pedestrians and bicycles sharing the road.

It is worth noting that such an enticing vision depends on more than just autonomous cars and smart traffic-management systems. It also requires much better market coordination. Today's car-sharing companies have independent platforms that do not talk to one another. Customers cannot compare options easily, and drivers cannot benefit from aggregated demand. The situation is similar to how the air travel industry looked before the Internet. Passengers can now compare many flight alternatives through several global distribution systems that follow standards established by the OpenTravel Alliance and thus benefit from increased transparency and competition.

In cities, two approaches could create a similar mobility architecture. The first would be a bottom-up effort in which small players start adopting standards. This is beginning to happen with a collaboration among Lyft, Didi Chuxing in China, Ola in India and GrabTaxi in Southeast Asia. The second effort would be top down, led by a government or a global organization, such as the World Wide Web Consortium. Because transportation services are already heavily regulated in most countries, this would not be too far-fetched. Either approach could create an incredibly powerful and transparent platform for transportation and logistical services.

POTENTIAL PITFALLS

VEHICLE AUTONOMY and ride sharing could create overwhelmingly positive changes in urban transportation. But if the transition to the driverless city is not managed carefully, it could also lead to negative consequences.

The first concern is safety. We all know what it is like for a virus to crash a computer. What if a virus crashes a car? Malicious hacking is difficult to combat with traditional government and industry tools, and it is particularly dangerous in the case of systems, such as self-driving cars, that combine the digital and the physical.

Additional problems might arise from what one could call the "unfair competitive advantage" of vehicle autonomy. The cost of traveling a mile might drop so substantially that people would abandon public transportation in favor of autonomous cars. That, in turn, could lead to an *increase* in the number of vehicles in a city—and with that increase, surreal gridlock. Additionally, keeping cars moving at all hours rather than parked 96 percent of the time could increase pollution.

Autonomous cars might generate another unintended consequence: aggravating urban sprawl. This would not be the first time that a technological innovation in mobility resulted in such an effect. In his 1941 book *The Four Routes,* Le Corbusier described how this unfolded in the first decades of the 20th century: "The railway converted the cities into true magnets; they filled and swelled without control, and the countryside was progressively abandoned. It was a disaster. Luckily the automobile, through the organization of the roads, will reestablish this broken harmony and start the repopulation of the countryside." In the future, what if people, newly able to commute while sleeping or working, decide to relocate out of the city, consuming land and expanding unsustainable, sprawling communities?

A couple of other threats are worth mentioning. Fines, parking fees and car-associated taxes such as driver registrations represent a substantial revenue source for all kinds of local and national jurisdictions. Widespread autonomous vehicles could eliminate this crucial flow of money. We can easily imagine what would happen to already battered American infrastructure if this scenario were to come true. Perhaps cities could compensate by redeveloping unneeded parking lots and building new, revenue-producing infrastructure. But we must also remember that millions of drivers working today in logistics or urban transport jobs could be left unemployed worldwide.

As Robin Chase wrote, "Simply eliminating the drivers from cars, and keeping everything else about our system the same, will be a disaster." As a result, it is imperative that we view these new technologies with a critical eye—and guide them toward the societal goals we desire. Good policy could help prevent the negative outcomes we have described. As was the case in the 20th century, much will depend on a healthy cycle of trial and error.

Still, if we can manage the transition in a thoughtful way, self-driving cars could help us achieve a safer and more pleasant urban experience. In doing so, they could ultimately enhance the very mission of our cities, which dates to the emergence of the first human settlements 10,000 years ago—bringing us together, regardless of the kind of vehicles we are moving in. SA

MORE TO EXPLORE

Trash-to-Treasure: Turning Nonrecycled Waste into Low-Carbon Fuel. Alex C. Breckel, John R. Fyffe and Michael E. Webber in *EARTH,* Vol. 57, No. 8, pages 42–47; August 2012.

The Upcycle: Beyond Sustainability—Designing for Abundance. William McDonough and Michael Braungart. North Point Press, 2013.

For details about Park 20|20: **www.park2020.com/en**

Massachusetts Institute of Technology's Senseable City Lab: **http://senseable.mit.edu**

FROM OUR ARCHIVES

Waste Energy. George Hill; May 12, 1894.

The Efficient City. Mark Fischetti; September 2011.

scientificamerican.com/magazine/sa

MEDICINE

OPERATION: DIABETES

Surgery that shortens intestines gets rid of the illness, and new evidence shows the gut—not simply insulin—may be responsible

By Francesco Rubino

Illustration by Kotryna Zukauskaite

Clinician and scientist **Francesco Rubino** is chair of the department of metabolic and bariatric surgery at King's College London and a surgeon at King's College Hospital. He is compensated as a member of scientific advisory boards for GI Dynamics and for Fractyl, companies developing intestinal diabetes treatments, and is a consultant to medical device makers Ethicon and Medtronic.

WHEN I BEGAN TRAINING AS A SURGEON ABOUT TWO DECADES AGO, I was eager to treat tumors, gallbladder stones, hernias and all other conditions within reach of a scalpel. Surgery seemed like a direct solution to some serious problems.

Type 2 diabetes was not one of them. Operations focus on single body parts, but doctors knew diabetes damaged multiple organs at the same time and involved a widespread failure to make efficient use of a blood glucose–regulating hormone, insulin. Clearly, this was not something that could be easily cut into or cut out.

But then one afternoon in the summer of 1999, my view of diabetes, and my career, took a radical turn.

I had just moved from Italy to New York City to start a fellowship in minimally invasive surgery at what is now called the Icahn School of Medicine at Mount Sinai. I was in the library trying to read about some technical aspects of an operation called biliopancreatic diversion when I stumbled across something odd. The operation is used on severely obese people. It makes them lose weight by shortening the route food takes through their intestines, bypassing nutrient-absorbing sections. Many of these patients had type 2 diabetes, which accompanies obesity. What struck me, however, was that as soon as one month after the surgery, these people had completely normal blood sugar levels. They had not yet lost much weight, they were eating without calorie or sugar restrictions, and they were not taking any diabetes medication. Still, most of them remained diabetes-free for years after surgery.

I was truly puzzled. How could an operation fix blood sugar problems in a disease that, all the textbooks said, is chronic, progressive and ultimately irreversible? Diabetes could be managed, but it was not supposed to go away.

Racking my brain for an explanation, I recalled that the small intestine produces hormones that stimulate the pancreas to make extra insulin. Could the surgical change to the anatomy affect these hormones in some way that restored normal glucose metabolism? Or could the gut harbor other mechanisms of disease that surgery was able to correct? If so, surgery could be used to treat diabetes, and understanding how surgery produced this effect could also provide a clue to diabetes' elusive cause.

At that time, in the late 1990s, we were just realizing the world was in the midst of an epidemic of the disease that continues today. The most recent estimates by the International Diabetes Federation and World Health Organization suggest at least 415 million people around the globe have the disorder, and the number is predicted to climb to about 650 million by 2040. (Ninety percent of these people have type 2 disease; the rest have another form of the illness, type 1, when the pancreas simply does not make enough insulin.) Finding the cause and a cure could save millions of lives.

After a sleepless night, excited by the possibilities, I went in the morning to my supervising surgeon, Michel Gagner, with the idea. He thought I was on to something. Together we approached our medical school officials to ask them to run a clinical trial in humans and see if surgery could improve diabetes more than conventional therapies, even in people who are not severely obese. Our proposal was turned down, not just then but repeatedly in the ensuing months.

The rejection was disappointing, though perhaps not surprising. Diabetes has been treated for centuries by diet, tablets and shots. Because the cause was presumed to be some dysfunction in the insulin-making cells of the pancreas, as well as the way the body handles that hormone, slicing into people and

IN BRIEF

Forty-five medical organizations now recommend operations originally intended for weight loss as standard treatment options for type 2 diabetes.

Numerous clinical trials show that surgery controls diabetes better, faster and longer than diet changes and drugs do.

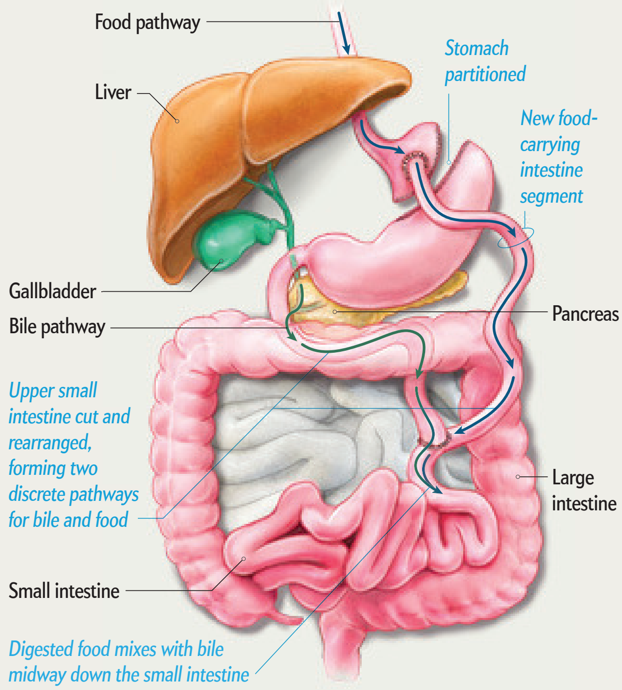
Surgical success links diabetes to the intestines. Operating may work because it changes gut hormones, bile acids or gut bacteria or removes a disease cause.

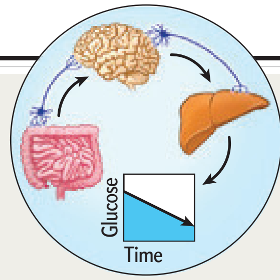
Cutting Out Diabetes

Weight-loss surgery,

is now recommended by more than 40 different

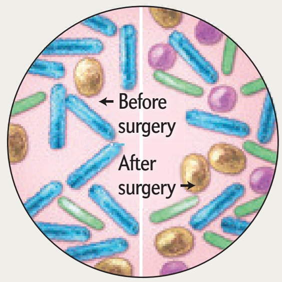
One common operation, called a Roux-en-Y gastric bypass, shortens the length of the upper intestine in which food mixes with digestive juices. Not only does this reduce absorbed calories, it limits the stimulation of intestinal cells by passing nutrients.





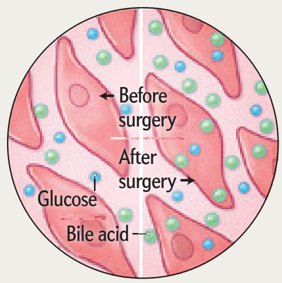
Neural Circuits

The intestines have branches of nerves, such as the vagus nerve, that send signals to and from the brain. These neural circuits alert the brain when the intestines detect passing nutrients. The brain then signals the liver to suppress glucose production. This feedback is enhanced after GI bypass operations.



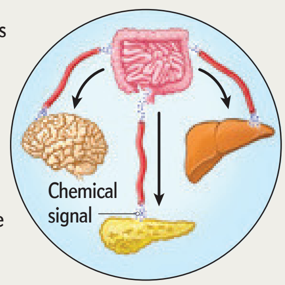
Gut Microbes

The gut microbial community influences a person's energy-harvesting efficiency. By altering the characteristics of intestinal contents, operations cause changes in the population of microbes. Such modifications can result in a higher metabolic rate and better glucose control.



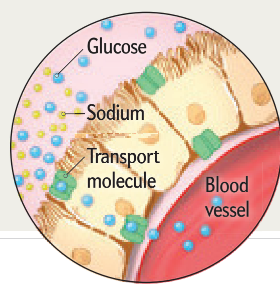
Bile Acids

Bile acids from the liver and gallbladder flow into the top of the small intestine. They also circulate in the blood like hormones, regulating cell metabolism. Surgery increases circulating bile acids and makes organs more sensitive to insulin.



Gut Hormones

The small intestine contains cells that release hormones into the bloodstream when nutrients stimulate them. These hormones can trigger activity in the liver, pancreas, and other organs that affects blood sugar levels. Gastric bypass operations shorten some intestinal segments, thus changing the amount of released hormones.



Glucose Transport

During digestion, glucose is taken from food particles in the intestine, moved through its lining and into the bloodstream. The process relies on special transport molecules that need sodium to work properly. In surgery a primary sodium source—bile—is rerouted away. That hinders transport molecules, lowering diabetic glucose spikes after a meal.

cutting out parts of intestines as a remedy must have seemed like heresy and a foolish risk.

Two decades later the heresy is starting to become conventional wisdom.

There are now dozens of animal studies and at least 12 randomized, controlled clinical trials involving hundreds of people that have explored surgery first developed for weight loss as a treatment for type 2 diabetes. They all show that reducing the surface of the gastrointestinal (GI) tract exerts more powerful effects on diabetes than any other existing therapy. And it is not simply the result of losing weight. In many patients, blood sugar levels go back to normal within weeks, long before fat levels or pounds start to melt away. In general, about 50 percent of patients are diabetes-free after surgery, and some have stayed so for years. The remaining people demonstrate major improvement of blood sugar control and can drastically reduce their dependence on insulin or other medication.

The evidence is so strong that last year 45 medical societies endorsed GI surgery as a standard diabetes treatment option even for patients who are mildly obese. Furthermore, knowledge about the mechanisms by which surgery on the gut affects glucose metabolism is inspiring the development of nonsurgical approaches that target the small intestine.

Illustration by Mesa Schumacher

GATHERING EVIDENCE

IN THE WEEKS AFTER my startling library discovery, as our proposals for testing surgery in humans with diabetes were being denied, I dug further into the medical literature for evidence that could bolster my case. I learned that physicians have been observing diabetes improvement after surgery on the GI tract for almost a century. In 1925 an article in the *Lancet* described the almost overnight disappearance of excess sugar in the urine, a symptom of diabetes, after one gastrointestinal operation to treat a peptic ulcer. After GI surgery became a treatment for severe obesity in the mid-1950s, similar observations became more common. During the 1980s and 1990s, many reports noted the antidiabetic effects of this kind of surgery, including a landmark study by surgeon Walter Pories of East Carolina University and his colleagues that involved more than 120 patients and was unequivocally entitled "Who Would Have Thought It? An Operation Proves to Be the Most Effective Therapy for Adult-Onset Diabetes Mellitus."

Despite such compelling observations, surgery was not considered as a serious therapy for diabetes itself. One major stumbling block was that to many physicians, it seemed more likely that postoperative weight loss—rather than the operation itself—caused the positive effects.

An impressive 89 percent of surgery patients with diabetes were not taking insulin five years after their operation.

Resolving that debate one way or another became important after Gagner and I were unable to start clinical studies. I turned to rats to investigate whether surgically altering the GI tract could influence glucose metabolism directly, independent of weight change. I had moved to the European Institute of Telesurgery in Strasbourg, France. There my co-workers and I took lean rats with type 2 diabetes and gave them a duodenal-jejunal bypass (DJB), an experimental operation designed to shorten the intestinal tract while maintaining the size of the stomach. (The idea is to avoid mechanical impediments to the intake of food.) Postsurgery, our rats showed improved glucose metabolism whether or not their food intake or body weight had changed.

Other investigators corroborated this finding using DJB and other procedures in different animal models. Then, in the early part of this century, they demonstrated it in people. During the past decade at least a dozen randomized clinical trials have been conducted, and all have shown similar results. In one of these studies, Geltrude Mingrone of the Catholic University of Rome, along with myself and other colleagues, showed that five years after surgery in 38 patients, more than 80 percent either were in complete remission from the disease or were able to maintain good control of blood sugar levels with small amounts of medication or with diet and exercise alone. Data from another trial of 96 surgical patients conducted by Philip Schauer and his colleagues at the Cleveland Clinic showed that although about 45 percent needed insulin before their operation, an impressive 89 percent were not taking the drug five years after their operation. Surgery may also reduce such complications of the disease as heart attack, stroke and diabetes-related mortality more than standard treatments, according to the large Swedish Obese Subjects study.

The safety of these procedures compares well with that of other commonly performed operations, including gallbladder surgery or hysterectomy, which are generally considered low-risk interventions. Several economic analyses suggest that the cost of surgery (roughly $20,000 to $25,000 for a procedure in the U.S.) may be balanced within two to three years by reduced spending on diabetes medications and care.

THE GUT AS A SWEET SPOT

WHY DOES SURGERY WORK SO WELL? No one is sure yet, but the GI tract has emerged as a key player both in the normal glucose metabolism and in the dysfunctions associated with diabetes. There are at least five ways the gut exerts such influence: through hormones, bile acids, molecules that move glucose out of the intestines, microbes that live within the intestines, and neural circuits.

The lining of the GI tract holds specialized cells that respond to food nutrients and other stimuli by releasing hormones. These substances then stimulate insulin secretion from the pancreas or affect feelings of hunger and fullness. Changes in the anatomy of the GI tract through surgery curtail the time that food takes to travel over these cells, reducing contact and stimulation in some tract segments. That also means more food is available when it reaches subsequent segments. The overall result is increased levels of some hormones and decreased secretion of others.

Elegant studies in human patients by David Cummings of the University of Washington showed that gastric bypass operations suppress circulating levels of ghrelin, a hunger-inducing hormone that also appears to regulate how certain cells take up glucose. Carel W. le Roux, now at University College Dublin, and other researchers have demonstrated that an intestine-shortening operation called a Roux-en-Y gastric bypass and some similar procedures boost levels of other hormones known as incretins that increase insulin production.

Bile acids, another type of molecule that regulates how the body uses energy, are also affected by GI operations for weight loss. Familiar to many for their role in digesting food, bile acids also enter the bloodstream and signal cell receptors in various organs and tissues. The signals cause cells to ramp up their use of lipids and glucose. Gastric surgery can heighten circulating bile acid levels, which helps cells to get glucose from the blood. Studies also show that bile acids can prevent immune system cells called macrophages from accumulating in fat tissue. Fewer macrophages reduce inflammation and insulin resistance, which are hallmarks of obesity and type 2 diabetes.

Surgery can also affect another mechanism that contributes to diabetes: glucose transport molecules. During digestion, food particles are broken down within the intestines and glucose is extracted. The glucose moves through the intestinal lining and into the bloodstream with the help of these transport molecules. The molecules need high concentrations of sodium to work properly. But in some types of gastric surgery, food-carrying segments of intestine are rerouted to bypass their primary sodium sources—bile and pancreatic digestive juices. Without sodium, the activity of glucose transport molecules is slowed down significantly, which, in turn, improves blood glucose control by reducing glucose spikes after a meal.

Microbes in the gut may also play a role. The GI tract hosts trillions of microorganisms. Certain species help the body extract energy from food and produce chemicals that reduce inflammation and insulin resistance. Because GI surgery alters the acidity of the gut as well as the amount and chemical composition of nutrients within the intestines, it can change the local microbe population. Lee Kaplan of Harvard Medical School and his colleagues showed this can affect metabolism. They started by giving a group of mice gastric bypass operations. Several weeks later the researchers transplanted gut bacteria populations from these mice into nonoperated mice whose native bacteria had been eradicated. This second group of mice was put on a high-fat diet. They gained little weight and improved their metabolism greatly when compared with rodents that received bacteria transplants from mice that did not get surgery.

Surgery's other well-known effect is on neural circuits that influence metabolism. One such circuit, for example, runs between the gut and the brain along a nerve called the vagus. It allows the small intestine to sense minute amounts of ingested nutrients and to inform the brain, which, in turn, suppresses glucose production in the liver and thereby lowers overall blood glucose levels. Experiments in rodents by Tony Lam of the University of Toronto and his colleagues have shown that GI bypass surgery increases activity in such nutrient-sensing mechanisms.

Finally, it is possible that surgery might remove some active insulin-blocking mechanism within the gut that could cause diabetes. The theory for this starts with the insulin-stimulating hormones, incretins. They need a counterweight. Left unchecked, incretins would flood the body with insulin after every meal. All people would suffer from low levels of blood sugar (hypoglycemia) after eating as the tide of insulin cleared glucose from the bloodstream. Because people do not routinely go into low-glucose comas after eating, something must block what incretins do. But if that countermechanism got extremely exaggerated, it would actually suppress the body's response to insulin—in other words, it could drive type 2 diabetes. Such substances, which I call "anti-incretins," have not yet been identified conclusively, but suspects are starting to emerge.

Gut hormones such as somatostatin-28 and galanin all reduce insulin secretion in rodents. And there are more. In 2013 Mingrone and her co-workers harvested a swath of unidentified proteins from a segment of the GI tract in diabetic mice. When the proteins were injected into nondiabetic mice, they triggered severe insulin resistance. (The proteins did the same thing when injected into normal human muscle cells that were grown in the laboratory.) My belief is that gastric bypass surgery can reduce the amount or availability of these insulin-blocking anti-incretins and thus restore a normal metabolic balance to the body.

Whatever the exact mechanism, these and other observations point to a gastrointestinal origin of diabetes. Dysfunctional intestinal mechanisms, triggered by food, could also explain how global increases in fatty and carbohydrate-rich food in recent years, plus increases in overall food availability in many countries, could cause a disease epidemic.

ANTIDIABETIC DEVICES

BUT ALTHOUGH SURGERY may be a powerful remedy, it is never going to be a mass solution to a widespread problem. It requires hospitals, highly trained staff and a degree of risk that comes with using a scalpel on any patient. We need less invasive remedies. At least one may already be at hand: a small sleeve that can be inserted into the intestines through the throat and stomach.

The idea is to cover up the duodenum, the part of the GI tract just below the stomach. This is where bile and pancreatic juices first mix with partially digested food, altering the chemical characteristics of everything that continues down the intestines. Therefore, this one key spot can influence the GI tract downstream and most of the mechanisms of glucose control I have described.

In a set of experiments, my co-workers and I "walled off" the duodenum in diabetic rats by inserting a flexible silicone tube that let nutrients flow past this section. The food particles never touched duodenal lining cells or mixed with bile. Blood glucose control markedly improved. But then we poked holes in the tube, letting nutrients leak out. This modification sabotaged the antidiabetic effects.

Flexible plastic sleeves that shield the duodenum in humans already exist. They were developed to mimic the effects of a gastric bypass without surgery, and they have been approved for clinical use in Europe and South America. Patients who undergo the procedure have seen marked improvement in diabetic symptoms. There is also a newer approach, now in human trials, in which doctors slip a balloon-tipped device down the throat and into the duodenum. The balloon is then filled with hot water to burn away some of the cells that ordinarily react to nutrients. Early tests have shown promising results on type 2 diabetes, and further investigations are under way to confirm long-term durability of the effect.

This is not the first time in medicine that surgery has paved the way for other kinds of treatments. It is not even the first time with diabetes. In 1889 Oskar Minkowski created diabetes in dogs by removing the pancreas, and this work provided the fundamental clue that led Frederick Banting and Charles Best to discover insulin in 1921. Nearly a century later the success of operations highlights the GI tract as a target for other novel approaches to diabetes therapy, approaches that—I hope—will help patients as much or even more than injections of insulin. SA

MORE TO EXPLORE

Mechanisms underlying Weight Loss after Bariatric Surgery. Alexander D. Miras and Carel W. le Roux in *Nature Reviews of Gastroenterology and Hepatology,* Vol. 10, No. 10, pages 575–584; October 2013.

Time to Think Differently about Diabetes. Francesco Rubino in *Nature,* Vol. 533, pages 459–461; May 26, 2016.

FROM THE ARCHIVES

Managing Diabetes. Sara Sklaroff and John Rennie; December 2007.

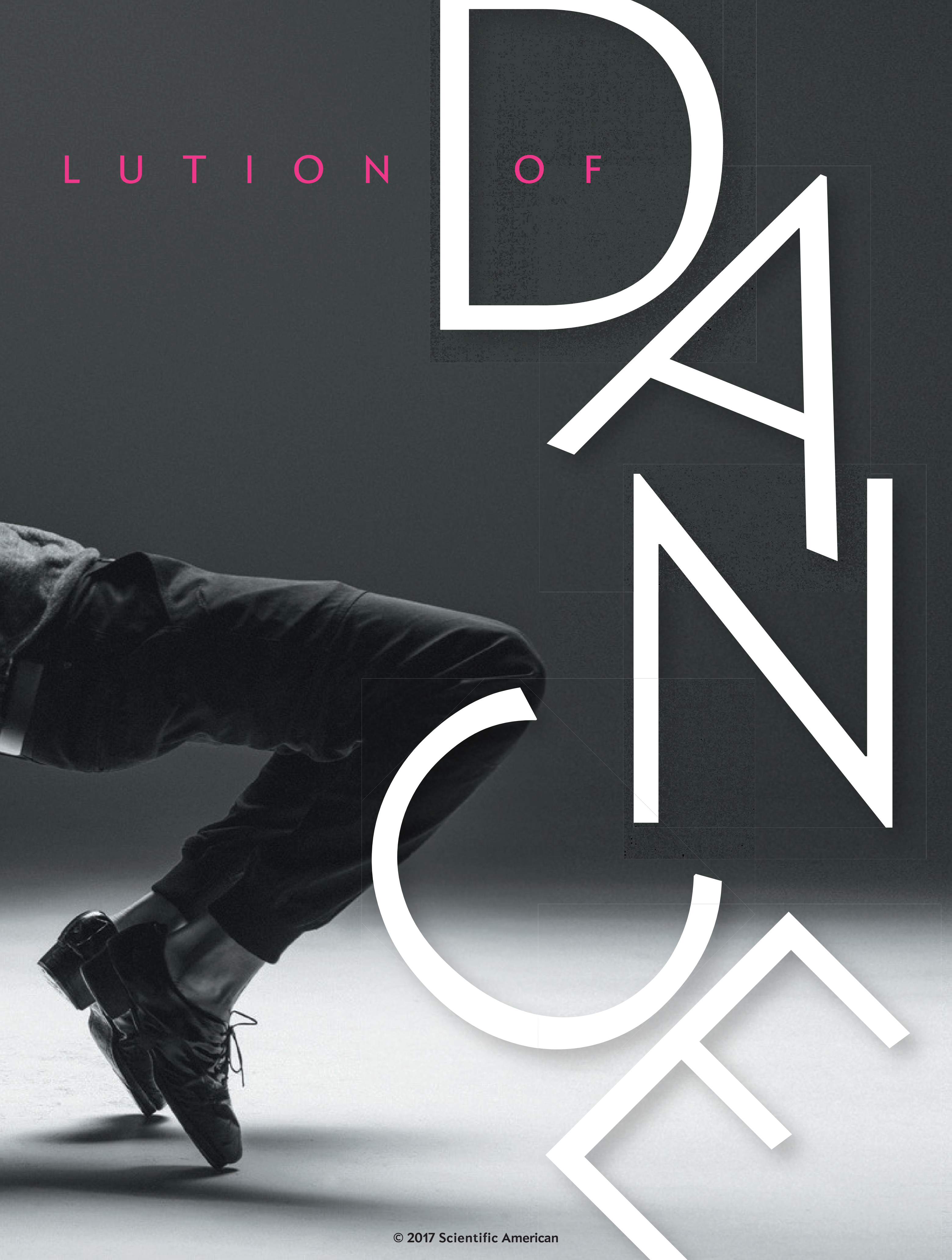
scientificamerican.com/magazine/sa

T H E   E V O

BIOLOGY

Do humans dance just for fun, or did it help our ancestors survive thousands of years ago?

By Thea Singer


LUTION OF
DANCE

Thea Singer is a Boston-based science journalist whose work has appeared in the *Washington Post, MIT Technology Review* and *Psychology Today,* among others. She is also author of *Stress Less* (Hudson Street Press, 2010).

THE ARGENTINE TANGO is famous for being a difficult but electrifying dance. Just one look at a performance by professional dancers Mora Godoy and José Lugones shows why. Whether dancing chest to chest or obliquely angled, Godoy and Lugones whip across the floor, legs whirring like blades on a fan. When she raises a bent leg forward, he answers with a quick kick aft. The pair slip easily between the two- and four-beat phrasing of the music, perfectly matching each other's every hip swivel and toe tap, leg lick and foot volley.

1

2

Not everyone can move with the fiery grace of this expert duo, of course. But we have all felt the call to dance, which has beckoned countless participants across all cultures throughout human history. Yet dance is rare in the animal kingdom. And although a few other species can move their bodies to a beat, none of them exhibits anything like the complexity seen in human dancing.

Why should dancing be such a common human trait, and why are we so good at it? In recent years scientists have begun to identify features of the brain and body that underpin our exceptional ability. Some of these features are linked to language and upright locomotion, two traits that have contributed significantly to the success of the human lineage. Perhaps, then, dance is a happy evolutionary accident, a by-product of natural selection for those other traits that helped our ancestors thrive. Insights from psychology and archaeology hint at another intriguing possibility, however: that dancing itself evolved as an adaptive trait, one that may have strengthened human social bonds in ways that enhanced survival.

SENSE THE BEAT

BROKEN DOWN to its basic elements, dancing is the act of sensing and predicting the timing of an external beat and then matching that beat with rhythmic movements of the body. These actions require a great deal of coordination among different parts of the brain.

Over the past decade researchers in Canada, the U.S. and England have begun to identify networks of nerve cells deep within the human brain that act in concert to isolate the beat from external auditory signals. Once these networks recognize the

IN BRIEF

Dance plays an important role in every human society known to researchers. Does its ubiquity imply a survival advantage, or is it merely an accidental byproduct of large brains and upright posture?

The ability to dance depends on a neurological process in which so-called motor neurons that control the muscles align, or entrain, with the auditory signals detected by sensory neurons.

Until recently, investigators assumed that only humans possessed the ability to entrain. But hummingbirds, parrots and a California sea lion have also demonstrated this talent.

Further investigations in a range of disciplines reveal that the origins of dance are complex and may never be fully understood.

PRECEDING PAGES: JEREMY JACKSON *Gallery Stock;* THIS PAGE: ARIJIT SEN *Getty Images* (1); GETTY IMAGES (2) underlying pattern, they predict the timing of subsequent beats, essentially generating a matching arrangement within the brain.

The next step is what makes dancing possible. The parts of the brain that control the muscles start to fire in conjunction with the predicted beats from the auditory networks. (Indeed, these so-called motor-planning areas of the brain kick into action even when we stand still and merely *perceive* a beat.) This coupling of auditory processing with rhythmic physical movement lies at the heart of our ability to tap out a beat with our fingers or to waltz across the floor. Scientists call it "entrainment."

Barring illness, we humans come by entrainment naturally, and we can sustain rhythmic movement across a wide range of tempos for long periods. "Our synchronization abilities are incredibly flexible," asserts Aniruddh D. Patel, a neuroscientist at Tufts University. "We can stay synchronized to a beat whether it slows down or speeds up by plus or minus 30 percent." This capacity generally emerges between three and five years of age.

For years scientists believed that only humans had the ability to entrain their physical behavior with external sounds. Then, in 2009, studies started to emerge showing that parrots, hummingbirds and perhaps songbirds can—to a limited extent—time their movements to music as well. Snowball, a male cockatoo famous for bobbing his head up and down in time to music from the Backstreet Boys, was among the birds studied. And in 2013 researchers reported that a California sea lion named Ronan could move her head to a range of tempos.

Humans are, however, the only animals that can produce the closely coordinated movements required of partner or group dancing. Birds that can entrain move in spurts to music on their own, Patel says. Even when multiple parrots live together in a shelter, he says, they do not coordinate their movements or dance with one another.

IMITATION GAME

DANCE IS NOT the only human attribute that depends on entrainment. Speech and singing also require the ability to match sound with physical movement—specifically, of the vocal cords and muscles in the throat. Tracing the neural pathways involved in vocalization gave Patel an idea about how entrainment between nerves that process sound and those that control muscles might have evolved. His work suggests that the same neural innovations that allowed humans to learn and produce spoken language also predisposed us to be dancers.

In Patel's view, the ability to mimic sounds paved the way for predictive, flexible entrainment. Such mimicry demonstrates what researchers call "vocal learning," in which an animal listens carefully to a sound, forms a mental model of it, aligns the motor control of its throat, tongue and mouth with that model, and then produces the modeled sound. When the animal listens to the output, it notes and corrects discrepancies between the predicted and the actual sound and tries again. Patel suggests that the coupling of auditory and motor processing required to imitate sounds laid the neurological groundwork for the later, more complex process of predictive auditory-motor entrainment.

Why might vocal learning have evolved in select animals? Some scientists speculate that it might have enabled songbirds to master complex acoustic displays to advertise for a mate. In parrots, Patel says, it furnished an "acoustic badge—something that marks them as a member of a group."

If Patel's hypothesis that vocal mimicry is a necessary precondition for auditory-motor entrainment is right, then the only animals that should be able to entrain are those that are already capable of imitating sounds. To date, the only animals that are known to imitate external sounds are humans, hummingbirds, parrots, songbirds, whales, certain flipper-footed marine mammals (pinnipeds), elephants and some bats. Meanwhile our nearest living relatives, bonobos and chimpanzees, are not vocal learners, and most evidence to date suggests that they do not entrain. Although one chimp in a study was apparently able to synchronize her taps with the beat at one tempo, she could not keep the beat at other tempos. Researchers also found one bonobo that seemed to be able to drum to a beat, but they caution that she might have been watching the tester for cues rather than just responding to what she was hearing.

Such observations support the idea that vocal mimicry might be a necessary precursor for entrainment. But they are by no means a slam dunk. Demonstrating entrainment in nonhuman species is not easy. Think of the complicated duets between some species of songbirds. Do they take turns singing

WORLD BEAT: Children perform a classical dance in Mumbai, India (*1*); break-dancers in Los Angeles demonstrate moves (*2*); modern ballet dancers show flexibility and grace (*3*); Bolshoi ballet lines up perfectly (*4*); street parade and festive dance in Cuba (*5*).

GETTY IMAGES (3); LINDA VARTOOGIAN *Getty Images* (4); CHRISTOPHER PILLITZ *Getty Images* (5) by keeping time—predicting when the other will finish—or are they merely reacting to their partner's silence? And how could you possibly test this?

The biggest problem for Patel's vocal-mimicry hypothesis, however, is Ronan, the head-bobbing sea lion. Sea lions are not known to be vocal learners, although they are related to walruses and seals, which are. Yet in 2013 researchers at the University of California, Santa Cruz, demonstrated that Ronan could move her head in time with simple beats and, later, more complex music. Further tests showed that she could correctly keep time with the beat even when it sped up or slowed down.

There are several ways to explain Ronan's apparent ability. Maybe she is just one very gifted sea lion—the exception that proves the rule. Or perhaps sea lions still possess the neural machinery for vocal mimicry and just no longer use it.

It is possible, of course, that Ronan's feat proves the vocal-mimicry hypothesis wrong. Patel and others have suggested that one way to test this hypothesis would be to determine whether horses—which are neither vocal learners nor related to them—can also be taught to entrain. Horses "should not be able to match a specific tempo, but there is widespread anecdotal evidence that they can," says Mara Breen, an assistant professor of psychology at Mount Holyoke College, who is testing Patel's hypothesis in horses. If it turns out that these animals can entrain, then perhaps the process is not so hard after all, or it evolved in other species for different reasons than it did in humans.

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GLOBAL REACH: Tribal dancers leap in Uganda (*6*); teenagers strike a pose in the U.S. (*7*); Jewish dancers celebrate in London (*8*); Sufi dancers whirl in Istanbul (*9*); Geisha performers display fans in Japan (*10*); dance company rocks to the beat in Cuba (*11*).

A ROLE FOR RUNNING?

UNLIKE DANCE in other creatures, human dance goes beyond head bobbing to include coordinated movement of the torso and limbs. How might the evolution of our unusual upright posture have affected our capacity for dance? One idea that has gained attention in recent years is that dance could have grown out of our ability to run—as opposed to just walk—on two legs. "Certainly we take advantage of being bipedal to dance," says Harvard University evolutionary biologist Daniel E. Lieberman, who, in 2004, co-authored a seminal paper in *Nature* on the role of endurance running in human evolution. But that differs from what humans *evolved* to do. "We evolved to walk and to run, to throw, to dig," Lieberman says. Natural selection for these abilities enabled our ancestors—in particular, *Homo erectus*—to upgrade their hunting and foraging skills.

"There are all kinds of fascinating adaptations that we think evolved for running," Lieberman continues. The toes of modern humans are much shorter, for example, than those of our forebears. From a biomechanical point of view, this is unnecessary for walking, but it makes running more efficient. The three semicircular canals of the inner ear have grown larger over the course of millennia, allowing us to maintain our balance whenever we move our head, so that we can move with greater speed and agility. Such adaptations are also useful for dancing.

In Lieberman's view, dance could be a coincidental outgrowth of the evolution of running that proved so useful it conferred its own additional selective advantage. "It doesn't have to be an all-or-nothing thing," he says. "It can be partial. It could be that dancing was selected for, or it could be that dancing was never selected for, or it could be that certain elements of dancing were selected for." He pauses. "Testing those hypotheses—boy, that is hard."

GROUP EFFORT

OBSERVATIONS of modern-day dancers offer some tantalizing clues to the kinds of advantages dancing might have conferred in our evolutionary past. A notable feature of human dance is that we tend to do it together. As we feel and predict one another's movements, there is a physical and emotional give-and-take between individuals, whether they are tango partners or throngs of millennials rocking out to Bruno Mars.

This group capability represents what can be called social entrainment, and it confers what Émile Durkheim, who helped to create the field of sociology in the late 1800s, termed "collective effervescence," or the feeling of being part of something larger than oneself. That kind of social cohesion could be valuable for life-sustaining activities such as food gathering or predator avoidance.

Anthropologist Edward Hagen of Washington State University Vancouver takes that idea a step further. He hypothesizes that music and dance might have evolved as a way for groups to appraise one another when seeking to form alliances that reached beyond the bonds of kinship. How well a group danced together, for instance, might give an indication of how well its

GEORGE F. MOBLEY *National Geographic* (6); GETTY IMAGES (7); DAN KITWOOD *Getty Images* (8) members would perform as part of a larger coalition.

Greater social cohesion imparts physiological benefits as well. A 2010 study by scientists at the University of Oxford shows that synchronized physical activity driven by a unified goal—in this case, rowing in the university's boat club—significantly increased participants' pain thresholds compared with solo training. The authors attributed the increase to the release of endorphins, natural opioids in areas of the brain associated with mood. Robin I. M. Dunbar, an anthropologist and evolutionary psychologist at Oxford, argues that these endorphins strengthen social bonds when people engage in group musical activities as well.

"You could imagine two societies, one that didn't dance and one that did, and the one that did would have much stronger social bonds," says archaeologist Clive Gamble, a professor at the University of Southampton in England. In a competitive situation between the two, he says, the society that danced "would have an evolutionary advantage."

Given the dearth of direct evidence for the origins of dance, scientists in varying fields have turned to the behavior of today's few remaining hunter-gatherer societies for clues about our ancestral past. Their way of life probably offers the closest approximation that anthropologists have of what human societies were like before the widespread adoption of agriculture 10,000 years ago.

Evolutionary anthropologist Camilla Power of the University of East London studies the Hadza people of northern Tanzania, who typically live in "camps" of 20 to 30 people, in which men and women are social equals. Over the generations, dance has emotionally bound the Hadza and other groups, including the Bayaka people in central Africa and the San people in the Kalahari Desert, together in "shared fictions." Participants enact initiations, healing rituals and gender relationships, among other things, Power says. Among the Hadza, key dance rituals include feigned "sex wars" in which women taunt men and the men return the favor. "This dynamic is what underlies the egalitarianism," she says. Women consolidate their power, even playing male roles, goading the men to hunt in return for later "cuddles."

There is indirect evidence that large group dances have taken place for thousands of years. So-called aggregation sites—large, heavily trampled areas where prehistoric musical instruments have been recovered—provide hints of such activities having taken place among Upper Paleolithic peoples. Among them is Isturitz, a cave in the French Pyrenees, where bone pipes dating to 35,000 to 20,000 years ago were found.

"It's clear from the other archaeological evidence that lots of different groups were gathering at these sites at particular times of the year," says Oxford paleoanthropologist Iain Morley, author of the 2013 book *The Prehistory of Music: Human Evolution, Archaeology, and the Origins of Musicality.* "When we see that kind of big group activity in hunter-gatherer societies today, music and dance occur." Thus, Morley believes, humanity's ancestors were likely making music and dancing for tens of thousands of years—plenty of time for evolution to influence the outcome.

There is one absolute about this most elusive of art forms. Dancing is about communicating, whether it is between the participants themselves or the participants and the observers. Dancers are, in essence, sharing a world of their own invention.

In doing so, they are also changing their brain. Clinicians and researchers alike have acknowledged the benefits of dance for people with movement disorders such as Parkinson's disease. Indeed, many who suffer from the tremors, stiffness and difficulty initiating movements that characterize Parkinson's can, by taking dance classes, regain some of their ability to entrain. As an added benefit, the classes help to form social bonds that may have been diminished by the disease.

Dance classes for people with Parkinson's do not, of course, aim to turn out the next Mora Godoy. But they offer their own transformations. This most ancient of human activities unites body and mind in ways we are only beginning to grasp. SA

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GURCAN OZTURK *Getty Images* (9); FRANK CARTER *Getty Images* (10); NIKA KRAMER *Gallery Stock* (11)

MORE TO EXPLORE

Musical Rhythm, Linguistic Rhythm, and Human Evolution. Aniruddh D. Patel in *Music Perception: An Interdisciplinary Journal,* Vol. 24, No. 1, pages 99–104; September 2006.

The Origins of Human and Avian Auditory-Motor Entrainment. Adena Schachner in *Nova Acta Leopoldina,* Vol. 111, No. 380, pages 243–253; 2013.

Rhythmic Entrainment: Why Humans Want to, Fireflies Can't Help It, Pet Birds Try, and Sea Lions Have to Be Bribed. Margaret Wilson and Peter F. Cook in *Psychonomic Bulletin & Review,* Vol. 23, No. 6, pages 1647–1659; December 2016.

FROM OUR ARCHIVES

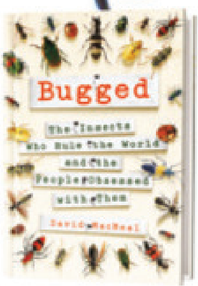
The Neuroscience of Dance. Steven Brown and Lawrence M. Parsons; July 2008.

scientificamerican.com/magazine/sa

By Andrea Gawrylewski

Bugged: The Insects Who Rule the World and the People Obsessed with Them

by David MacNeal. St. Martin's Press, 2017 ($25.99)

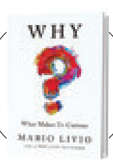


RHINOCEROS BEETLE, Thailand. It can grow to more than seven inches long, of which four inches can be horn.

During the steamy summer months many people dream of a world without mosquitoes, ants and other pesky bugs. But remove all the insects, which comprise about 75 percent of species in the animal kingdom, and the world as we know it could not exist. Insects bind together nearly every ecosystem by pollinating 80 percent of food plants and recycling dead organic matter. Science writer MacNeal travels the globe documenting the science and culture of all things "bug." There is the painstaking work of taxonomists who continue to catalogue the earth's estimated 10 quintillion insects; the Greek island beekeepers; and the Zika-fighting mosquitoes in Brazil. The world is surprisingly full of insect lovers, one of whom tells MacNeal that "bugs are more interesting than people." Interesting or not, insects provide "beneficial, multibillion-dollar services keeping life on this planet humming along."

Why?: What Makes Us Curious

by Mario Livio. Simon & Schuster, 2017 ($26)



We humans are different from other animals in our ability to wrap our mind around abstract ideas, imagine scenarios and formulate questions. Arguably, we are the most voraciously curious creatures on the planet, and the drive to discover, a crucial part of our survival on earth, has led not only to the many fields of science but to religion and philosophy as well. Renowned astrophysicist Livio takes a fascinating walk through the science of curiosity (a good deal of experimental evidence shows that an individual's level of curiosity is heritable) and profiles some of the most inquiring human minds to have lived. Leonardo da Vinci and Richard Feynman are examples of exceptional inquisitiveness, with their wide and varied interests and hunger to uncover answers for themselves rather than relying on previous proofs and demonstrations.

Into the Gray Zone: A Neuroscientist Explores the Border between Life and Death

by Adrian Owen. Scribner, 2017 ($28)

What if a victim of brain trauma who is supposedly in a vegetative state is actually fully awake but unable to even blink an eye to communicate? During the past 20 years advances in neuroscience have shown that this sometimes happens. Neuroscientist Owen explains how his team began using PET and functional MRI scans in the late 1990s to detect brain activity in vegetative patients. Their brains responded like those of conscious people to photographs of loved ones and recordings of recognizable yet neutral words such as "candle," "lemon" and "sofa." Some patients survive "the gray zone," come out of their vegetative state and live to tell about it. But many do not, including some of Owen's own loved ones, who, he says, drove him beyond pursuing science for science's sake. *—Andrea Marks*

The Ends of the World: Volcanic Apocalypses, Lethal Oceans, and Our Quest to Understand Earth's Past Mass Extinctions

by Peter Brannen. HarperCollins, 2017 ($27.99)

Five times in the earth's history a mass extinction has almost entirely extinguished all animal life. Science journalist Brannen explores the unique story of each of these tumultuous endings by tagging along with fossil hunters and geologists, from the volcanic outcroppings of Palisades, N.Y., to the center of the 110-mile-wide crater in Yucatán, Mexico. Each extinction was in some way associated with drastic changes in the planet's atmospheric CO_2 levels. Portentous, considering that the current concentration of CO_2, now more than 400 parts per million, is reaching a level not seen for perhaps three million years, since the Pliocene epoch. As Brannen demonstrates again and again, "life on earth is resilient, but not infinitely so."

GETTY IMAGES

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His next book is *Heavens on Earth*. Follow him on Twitter @michaelshermer

Who Are You?

Memories, points of view and the self

By Michael Shermer

***The Discovery* is a 2017 Netflix film** in which Robert Redford plays a scientist who proves that the afterlife is real. "Once the body dies, some part of our consciousness leaves us and travels to a new plane," the scientist explains, evidenced by his machine that measures, as another character puts it, "brain wavelengths on a subatomic level leaving the body after death."

This idea is not too far afield from a real theory called quantum consciousness, proffered by a wide range of people, from physicist Roger Penrose to physician Deepak Chopra. Some versions hold that our mind is not strictly the product of our brain and that consciousness exists separately from material substance, so the death of your physical body is not the end of your conscious existence. Because this is the topic of my next book, *Heavens on Earth: The Scientific Search for the Afterlife, Immortality, and Utopia* (Henry Holt, 2018), the film triggered a number of problems I have identified with all such concepts, both scientific and religious.

First, there is the assumption that our identity is located in our memories, which are presumed to be permanently recorded in the brain: if they could be copied and pasted into a computer or duplicated and implanted into a resurrected body or soul, we would be restored. But that is not how memory works. Memory is not like a DVR that can play back the past on a screen in your mind. Memory is a continually edited and fluid process that utterly depends on the neurons in your brain being functional. It is true that when you go to sleep and wake up the next morning or go under anesthesia for surgery and come back hours later, your memories return, as they do even after so-called profound hypothermia and circulatory arrest. Under this procedure, a patient's brain is cooled to as low as 50 degrees Fahrenheit, which causes electrical activity in neurons to stop—suggesting that long-term memories are stored statically. But that cannot happen if your brain dies. That is why CPR has to be done so soon after a heart attack or drowning—because if the brain is starved of oxygen-rich blood, the neurons die, along with the memories stored therein.

Second, there is the supposition that copying your brain's connectome—the diagram of its neural connections—uploading it into a computer (as some scientists suggest) or resurrecting your physical self in an afterlife (as many religions envision) will result in you waking up as if from a long sleep either in a lab or in heaven. But a copy of your memories, your mind or even your soul is not you. It is a *copy* of you, no different than a twin, and no twin looks at his or her sibling and thinks, "There I am." Neither duplication nor resurrection can instantiate you in another plane of existence.

Third, your unique identity is more than just your intact memories; it is also your personal point of view. Neuroscientist Kenneth Hayworth, a senior scientist at the Howard Hughes Medical Institute and president of the Brain Preservation Foundation, divided this entity into the MEMself and the POVself. He believes that if a complete MEMself is transferred into a computer (or, presumably, resurrected in heaven), the POVself will awaken. I disagree. If this were done without the death of the person, there would be two memory selves, each with its own POVself looking out at the world through its unique eyes. At that moment, each would take a different path in life, thereby recording different memories based on different experiences. "You" would not suddenly have two POVs. If you died, there is no known mechanism by which your POVself would be transported from your brain into a computer (or a resurrected body). A POV depends entirely on the continuity of self from one moment to the next, even if that continuity is broken by sleep or anesthesia. Death is a permanent break in continuity, and your personal POV cannot be moved from your brain into some other medium, here or in the hereafter.

If this sounds dispiriting, it is just the opposite. Awareness of our mortality is uplifting because it means that every moment, every day and every relationship matters. Engaging deeply with the world and with other sentient beings brings meaning and purpose. We are each of us unique in the world and in history, geographically and chronologically. Our genomes and connectomes cannot be duplicated, so we are individuals vouchsafed with awareness of our mortality and self-awareness of what that means. What does it mean? Life is not some temporary staging before the big show hereafter—it is our personal proscenium in the drama of the cosmos here and now. 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.

Drilling for Fossil Gold

Two new books look at evolution from head to below your toes

By Steve Mirsky

Brush your fossils twice a day. Do it for yourself and for future researchers and museum visitors. Because if any part of you is going to get unearthed millions of years from now, it'll probably be a tooth. "Teeth are stronger than bones, and they are much more likely to survive the ages," writes University of Arkansas paleoanthropologist Peter S. Ungar in his book *Evolution's Bite: A Story of Teeth, Diet and Human Origins.* Not to be confused with Felix Unger, who once invested in a dental adhesive based on the substance barnacles produce to stick to ships. (Watch *The Odd Couple,* season 4, episode 13: "A Barnacle Adventure." Spoiler alert: the glue fails when the patient's mouth gets dry.)

In fossil bones, most of the material that existed while the animal was alive gets slowly replaced over time by minerals. The resulting buried treasure is really a natural cast of the bone with properties more like rock than like what's inside The Rock (aka Dwayne Johnson). Teeth start out most of the way there. "Teeth are essentially ready-made fossils," Ungar writes. "The enamel that coats ours, for example, is 97% mineral." Such prefossilization means "there are often hundreds if not thousands of teeth for every skeleton or complete skull we find.... Fortunately for paleontologists, they are also excellent tools for understanding life in the past."

Teeth tell such tales because their shapes and the usage patterns etched on them offer up heaping helpings of information about what animals ate and how they lived. "If we can reconstruct diet from teeth, for example," Ungar writes, "we can use them as a bridge to the worlds of our ancestors." Likewise, your teeth could one day serve as a bridge. Unless, of course, you have a bridge.

While reading Ungar, I could not help but think about Don McLeroy, a man who vexed scientists and educators for the first decade of this century in his roles as a member and then chair of the Texas State Board of Education. McLeroy fought against the inclusion of evolution in curricula. He believed that the earth is only a few thousands of years old. He was quoted as saying, "Evolution is hooey." And that "somebody's got to stand up to experts." All those views would be irritating if McLeroy's day job had been as a plumber or an architect or an insurance agent. But what made McLeroy particularly maddening was that he worked on a daily basis with the most abundantly clear evidence of evolution that can be found in the fossil record: he is a dentist.

While you're chewing on that irony, consider that for hundreds of millions of years some animals have avoided the teeth of predators by getting down and dirty. "Imagine yourself the size of a shrew and living in environments where dinosaurs are everywhere," writes Emory University paleontologist Anthony J. Martin in his book *The Evolution Underground: Burrows, Bunkers, and the Marvelous Subterranean World beneath Our Feet.* Yes, that's a mouthful.

"Some want to eat you, while others will carelessly step on you and carry your squashed remains like chewing gum on their feet for days," Martin continues. "Oh, you say you live in deep burrows where no dinosaurs can find you or compress you into two dimensions? Yes, that will do nicely.... Congratulations, shrew-sized mammal: You win the survival sweepstakes, and one tiny branch of your descendants eventually gets to a point where it can discuss how you outlived the dinosaurs." Plus, when the asteroid bit into a big chunk of what's now the Yucatán Peninsula 66 million years ago, stuff that lived underground—and far away—clearly had a significant survival advantage.

In fact, Martin argues that "the evolutionary paths taken by most modern animals, whether these are crocodilians, turtles, birds, lungfish, amphibians, earthworms, insects, crustaceans, or mammals, are connected to their burrowing ancestors." That passage can be found deep in the book under the subhead "Living on Burrowed Time." Holy moly.

I dug both books. Sink your teeth into them. 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

JULY

1967 End of the "Monkey Law"

"Tennessee's 'monkey law' prohibiting the teaching of evolution in the state's public schools has been repealed. The law was adopted in 1925 and led later that year to the celebrated test case involving John T. Scopes, William Jennings Bryan and Clarence Darrow. The 11-day trial became a bitter contest between religious fundamentalism and biological theory; the judge held, however, that only evidence on whether or not Scopes had taught evolution was admissible, and Scopes was convicted. The conviction was reversed on a technicality, but the law was permitted to stand. In April of this year the lower house of the Tennessee legislature voted to repeal the statute; in May the Senate agreed and the governor approved the repeal."

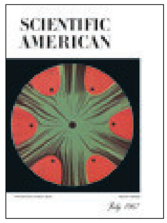
Random-Access Memory

"Since the early 1950s the standard random-access memory has been provided by an array of tiny ring-shaped cores made of a ferrite, an easily magnetized material. In its simplest form the array of cores is threaded by $2n$ 'word' conductors in one direction and by m 'digit' conductors in the other. Each core can hold one bit of information, which is stored in terms of the direction of imposed magnetization; in other words, the core 'remembers' the direction of the effective magnetizing current sent through it last. The cores are wired into arrays by painstaking handwork with only rudimentary mechanical aids.

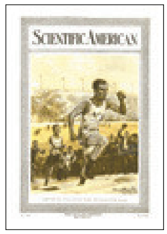
"The situation is somewhat ironic: the heart of the computer, which itself is the symbol of mechanization, is made by the age-old kind of labor that produced brocades and carpets. Made as they are, the core arrays have provided reliable, fast random-access memories for practically all computers in use today. At the same time one principal goal has been to produce 'integrated' memories—memories in which the active elements and their connections are mechanically fabricated in a unitary process."

1917 Night Flight

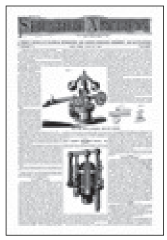
"It has been suggested to maintain an aerial patrol along the routes followed by shipping, seaplanes and dirigibles taking their supplies of bombs and fuel from mother ships of the class officially known as 'seaplane carriers' [*see illustration for a seaplane night landing*]. With hundreds of aircraft constantly in the air and covering a wide expanse of water, it should be possible to make it extremely dangerous for any U-boat to show itself above the surface during daylight; and at night large seaplanes equipped with searchlights could make it almost as dangerous for submarines to rest on the surface while charging their batteries."



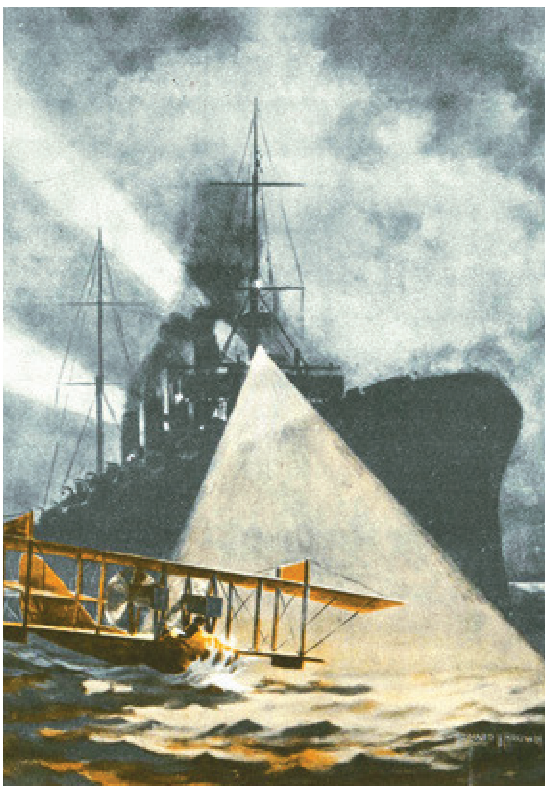
1967



1917



1867



War at sea, 1917: a scout seaplane returning to its mother ship at night.

SCIENTIFIC AMERICAN, VOL. CXVII, NO. 4; JULY 28, 1917

1867 Sweet Tooth

"In 1860, in Great Britain, the average consumption of sugar was 34 lbs. for each inhabitant. In Belgium, though coffee is usually drunk without sweetening, 21 pounds of that sugar is disposed of yearly for each inhabitant. Among the peasantry of Russia sugar must be an unknown luxury, or at least its use by the people must be confined to Holy days and Festivals, for the consumption per head is but 2 pounds a year. Next to the British, the people of the United States use more sugar than any other nation in the world; and if the consumption of molasses and syrup were added—fully 2½ gallons for every man, woman and child—to that of sugar, it would be found that the free use of saccharine food was far greater among us than with our transatlantic friends."

French Laundry

"The soiled linen of the Grand Hotel, the Hôtel du Louvre, the Grand Café, and other hotels and cafés in Paris, is washed at the rate of 40,000 pieces a day, at the Blanchisserie de Courcelles, three miles or so from the St. Lazare terminus of the Western Railway. The linen is boiled with soap and soda and then washed in hollow wheels, rinsed, partly dried by centrifugal machines, and for the rest in hot-air ovens, which carry off nearly three pounds of moisture per pound of coal burnt, and is finally ironed between polished rollers, and then packed ready for return to Paris."

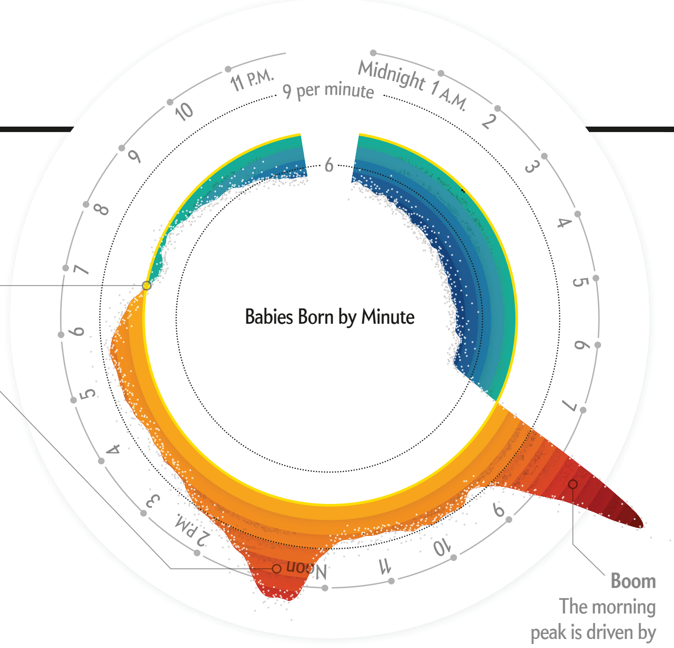
The Baby Spike

Births peak on weekdays during daytime work hours

Two generations ago babies were born pretty much spontaneously, around the clock. But today in the U.S., about half of all births are cesarean sections prescheduled by Mom or deliveries induced by doctors concerned about the mother's or baby's health. These medical procedures have skewed the days of the week, and hours of the day, during which those little bundles of joy arrive.

The procedures dominate because more than 98 percent of infants are born in a hospital, despite what seems to be the rising popularity of home births. Far more babies now arrive on weekdays than on weekends, most between 8 A.M. and 6 P.M. "We can't schedule spontaneous labor, obviously," says Neel Shah, a physician and professor at Harvard Medical School. "But we can schedule delivery."

—*Mark Fischetti and Zan Armstrong*

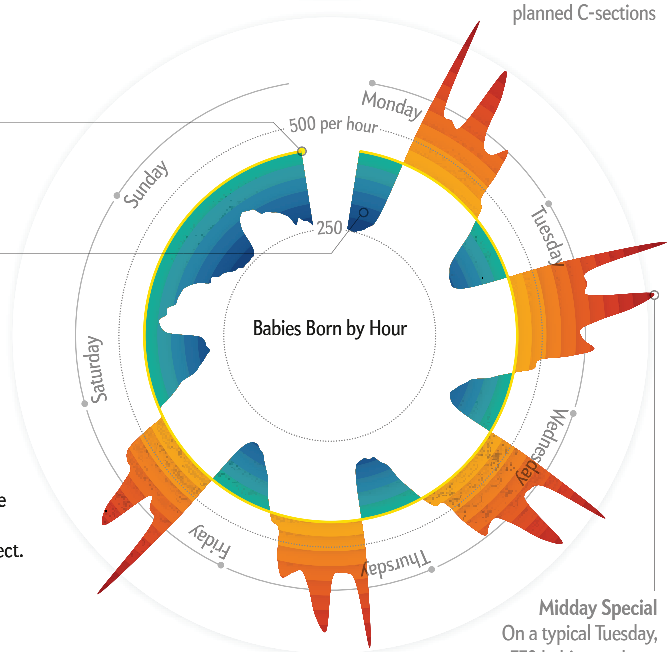


The Average
7.3 babies born per minute

Eat First
More births of all types occur right after lunch

Day Shift
Births peak around 8 A.M., then rise again between noon and 1 P.M. Hospitals typically have more doctors and nurses on hand during the morning and fewer later in the day.

Boom
The morning peak is driven by planned C-sections

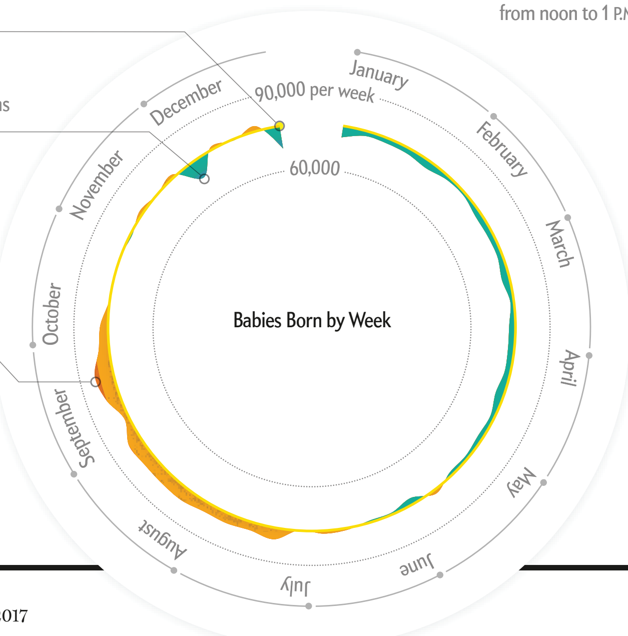


The Average
447 babies born per hour

Fewest Births
Sunday night between 2 and 3 A.M.

Early Riser
More babies than average are born on weekdays during daylight hours. Fewer are born on weekends or at night, primarily because fewer hospital staffers are on duty, so women tend not to schedule their delivery then. Despite folklore, a full moon has no effect.

Midday Special
On a typical Tuesday, 770 babies are born from noon to 1 P.M.



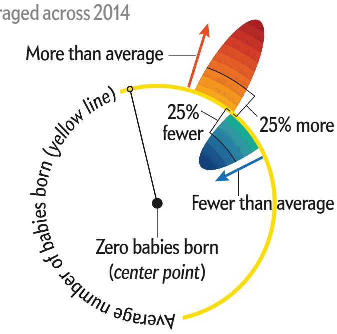
The Average
77,000 babies born per week

No, Thanks
Moms do not schedule C-sections around Thanksgiving

Happy Holidays
Babies seem to arrive nine months after Christmas and New Year's Eve

Summer Son
Evidently, more people have sex during colder months, leading to more births nine months later from July through October, and less sex during warmer months.

Each graph shows U.S. data averaged across 2014



SOURCES: FIVETHIRTYEIGHT, FROM DATA SUPPLIED BY U.S. SOCIAL SECURITY ADMINISTRATION (*week data*); CENTERS FOR DISEASE CONTROL AND PREVENTION (*minute and hour data*)

Graphic by Nadieh Bremer and Zan Armstrong