SPECIAL ISSUE: THE SCIENCE OF BEING HUMAN

SCIENTIFIC AMERICAN

HUMANS

Why we're unlike any other species on the planet

SEPTEMBER 2018
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SEPTEMBER 2018

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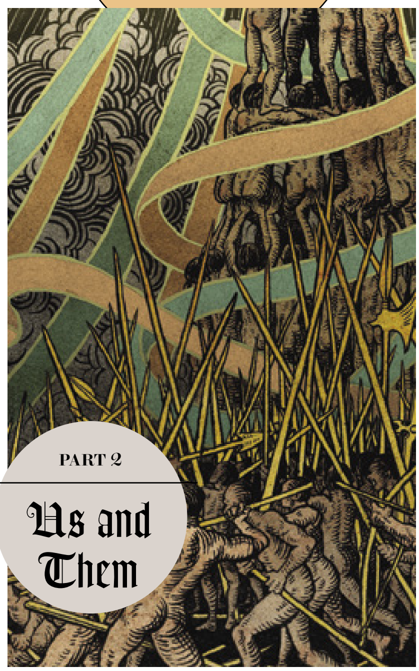
SPECIAL ISSUE

A SINGULAR SPECIES: THE SCIENCE OF BEING HUMAN

PAGE 28

PART 1

Why Us?

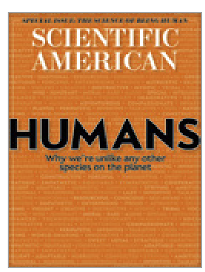


PART 2

Us and Them

PART 3

Beyond Us



ON THE COVER
The mix of an outsized brain and hypersocial culture explains humans' unparalleled success.

Illustrations by Victo Ngai, Yuko Shimizu and Armando Veve

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ON THE WEB

Microplastics Threat
Scientific American examines researchers' efforts to locate microplastics pollution and to stem the tide of these particles entering the environment.
Go to www.ScientificAmerican.com/sep2018/microplastics

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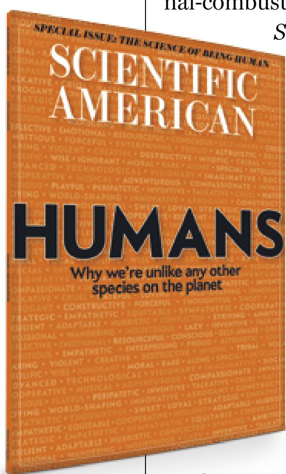
Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

A Very Human Story

"What a piece of work is a man," proclaimed Hamlet in the play of the same name, partly in admiration over our nobility and intelligence, partly in despair over our flaws. We *Scientific American* editors have to agree with Shakespeare's sentiments, and in this special single-topic issue, we join him in his apparent obsession to try to understand our species anyway.



We do have the benefit of perspective gained from the process of science instead of relying on storytelling alone. For instance, there's the matter of how *Homo sapiens* came to be the only human species on the earth when we were once just one of a diverse array of bipedal species. In her article, "Last Hominin Standing," senior editor Kate Wong paints the picture of our rise. Turn to page 64.

Although we do seem to share many cognitive traits with animals, our intellectual capabilities have no equal on this planet ("Inside Our Heads," on page 42). Humans are apparent standouts because of the richness of our subjective experience ("The Hardest Problem," on page 48) and an ability to communicate thoughts to others ("Talking through Time," on page 54). A defining characteristic of our species is that we can transmit knowledge from one generation to the next and then build and innovate on these cultural bequests from our ancestors. All of this, in turn, selects for better cognitive skills and bigger brains ("An Evolved Uniqueness," on page 32). We demonstrate our communal cleverness by devising machines that combine numerous past innovations. The internal-combustion engine is just such a stellar example ("Techno *Sapiens,*" on page 40). As a species whose members number in the billions and are extensively settled across nearly all the continents, we have an inclination to establish norms and conventions that regulate our behavior when living in large groups ("The Origins of Morality," on page 70).

Looking ahead, we may even, through AI, or artificial intelligence, design a master algorithm that could enable models of ourselves to act as the ultimate personal assistant that performs many of our everyday tasks ("Our Digital Doubles," on page 88). As we continue an influx into cities, animals around us are necessarily adapting rapidly to a more urban world ("Darwin in the City," on page 82). Seeds are reshaping on dandelions. Instead of being distributed on the winds, they drop straight down onto precious, limited soil. Peregrine falcons are settling in, snapping up plentiful pigeons. What is to come? Perhaps only we can imagine where the complex changes we've set in motion may lead. And if we don't like what we envision, only we have the knowledge and the power to refashion the world for a more hopeful future. That's an awful lot of responsibility for a physically weak, though cognitively powerful, biped, but we'll have to shoulder it. SA

Illustration by Nick Higgins

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May 2018

"Maybe if we can get people to realize that they have a stake in good welfare, then they will begin to care about themselves, if not others."

JOSEPH JAGELLA *VIA E-MAIL*

SOCIETY'S ILLNESS

"American Epidemic," by Melinda Wenner Moyer, is very timely and relevant in describing how resurgent infectious disease outbreaks in U.S. cities are tied to increasing economic inequality.

I am a paraplegic who is retired because of health problems, and most of my medical bills are paid through Medicare. I also receive other government support, such as Social Security, food stamps and a housing subsidy. There is an agenda against such funding for the poor and the disabled, as has been evident in the Trump administration's attempts to cut Medicaid.

Although I cannot even stand and must use a wheelchair, I have been harassed by people who seem to believe that I don't deserve the support I get from the government. The Americans with Disabilities Act (ADA) was supposed to remedy the exclusion of disabled people from public services and employment, but because of opposition from the very people who insist that people like myself should be employed, it has not delivered on most of its promises.

I have tried to explain to many such people that we are a society and must work together for the common good. If some people suffer in our society, then we may all suffer because we have an effect on others. Moyer's article really helps to back up what I argue. The same individuals who don't seem to care if the poor and homeless get sick will ultimately reap the results of their own callous attitudes when diseases caused by poverty spread to the wealthy. Maybe if we can get people to realize that they have a stake in good welfare, then they will begin to care about themselves, if not others.

Joseph Jagella *via e-mail*

"American Epidemic" should be required reading for every politician in this country. Moyer does an excellent job of pulling together disparate strands of information and weaving them into powerful conclusions that suddenly seem so simple and obvious. I hope she expands this article into a book. It could be a very important one.

Eric Smith *Woodbury, Minn.*

SMOKING PROBLEM

In arguing that federal marijuana laws are too harsh in "End the War on Weed" [Science Agenda], the Editors assert that the drug is "relatively safe for adult recreational use." While that may indeed be so, I have to ask: Do any of them live in an apartment?

I voted against "legalization" here in California because nobody seems to have considered the exposure of nonconsenting adults and children with developing brains to secondhand marijuana smoke. Advocating a policy of legalization for recreational purposes seems premature until you consider the rights of those who do not wish to be compelled to partake in the drug use of others and the welfare of children who live in proximity. But I have no objections to the legalization of ingested marijuana for both medical and recreational purposes for adults.

Donald D. deRosier *via e-mail*

POWERING EDUCATION

"The Suns in Our Daughters" [Forum], Lisa Einstein's commentary on her experiences teaching young girls in Guinea through the Let Girls Learn program, brought tears to my eyes. It truly illustrates untapped human potential restrained or blocked by custom and social oppression that exists almost everywhere.

Robert Svec *Portland, Ore.*

CHEATING DILEMMA

In "You Kant Be Serious" [Skeptic], Michael Shermer discusses different approaches to morality and mentions the well-known dilemma in which a runaway trolley will kill five people unless you switch it to a side track, where it will kill one person. A humorous accompanying illustration shows a means of cheating the problem with a helicopter. (There's an easier way: derail the trolley by throwing the switch before the rear wheels go through.) Shermer's example of a doctor who can save five patients by harvesting organs from one could be similarly cheated if the doctor can manufacture organs from stem cells.

I suspect that most, if not all, such moral dilemmas could be cheated through the appropriate technology today, so such dilemmas do go away as we advance.

Dennis Anthony *via e-mail*

SHERMER REPLIES: *The point of philosophical thought experiments such as the trolley problem is that you're not allowed to cheat, thereby forcing you to choose one evil over another and then inquire about your reasoning or feelings behind your decision. But in the real world, many workarounds abound, such as those Anthony proposes (or an even easier solution in the case of the trolley problem: shout, "There's a train coming!" to the workers). And with the right knowledge and technology, most moral dilemmas can indeed be reconfigured as soluble problems.*

In my Skeptic column on abortion in this issue, for example, I argue that instead of intractable moral problems of determining when life begins or when it is permissible to take a life, we should treat unwanted pregnancies as a problem to be solved through birth control and comprehensive sex education. The animal-rights debate over factory farming will disap-

pear when synthetic meat becomes economically viable. Income inequality will vanish as a problem when poverty is completely eradicated and everyone has abundance. Not all moral issues are so readily soluble, but many are, which is why science and technology should be in the moral philosopher's toolkit.

OBJECTIVE MEMORY

In "Our Stuff, Ourselves," Francine Russo reports on research showing a connection between low emotional security and greater attachment to inanimate objects, including a 2015 study involving young children and their favorite possession.

Russo does not describe the experimenters as having accounted for the feelings or significance that the adult providers of those youngsters may have had toward objects. As a child of the Depression, I did not have as many possessions to attach my affections to as children do today. My relationship with my mom was clearly established, and she did not seem to attach a great deal of extramaternal meaning to her gifts of time or kitchen tidbits. Things that gave meaning to my life in those days were things more related to a child's developing skills than to possession: climbing trees, riding a trike, creating imaginary landscapes out of mud or melting ice, singing songs, skipping rope. Possessions still mean little to me. My furniture is old and unfinished and serves only the purposes for which it is used.

I wish Russo's article had considered adult providers and the present-day culture they represent, which could have exposed deeper issues than an individual child's mental equilibrium.

June Harner *via e-mail*

CLARIFICATION

"Our Planet, Ourselves," by Mariette DiChristina [From the Editor], referred to mosquitoes and the viruses they carry spreading diseases such as malaria and Rift Valley fever. And "Catching Fever," by Lois Parshley, noted that the expansion of habitats of mosquitoes and other insects has exposed new populations to viruses, as well as that malaria is globally on the rise. To clarify, Rift Valley fever is caused by a virus, and malaria is caused by a parasite.

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Clinical Trials Need More Diversity

It's unethical and risky to ignore racial and ethnic minorities

By the Editors

Nearly 40 percent of Americans belong to a racial or ethnic minority, but the patients who participate in clinical trials for new drugs skew heavily white—in some cases, 80 to 90 percent. Yet nonwhite patients will ultimately take the drugs that come out of clinical studies, and that leads to a real problem. The symptoms of conditions such as heart disease, cancer and diabetes, as well as the contributing factors, vary across lines of ethnicity, as they do between the sexes. If diverse groups aren't part of these studies, we can't be sure whether the treatment will work in all populations or what side effects might emerge in one group or another.

This isn't a new concern. In 1993 Congress passed the National Institutes of Health Revitalization Act, which required the agency to include more women and people of color in their research studies. It was a step in the right direction, and to be sure, the percentage of women in clinical trials has grown significantly since then.

But participation by minorities has not increased much at all: a 2014 study found that fewer than 2 percent of more than 10,000 cancer clinical trials funded by the National Cancer Institute focused on a racial or ethnic minority. And even if the other trials fulfilled those goals, the 1993 law regulates only studies funded by the NIH, which represent a mere 6 percent of all clinical trials.

The shortfall is especially troubling when it comes to trials for diseases that particularly affect marginalized racial and ethnic groups. For example, Americans of African descent are more likely to suffer from respiratory ailments than white Americans are; however, as of 2015, only 1.9 percent of all studies of respiratory disease included minority subjects, and fewer than 5 percent of NIH-funded respiratory research included racial minorities.

The problem is not necessarily that researchers are unwilling to diversify their studies. Members of minority groups are often reluctant to participate. Fear of discrimination by medical professionals is one reason. Another is that many ethnic and racial minorities do not have access to the specialty care centers that recruit subjects for trials. Some may also fear possible exploitation, thanks to a history of unethical medical testing in the U.S. (the infamous Tuskegee experiments, in which black men were deliberately left untreated for syphilis, are perhaps the best-known example). And some minorities simply lack the time or financial resources to participate.

The problem is not confined to the U.S., either. A recent study of trials involving some 150,000 patients in 29 countries at five different time points over the past 21 years showed that the ethnic makeup of the trials was about 86 percent white.

Drug regulators such as the FDA should create and enforce tougher requirements: for a drug to be approved for market, the patient panels of its clinical trials should closely resemble the makeup of the patient populations who will actually use the candidate medicine. And drugmakers should adopt their own testing policies, including strong standards for diverse patient groups.

The FDA currently requires drug developers to provide extra test results for a candidate drug that may have applications in a special age population—say, older patients. It could apply those same criteria regarding race and ethnicity. These requirements could even extend to a more diverse array of genetic subtypes. Some medicines are ineffective or dangerous in certain genetic populations. For example, carbamazepine, a medication used to treat epilepsy, can cause a severe skin disorder in patients of Asian heritage with a particular gene variant.

In 2015 the FDA launched the Drug Trials Snapshots program, which makes public the demographic details of clinical trial participants, including their age, sex and race. But the onus is on the patients and their doctors to seek out that information.

It's unethical and dangerous to approve drugs without making every attempt to certify their safety and efficacy. Yet by failing to include members of racial and ethnic minorities in clinical trials, that is just what the FDA is doing. SA

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Illustration by Lisk Feng

Rebecca Nebel is director of scientific programs at the Society for Women's Health Research, a national nonprofit organization.

Why Sex Matters in Alzheimer's

To fight the disease, we need to look at sex-specific risks

By Rebecca Nebel

Growing older may be inevitable, but getting Alzheimer's disease is not. Although we can't stop the aging process, which is the biggest risk factor for Alzheimer's, there are many other factors that *can* be modified to lower the risk of dementia.

Yet our ability to reduce Alzheimer's risk and devise new strategies for prevention and treatment is impeded by a lack of knowledge about how and why the disease differs between women and men. There are tantalizing hints in the literature about factors that act differently between the sexes, including hormones and specific genes, and these differences could be important avenues of research. Unfortunately, in my experience, most studies of Alzheimer's risk combine data for women and men.

For that reason, researchers at the Society for Women's Health Research Interdisciplinary Network on Alzheimer's Disease recently published a review paper in *Alzheimer's & Dementia: The Journal of the Alzheimer's Association* that calls for greater analysis of research data by sex to stimulate new approaches that will improve prevention, diagnosis and treatment of Alzheimer's.

We have some evidence, for example, that sex hormones such as estrogen influence the course of the disease, but we do not understand enough about why and how. Ovaries are the primary source of estrogen for premenopausal women, and surgical removal of a woman's ovaries before menopause is associated with a higher risk of dementia. But using estrogen therapy after surgery until age 50 negates that risk. This fact suggests that estrogen may be protective in premenopausal women.

In men, there are conflicting studies as to whether androgen-deprivation therapy, which is used to treat prostate cancer, increases the risk for Alzheimer's. Further investigation is needed into the role of sex hormones, the use of different hormonal treatments and the ways they each impact Alzheimer's risk.

Among risk factors that affect both women and men, some are more common in one sex. For example, depression and sleep apnea are both risk factors for dementia, but depression is twice as common in women, and sleep apnea is much more common in men. Similarly, low education and poor job attainment are Alzheimer's risk factors, but traditionally women have not had the same access to education and job opportunities as men, which puts them at increased risk.

The e4 allele of the *APOE* gene is the strongest and most common genetic risk factor for Alzheimer's in both women and men, but it confers a greater risk in women. Women with *APOE* e4 are at increased risk of developing Alzheimer's, compared with women without the allele and men with and without it.

Learning how sex impacts risk factors at various times across a life span is also critical. For example, in cardiovascular disease, taking aspirin helps to reduce heart attack and stroke risk in women aged 65 years and older. This effect is not seen in younger women. It is possible that certain Alzheimer's risk factors may be strongest at certain points during our lives, and exploring this correlation is key for prevention and early intervention.

Risk factors are just one of the areas in which we need more research into the differences between the sexes in Alzheimer's. Scientists have often overlooked sex differences in diagnosis, clinical trial design, treatment outcomes and caregiving. This bias has impeded progress in detection and care.

Approaches that incorporate sex differences into research have advanced innovation in respect to many diseases. We need to do the same in Alzheimer's. Looking at these differences will greatly enhance our understanding of this thief of minds and improve health outlooks for all. SA

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Illustration by Cornelia Li

ADVANCES

Borophagus dogs such as *B. secundus* (*fossil shown*) were thought to have had jaws strong enough to crunch through bone.

INSIDE

FROM "FIRST BONE-CRACKING DOG COPROLITES PROVIDE NEW INSIGHT INTO BONE CONSUMPTION IN *BOROPHAGUS* AND THEIR UNIQUE ECOLOGICAL NICHE," BY XIAOMING WANG ET AL., IN ELIFE, VOL. 7, ARTICLE NO. E34773; MAY 22, 2018

PALEONTOLOGY

Bone Crushers

Fossilized poop reveals ancient dog had a fearsome bite

An extinct group of brawny carnivores could bite through bone, a cache of six-million-year-old fossilized feces reveals. The bone-crushing dogs, which include the genus *Borophagus* ("gluttonous eater"), occupied a niche in North America that has not been filled since.

Most carnivores, including today's dogs, sport long, pointy teeth that would likely shatter under the bite force needed to crack open large bones. In contrast, their *Borophagus* kin had thicker, flattened teeth, as well as shorter snouts that maximized their jaw power. "There is no modern dog that looks like these bone crushers," says Xiaoming Wang, a paleontologist at the Natural History Museum of Los Angeles County and co-author of a study on the find. "The only analogue that you can try to envision is the spotted hyena in Africa."

Scientists first noticed the *Borophagus*' resemblance to hyenas in the late 19th century. Pioneering paleontologist Edward Drinker Cope wrote in an 1893 description of one of the species: "Its dental structure is adapted for crushing bones, while its canine teeth served their usual purpose of tearing." This was conjecture based only on anatomy, however. The "bone-crushing" nickname stuck, but scientists had no direct evidence that the carnivores could chomp through large femurs and ribs—until now.

Fossil collector and retired soil scientist

Coprolites, or poop fossils, provide direct evidence of bone-crushing dogs.

NATURAL HISTORY MUSEUM OF LOS ANGELES COUNTY

Dennis Garber says he found the fossilized excrement serendipitously. He was boating on Turlock Lake in California's San Joaquin Valley in 1995 when he spotted a bluish-gray object on the shore. Garber, who has been gathering fossils in that area since 1956, quickly recognized it as a fossilized animal dropping, or coprolite. Because it had bone fragments visible near the surface, it most likely came from a large carnivore—and the *Borophagus* were the only such creatures known from that area at the time, he says: "I started digging around, and I found quite a few more."

The study's paleontologist co-authors think what Garber found was a "latrine" area, suggesting that the *Borophagus* lived in packs and pooped in the same spot, as many modern social carnivores do. The finding, which was published in May in eLife, "gives us an insight, not only into the physiology of these extinct carnivores but also into their social systems," says paleontologist Julie Meachen of Des Moines University, who was not involved in the study.

To peer inside the coprolites, the study authors enlisted researchers at the University of California, Los Angeles, School of Dentistry to run CT scans. The resulting images revealed skeletal fragments within each lump. These included a large piece of rib from a deer-size herbivore, which the scientists estimate could have weighed up to four times as much as one of its attackers. This adds to the evidence that the *Borophagus* were pack hunters—but it does not completely rule out scavenging, Wang says. "What surprised me is the number of bones," he adds. That quantity, combined with the dogs' jaw adaptations, indicates that biting through and swallowing large chunks of bone seem to have constituted part of their routine.

Wang suggests that in addition to being pack hunters, endurance runners and social poopers, the *Borophagus* may have been competitive eaters. Hyena packs can devour entire wildebeests—bones and all—in a few minutes, and the carcass is first come, first served. When every meal is a race, being able to crunch straight through femurs and tear off a large hunk of leg for oneself is a big advantage. The *Borophagus* may have had similar dining etiquette. Meachen agrees with this assessment. "All these carnivores [would] have [had] the same

PSYCHOLOGY

An Honest Liar

The president's dishonesty may have contributed to his perceived authenticity

Last year Donald Trump falsely claimed that the size of his inauguration audience was "the biggest ever," despite photographic evidence to the contrary—one of his many demonstrable whoppers. Of course, neither candidate in the 2016 presidential election was seen as a paragon of honesty. Yet that seemed to hurt Hillary Clinton more than Trump. Why? New research suggests that sometimes lying can actually make a politician seem more authentic: followers see bald-faced lies by an interloper as symbolic protests against a crooked establishment.

In an online study, 424 participants read about a hypothetical race for a college student body president. The fictional candidate running against the incumbent had no student government experience. During a debate, the incumbent mentioned research supporting a campus alcohol ban. Half of the study subjects read that the research was not in a peer-reviewed journal and that the outsider candidate had noted this. The other half read that it *was* peer-reviewed, but the outsider lied and said it was not—an easily checkable claim—and that the outsider made a sexist remark about the researchers, violating another social norm.

Within each of those two groups, half also read that the incumbent's legitimacy was in question. The other half read that he was a good student representative. Study participants also completed a personality test and were randomly told the result matched either the incumbent's or the outsider's. Finally, they rated the outsider's authenticity.

When subjects were told they shared the outsider's personality type and the incumbent's legitimacy was in question, both men and women rated the lying, misogynistic outsider as more authentic than the honest outsider. The research appeared in the

Illustration by Thomas Fuchs

constraints in terms of 'you must gulp your food down, or it will all be gone,'" she says.

The ancient dogs may also have boosted certain nutrient cycles. Modern hyenas break down skeletal matter much faster than microbes do and leave nutrients such as calcium scattered across the savanna in their chalky, white feces. In contrast, Wang says the *Borophagus*' digestion was apparently less thorough. "Unlike hyenas, they don't have the kind of advanced, highly acidic digestive system to help them really—shall we say—melt down the bones inside the digestive system," he says. But crushing up and transporting tiny fragments across the grassland may have had a similar nutrient-spreading effect, he notes.

The borophagine lineage died off mysteriously about two million years ago, leaving no descendants. But it was a major group of carnivores, with dozens of species spanning about 30 million years of North American fossil history. "There's really nothing like this group of animals around today, and yet they lived in North America and potentially had a really important role in the ecosystem, especially allowing for increased processing of carcasses or recycling of nutrients," says paleoecologist Larisa DeSantis of Vanderbilt University, who was not involved in the study. "So this is a bit of a detective mystery in trying to reconstruct the ecology of these animals." *—Diana Crow*

February issue of *American Sociological Review.*

Hypothetical student governments "are a far cry from studying the American public and real political issues, so I'd hesitate to generalize," says Diana Mutz, a political scientist at the University of Pennsylvania, who has studied Trump's supporters and was not involved in this study. But "the idea is interesting," she adds.

The researchers did tie the study to the 2016 election by surveying 402 participants, who were told that one of Trump's tweets about global warming being a hoax had been definitively debunked. Trump supporters were more likely than Clinton supporters to see the tweet as not literal but as a challenge to the elite. They were also twice as likely to rate their preferred candidate as highly "authentic."

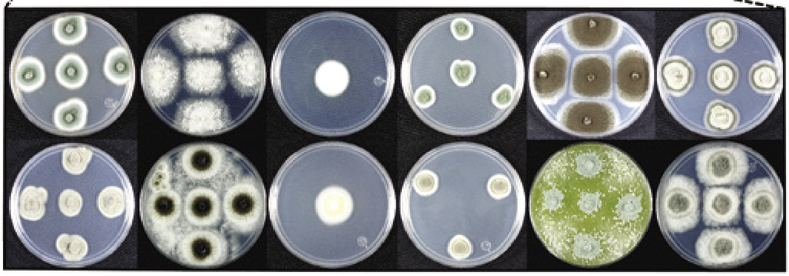
Oliver Hahl, a management researcher at Carnegie Mellon University and the paper's lead author, says his studies have helped him understand Trump's supporters: "It gives me the sense that the world is still rational to some degree." *—Matthew Hutson*

MICROBIOLOGY

Art-Eating Fungi

Two new species discovered chomping on ancient lithographs

1



2

Fungal samples (*2*) isolated from a lithograph by Bernard Romain Julien (*1*).

FROM "TWO NEW CELLULOLYTIC FUNGAL SPECIES ISOLATED FROM A 19TH-CENTURY ART COLLECTION," BY CAROLINA CORONADO-RUIZ ET AL., IN *SCIENTIFIC REPORTS*, VOL. 8, ARTICLE NO. 7492; MAY 10, 2018

Scientists in Costa Rica have found some new species of fungi thriving in an odd place: on a collection of lithographs by 19th-century French artist Bernard Romain Julien. The microorganisms are speeding the degradation of the printed artworks, which are among the oldest items in the University of Costa Rica's art collection and were acquired as a tool to teach drawing techniques.

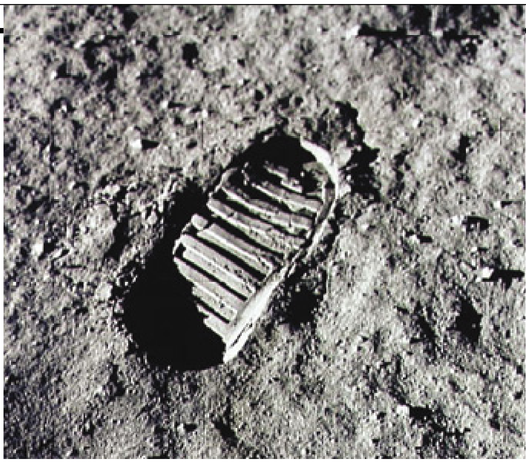
To preserve the lithographs, Geraldine Conejo-Barboza, a researcher at the university's chemistry department and its Institute of Art Research, and her colleagues are developing a spray that could eliminate or slow the fungi's growth and stop natural acidification processes that are destroying the artwork. "Our idea is to take the biomolecule hydroxyapatite, which has been reported to improve the acidity of paper, and develop a hybrid [molecule] that can also eliminate the fungi," Conejo-Barboza says. She plans to add zinc oxide and zinc ions to the molecule's surface to act as antifungal agents.

Before applying a medicine, however, one must identify the disease. To find out what microbes are attacking the artwork, Max Chavarría, a molecular biologist at Costa Rica's National Center for Biotechnological Innovation, studied 20 out of more than 1,000 lithographs in the collection. He extracted 21 fungi samples, two of which were unknown to science. "It was a surprise to find two new species in such a limited environment," Chavarría says. The discovered species, *Periconia epilithographicola* and *Coniochaeta cipronana,* were described in May in *Scientific Reports.*

Conejo-Barboza has already synthesized a few fungi-fighting products that she aims to test in the laboratory. Salomón Chaves, subdirector of the Institute of Research in Art, has spent the past five years restoring the lithographs. The new product has the advantage of being a spray, he says. Protecting paper from acidification currently requires bathing it in alkaline substances and then carefully drying it—which can shrink the paper if not done correctly. The researchers hope the new chemicals will fight the microbes and acidification effectively and prove useful for preserving collections elsewhere.

Such fungi are not all bad, however: their ability to degrade cellulose—a tough substance found in plant cell walls—could be useful for treating agricultural waste from crops such as pineapple, coffee and sugarcane.

—Debbie Ponchner



GETTY IMAGES

SPACE

Moon Mystery

The recovery of missing tapes reveals the cause of lunar heating

When *Apollo* astronauts returned from the moon in the 1970s, they left behind two pairs of temperature probes drilled into the surface. The sensors measured how easily the soil radiated heat, in the hope of learning how much radioactive heating the moon produced and details about its recent geological activity.

The nuclear-powered lunar heat flow probes broadcast data back to Earth, where they were stored on tapes, until 1977. But the experiments' principal investigator Marcus Langseth studied it only through December 1974. The remaining tapes were thought to be lost because sloppy paperwork failed to document their location. But over the past decade an effort to scour attics, garages and government facilities for information led to the recovery of a handful of the missing tapes.

Langseth's report on the original data revealed that heat was moving downward from the moon's surface, rather than up from the core as would be expected. Several theories emerged to explain the phenomenon: that the astronauts' presence had somehow warmed the surface; that the instruments themselves had produced excess heat; or that the moon was going through a long-term warming cycle. The uncertainty meant scientists could not trust the experiments' results.

But the newly recovered tapes reveal that heat traveled all the way from the lunar surface to the bottoms of the boreholes, ruling out every explanation except for surface disturbance by the astronauts. As they explored the moon, their footprints and rover tracks compressed and darkened its surface. "It was the [absorption of] sunlight from where the astronauts were walking around that caused the moon to get hotter in those specific locations," says study co-author Walter Kiefer of the Lunar and Planetary Institute in Houston. The results were published in May in the *Journal of Geophysical Research: Planets.*

The findings suggest that measurements taken at the start of the experiments—when the heat was still near the surface—were the most reliable, making the original data correct. "We now know we can trust those measurements in a way that we were not sure of a few years ago," Kiefer says.

—Nola Taylor Redd

ECOLOGY

Rumbles in the Deep

Nuclear-test monitors detect whales instead of bombs

REINHARD DIRSCHERL *Getty Images*

An unlikely source is revealing some secretive habits of whales: the group tasked with monitoring nuclear weapons testing. The underwater hydrophone network of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) was designed to listen for massive explosions, but its sonic sensors more often pick up the peaceful rumblings of the world's largest animals. Now scientists are exploiting this unique data set to estimate fin whale population sizes and movements, which could improve the species' uncertain conservation prospects.

In the past 20 years the CTBTO has installed 11 acoustic stations throughout the world, including six in the oceans. Each contains two sets of three hydrophones that receive signals and determine their origin. CTBTO observations helped to detect North Korea's 2017 nuclear tests and have yielded a treasure trove of scientific data.

These recordings are producing revelations about endangered fin whales, a species rebounding from hunting during the 20th century. Tarun Chandrayadula, an ocean engineer at the Indian Institute of Technology Madras, and his colleagues recently detected fin whales in CTBTO recordings off the southern tip of India—a region the species was not known to frequent. The finding, which Chandrayadula is working to publish, is helping boost his efforts to build a "whale atlas" detailing the annual movements of Indian Ocean cetaceans.

CTBTO data can also help determine whales' population sizes—a prerequisite for effective conservation efforts. Danielle Harris, a marine biologist at the University of St. Andrews in Scotland, led a study published in May presenting a new method for estimating whale numbers using CTBTO's sparse hydrophone array. Harris calculates there is approximately one fin whale per 2,000 square kilometers near Wake Island, a coral atoll in the central Pacific Ocean.

"The first step is knowing how many animals you're trying to conserve," says Sean Wiggins, a project scientist at the Scripps Institution of Oceanography, who was not involved in either Harris's or Chandrayadula's studies. But the CTBTO data have their limitations, Wiggins adds. The hydrophones detect sounds below 100 hertz, so they cannot sense the vocalizations of small whales or dolphins. Furthermore, the vast spaces between hydrophone stations make it difficult to pinpoint a whale's distance from a sensor—a problem Harris's new method attempts to resolve.

Still, CTBTO's 15-year record of global whale chatter is a boon for marine biologists, and the recordings can spark joy. "I thought it was the most fun thing," Chandrayadula says, "just sitting at my desk and listening to these otherworldly creatures."

—*Daniel Ackerman*

PALEONTOLOGY

Death Masks

How the earth's earliest known animals became fossils

Imagine a mask made when you die that could preserve your face for millions of years. In a way, this is what happened to some of our planet's oldest known animals. Encased in "death masks" made of the mineral pyrite ("fool's gold"), these soft-bodied organisms avoided rot and decay long enough to make it into the fossil record, paleontologists say.

The creatures are known to have thrived around the world roughly 575 million to 541 million years ago, during the Ediacaran period. They looked like aliens: one, *Kimberella,* resembled an avocado wearing a garter; another, *Dickinsonia,* could pass for a cross between a pancake and an earthworm. Where this group fits on the evolutionary tree is a mystery—not all its members were animals, but some were, and those species most likely include ancestors or close relatives of all subsequent animal life. Another nagging mystery has been how Ediacaran organisms became fossils in the first place because most are thought to have been soft-bodied. Such squishy critters are prone to immediate consumption or decay, so they rarely fossilize when they die.

To investigate these questions, a team led by paleontologist Brandt Gibson of Vanderbilt University euthanized sea anemones and mollusks, the modern animals whose bodies are thought to be most similar to Ediacaran biota. They put the corpses in seawater tanks to mimic the ancient ocean's chemistry and watched as iron-rich pyrite was deposited around the bodies over the course of about a month. The study, published in May in *PALAIOS,* was the first to observe these death masks forming in the laboratory.

The shrouds did not completely impede decay, however. Sea anemone tentacles, for instance, "disappeared rapidly," Gibson notes. This result suggests Ediacaran fossils

Fossil of the species *Dickinsonia costata.*

GETTY IMAGES

may not be complete pictures of the original organisms. Filling in that information could be key to understanding how these strange creatures fit into the tree of life.

Alex Liu, a paleobiologist at the University of Cambridge, who was not involved in the research, says the study "adds to a growing realization that the Ediacaran period is not the 'enigmatic' interval it has been portrayed as for decades … and the questions within it are tractable." —*Lucas Joel*

IN THE NEWS

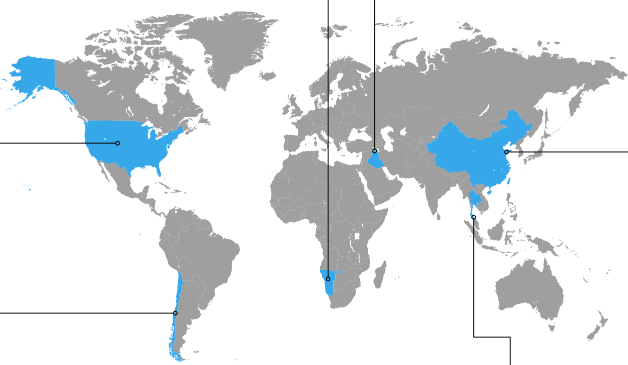
Quick Hits

By Maya Miller

NAMIBIA
About 100 high school girls from Ethiopia, Kenya and Swaziland joined girls in Namibia for a two-week "boot camp" to learn how to write code and develop mobile apps. They also got a crash course in basic sciences.

IRAQI KURDISTAN
Archaeologists found remnants of a city that dates back 4,800 years in the autonomous Kurdish region of northern Iraq. Among the ruins were 92 clay tablets—some of which contained the city's name, Mardaman.

U.S.
A judge dismissed two environmental lawsuits against five of the world's largest oil companies. During the trial, however, the companies' representatives said they recognize and agree with the scientific consensus that humans have caused unprecedented climate changes.



CHINA
A chemical that helped to create a hole in the ozone layer is reappearing. An international investigation traced the resurgence of the banned gas, known as CFC-11, to factories in a town in the eastern province of Shandong.

CHILE
The National Congress of Chile passed a bill outlining plans to establish a ministry of science. The goal is to invest more in research, as part of a shift toward an economy of "knowledge and creativity."

THAILAND
A pilot whale washed ashore in Thailand's southern Songkhla province with nearly 18 pounds of plastic in its stomach. The whale died days later, renewing concerns about the amount of such waste humans have put into the world's waterways.

For more details, visit www.ScientificAmerican.com/sep2018/advances

CHEMISTRY

Oil in Your Wine

Argan oil could pave the way for wine made with more exotic yeasts

Every great bottle of wine begins with a humble fungal infection. Historically, winemakers relied on naturally occurring yeasts to convert grape sugars into alcohol; modern vintners typically buy one of just a few laboratory-grown strains. Now, to set their products apart, some of the best winemakers are revisiting nature's lesser-used microbial engineers. Not all these strains can withstand industrial production processes and retain their efficacy—but a natural additive offers a possible solution, new research suggests.

Industrial growers produce yeast in the presence of oxygen, which can damage cell walls and other important proteins during a process called oxidation. This can make it harder for yeasts—which are dehydrated for shipping—to perform when winemakers revive them. Biochemist Emilia Matallana of the University of Valencia in Spain and her colleagues have been exploring practical ways to fend off such oxidation for years. After showing that

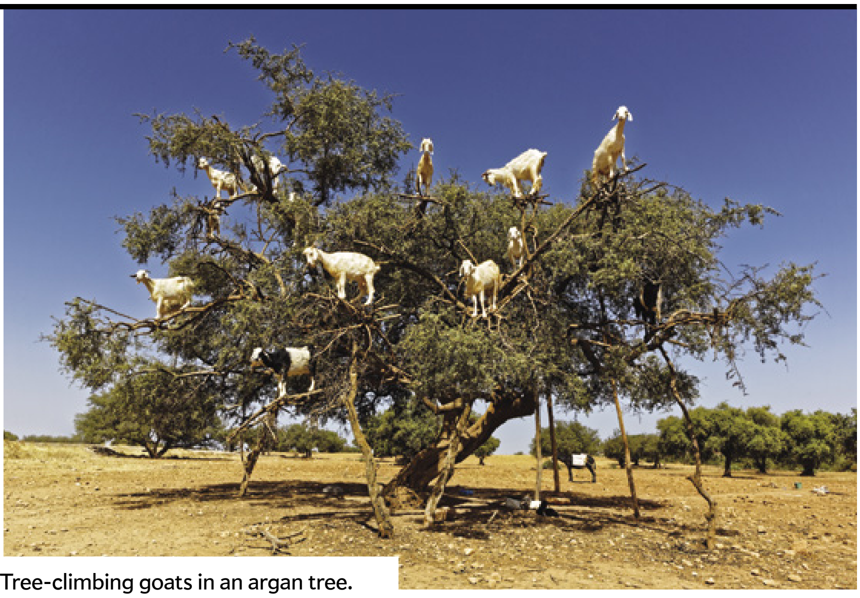
HEALTH

The Inside Scope

Colon cancer screening guidelines should be individualized

No one looks forward to that first colonoscopy, but this glimpse into the gut is one of the most powerful existing weapons against colon cancer. Yet current protocol for when to start checking for the disease may be too late for many men and may put many women through an expensive and unnecessary ordeal, a new study suggests.

Doctors currently advise men and women with no family history of colon cancer or other risk factors to start undergoing screening at age 50, and sooner for those deemed more at risk. But this sweeping guideline does not account for individual genetic and lifestyle differences.



Tree-climbing goats in an argan tree.

YAVUZ SARIYILDIZ *Getty Images*

pure antioxidants worked, they began searching for a more affordable natural source. They found it in argan, an olivelike fruit used for food and cosmetics. The trees it grows on are famously frequented by domesticated goats.

Matallana and her team treated three varieties of wine yeast (*Saccharomyces cerevisiae*) with argan oil, dehydrated them and later rehydrated them. The oil protected important proteins in the yeasts from oxidation and boosted wine fermentation, the researchers reported in a study published online in June in *Innovative Food Science & Emerging Technologies.*

Microbiologists are now interested in studying how and why each yeast strain responded to the argan oil as it did, says enologist Ramón González of the Institute of Grapevine and Wine Sciences in Logroño, Spain, who was not involved in the work. The oil may one day enable vintners to use a wider range of specialized yeasts, putting more varied wines on the menu. As for how the oil affected the wine's taste, Matallana says it was "nothing weird." *—Lucas Laursen*

To calculate the ideal age for the first screening, researchers at the Fred Hutchinson Cancer Research Center in Seattle and their colleagues analyzed patient data detailing 19 behavioral patterns—including exercise, alcohol and red meat consumption, body mass index and aspirin use—and 63 genetic markers associated with colorectal cancer.

The results suggest that 15 percent of men with no family history of the disease should start getting scoped before age 45, whereas half of women with no family history could wait until they are at least 56—and 10 percent of those could start as late as 64. Thirteen years of data from participants of European descent showed that hormone replacement therapy reduced women's cancer risk, that men were more likely to engage in risky behaviors such as drinking and smoking, and that being overweight was a higher risk for men than women.

The study's findings, published in June in *Gastroenterology,* also call into question the assumption that a family history of the disease always calls for early screening. The researchers found that more than half of women—and 15 percent of men—with a family history could wait until 50 for a first colonoscopy. These findings are a step toward individualized screening guidelines but should not be considered medical advice, says Jihyoun Jeon of the University of Michigan, the study's lead author.

"The study is significant because [disease] models don't usually combine both genetics and habits to predict colon cancer risk," says Brian Wells, a biostatistician at the Wake Forest School of Medicine, who was not involved in the work. "But the authors did not tell us how many colonoscopies could be avoided and how many colorectal cancers could be prevented using this model and how this compares with the current guidelines. This comparison is needed to evaluate risks versus benefits for the real world." *—Heather Stringer*

SOCIOLOGY

The Facebook Gender Gap

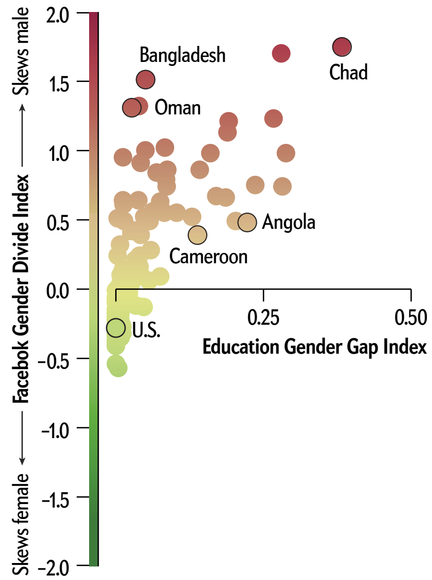
Social network use may be a valuable metric for equality

In addition to purveying cat videos and baby pictures, social networks can provide useful demographic information. A new study finds that worldwide, Facebook use by women is associated with greater gender equality.

Researchers looked at the anonymized data of 1.4 billion users in 217 countries, territories and autonomous regions and calculated the proportion of women and men ages 13 to 65 who actively used the social network. Places with a lower female-to-male usage ratio, such as Afghanistan, were deemed to have a greater "Facebook gender divide" (*chart* and *map*). The team also collected World Economic Forum data on countries' gender equality in terms of economic opportunity, education and health. The study found that the smaller a country's Facebook gender divide in 2015, the more economic gender equality increased the following year. In contrast, an increase in economic gender equality in 2015 was not associated with a reduction in the Facebook gender divide during 2016. This finding suggests that a smaller Facebook gender gap is more likely a contributor to—rather than a result of—economic gender equality. The results were published in July in the *Proceedings of the National Academy of Sciences USA*.

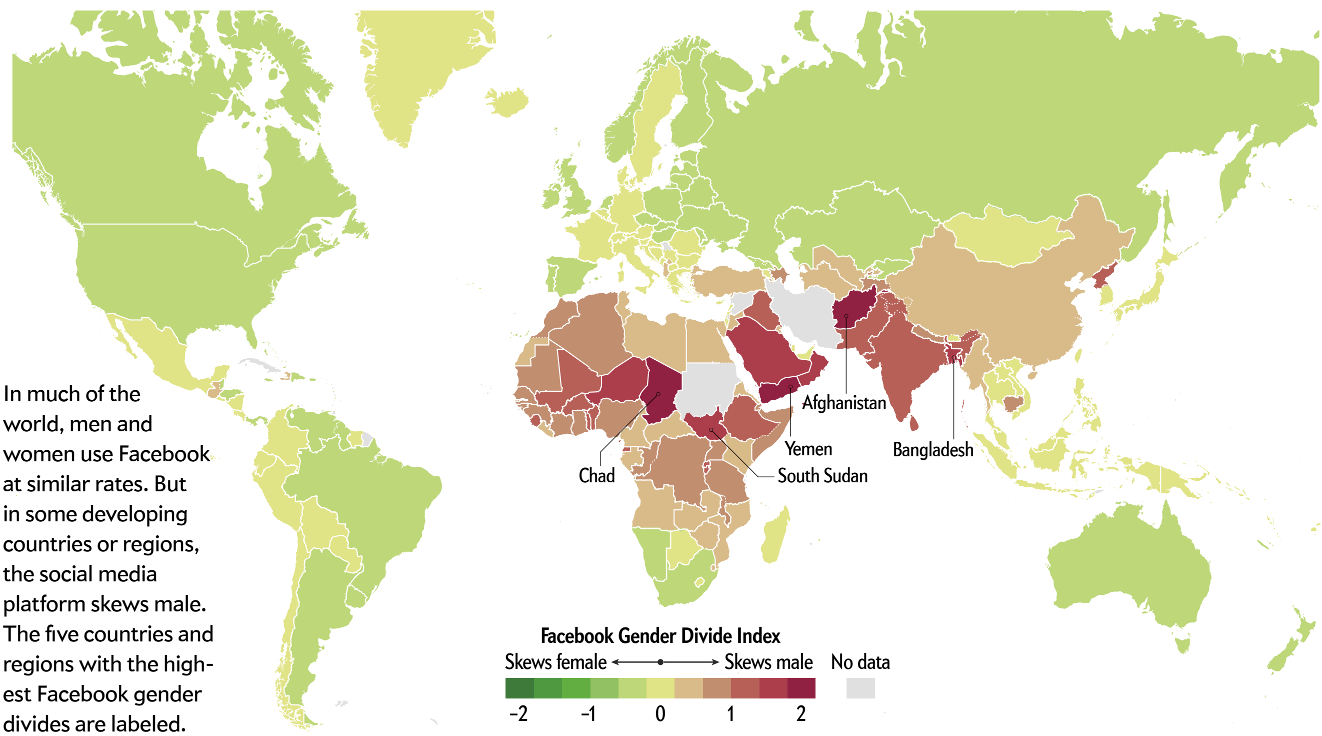
Ridhi Kashyap, a demographer at the University of Oxford, who was not involved in the study, has published a separate map of the Internet gender gap, also using Facebook data. She found that gender gaps in Facebook use proved to be a good measure of gender gaps in Internet use in general; data on the latter are often unavailable. Kashyap says the Internet can provide users with valuable health and employment information and "can also be a great way to enhance skills." David Garcia, a computational social scientist at the Medical University of Vienna and the lead author of the *PNAS* study, says Facebook data could help policy makers estimate gender inequality in poor countries and could track its evolution on a daily basis. —*Matthew Hutson*

The Facebook Gender Divide vs. the Education Gap



Researchers compared Facebook gender divide values with the World Economic Forum's gender gap indices for each country or region and found a particularly strong link with education inequality. The graph includes only countries and regions for which data are available for both measures.

The Facebook Gender Divide around the World



In much of the world, men and women use Facebook at similar rates. But in some developing countries or regions, the social media platform skews male. The five countries and regions with the highest Facebook gender divides are labeled.

SOURCES: "ANALYZING GENDER INEQUALITY THROUGH LARGE-SCALE FACEBOOK ADVERTISING DATA," BY DAVID GARCIA ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 115, NO. 27; JULY 3, 2018 (*Facebook gender divide data*); THE GLOBAL GENDER GAP REPORT 2016. WORLD ECONOMIC FORUM, 2016 (*education gender gap data*)

Graphics by Amanda Montañez

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

The So-Called Right to Try

A new law to let dying patients access unapproved drugs raises false hope

By Claudia Wallis

There's no question about it: the new law sounds just great. President Donald Trump, who knows a thing or two about marketing, gushed about its name when he signed the "Right to Try" bill into law on May 30. He was surrounded by patients with incurable diseases, including a second grader with Duchenne muscular dystrophy, who got up from his small wheelchair to hug the president. The law aims to give such patients easier access to experimental drugs by bypassing the Food and Drug Administration.

The crowd-pleasing name and concept are why 40 states had already passed similar laws, although they were largely symbolic until the federal government got onboard. The laws vary but generally say that dying patients may seek from drugmakers any medicine that has passed a phase I trial—a minimal test of safety. "We're going to be saving tremendous numbers of lives," Trump said. "The current FDA approval process can take many, many years. For countless patients, time is not what they have."

But the new law won't do what the president claims. Instead it gives false hope to the most vulnerable patients. "This is a right to ask, not a right to try," says Alison Bateman-House, a medical ethicist at New York University and an expert on the compassionate use of experimental drugs. The right to ask was already firmly in place. "If I had a magic wand," she says, "rather than passing a new law, I would have figured out a way to educate people about the system we already have."

In fact, for decades pharmaceutical companies have made unapproved drugs available through programs overseen by the FDA. This "expanded access" is aimed at extremely ill patients who, for one reason or another, do not qualify for formal drug studies. A 2016 report shows that the FDA receives more than 1,000 annual requests on behalf of such patients and approves 99.7 percent of them. It acts immediately in emergency cases or else within days, according to FDA commissioner Scott Gottlieb.

Of course, there are barriers to getting medicines that may not be effective or safe. Some patients cannot find a doctor to administer them or an institution that will let them be used on-site. And many of these drugs are simply not made available. Drugmakers cannot be compelled to do so: a 2007 federal court decision found "there is no fundamental right … of access to experimental drugs for the terminally ill." The new law changes none of this.

Pharma companies have many reasons to be cautious about providing what is in their labs. A drug in early stages of testing may have risks and benefits that are wildly uncertain. Supplies may be limited and production costly, so a company may wish to save its precious stock for clinical trials. Developers may also be concerned that their drugs will do poorly in fragile, dying patients, word will get out, and the consequences will be dire: patients will be scared away from studies, investors will retreat, stocks will tank. Thus, work on a potentially valuable new medicine might get derailed by acts of compassion.

"If you said patients could just call up and say, 'I want the drug—give it to me,' how could you ever run a clinical trial?" asks Kenneth Moch, president and CEO of Cognition Therapeutics in Pittsburgh. "What happens for future patients?" In a long career, Moch has had a hand in making drugs available for compassionate use and holding them back. "There are no simple, monolithic solutions," he says. He doubts his industry will embrace "Right to Try" and said so at a congressional hearing on the bill: "My comment was that no ethical developer of an experimental medicine I know of would let it be used outside of the FDA's regulatory oversight."

Unethical companies, however, may find fresh opportunities to prey on desperate patients under the new law. It releases doctors, hospitals and drugmakers from liability. And although it stipulates that manufacturers can charge patients only what it costs to provide the drug, there is no required preapproval of these charges by the FDA, as there is with expanded access. Such issues led dozens of major patient-advocacy groups to oppose the legislation, which was originally drafted and promoted by the Goldwater Institute, a libertarian think tank.

Vibhav Rangarajan, an Illinois cardiologist, had hoped the law would help his two-year-old daughter, Radha, gain access to an experimental drug for a rare disease called metachromatic leukodystrophy that is destroying her nervous system. He wrote movingly about her plight in a recent piece published online in Stat and says he is saddened that this law lacks meaningful incentives for drug companies: "It's not really going to change the landscape." SA

Illustration by Celia Krampien

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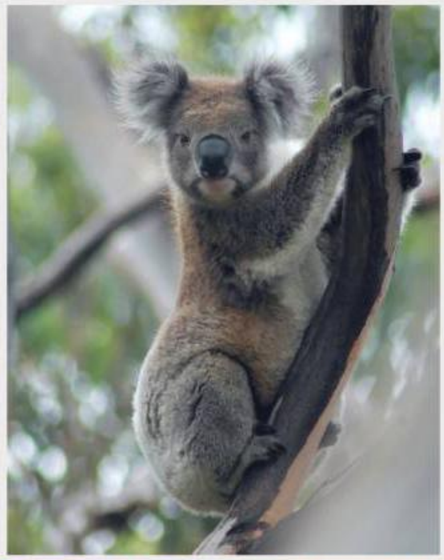

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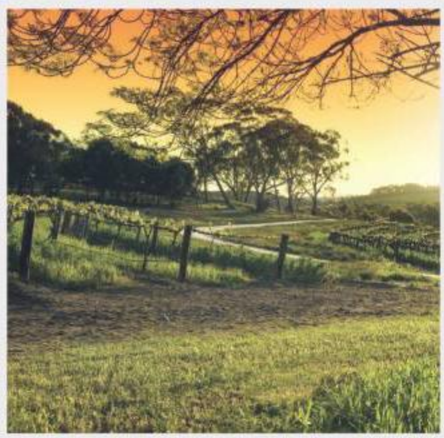

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David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

Not Your Dad's Hearing Aid

This outdated, expensive tech is getting a big makeover

By David Pogue

Most people probably associate three things with hearing aids: an elderly demographic, beige plastic construction and high-pitched feedback in public places. As it turns out, all those notions are now obsolete—or will be soon.

The most popular hearing-aid style is still the one that rests over your ear—a design that debuted in the 1950s. You know what else is decades old? Our country's system for getting and paying for hearing aids.

Basic Medicare and most other insurance providers have never paid for adult hearing aids. At an average cost of $4,700 a pair, that makes hearing aids the third-largest purchase in most people's lives after a house and a car.

The channel for buying hearing aids hasn't changed in 60 years, either: You must buy them from an audiologist or doctor. They're not available over the counter or by mail order.

Only six companies make most of the world's hearing aids, and they sell them directly through hearing specialists. (You can buy "personal sound amplification products" in stores, but they can't be marketed as hearing aids. In any case, most are fairly crude and ineffective for severe hearing loss.)

That's one reason the price of hearing aids hasn't dropped over time, the way most electronics do: the medical professionals you have to go through account for a significant fraction of the cost. Bottom line: many people who need them don't get them.

"This is the sad part," says Frank Lin, director of the Cochlear Center for Hearing and Public Health at the Johns Hopkins Bloomberg School of Public Health. "About 20 percent of adults who have a hearing loss actually use a hearing aid. I mean, 20 percent. And this figure hasn't changed in decades."

The other 80 percent may wind up missing out on a lot more than conversation in a noisy restaurant. Lin's studies, which followed older adults for many years, revealed that hearing loss is "incredibly strongly" linked to serious outcomes, including impaired thinking, greater risk of hospitalization, even dementia.

Appalled at these findings, Lin teamed up with the President's Council of Advisors on Science and Technology, under Barack Obama, and other groups to pursue a radical agenda: deregulating hearing aids. The result passed last year with bipartisan support. It requires that the FDA develop a new category of over-the-counter hearing aids, including safety and reliability standards.

The new law, Lin says, will lower the price and remove obstacles to innovation—and so help more patients. "People widely expect that companies like Bose, Samsung and Apple could all enter the market now," he observes. Obviously the concept of over-the-counter aids isn't popular with today's manufacturers, who will lose their exclusivity.

"The concern is people trying to self-diagnose, people trying to self-program," says Chris McCormick, chief marketing officer at Starkey Hearing Technologies, the only U.S.-based company among the big six hearing-aid makers. "The products will have to be standardized, and the problem is that everybody's hearing is different." Even so, Starkey and others are preparing for the new marketplace. Part of that is taking the hearing aid well beyond the realm of sound processing.

Later this year Starkey will release a new model that incorporates Fitbit-like health and heart rate monitoring and another that will automatically notify a loved one if you fall and can't get up. Bose already sells something called Hearphones—with noise cancellation, directional microphones and various sound-processing options—that are moderate-strength hearing aids in all but name.

As for those popular misconceptions: Many hearing aids today *aren't* beige (turns out that matching them to your hair color is better camouflage). Most have antifeedback circuitry.

And now, thanks partly to the new law, older people may not be the primary customer demographic. Your ear turns out to be a great, inconspicuous place for a computer to hide, as the movie *Her* brilliantly depicted. Hearing aids may mostly aid your hearing—but soon they'll help with directions, read our messages, play our music and track our health, all without the distraction of a smartphone screen. This could be the dawn of a new ear era. SA

SCIENTIFIC AMERICAN ONLINE
READ MORE ABOUT WHAT'S COMING IN HEARING AID TECH:
scientificamerican.com/sep2018/pogue

Illustration by Jay Bendt

A SINGULAR SPECIES

The Science of Being Human

PART 1

Why Us?

Illustration by Victo Ngai

PART 2

Us and Them

Illustration by Yuko Shimizu

PART 3

Beyond Us

Illustration by Armando Veve

HOW WE BECAME A DIFFERENT KIND OF ANIMAL

PART 1

Why Us?

AN EVOLVED UNIQUENESS

BY KEVIN LALAND :: *ILLUSTRATION BY VICTO NGAI*

MOST PEOPLE ON THIS PLANET BLITHELY ASSUME, LARGELY without any valid scientific rationale, that humans are special creatures, distinct from other animals. Curiously, the scientists best qualified to evaluate this claim have often appeared reticent to acknowledge the uniqueness of *Homo sapiens,* perhaps for fear of reinforcing the idea of human exceptionalism put forward in religious doctrines. Yet hard scientific data have been amassed across fields ranging from ecology to cognitive psychology affirming that humans truly *are* a remarkable species.

IN BRIEF

Human accomplishments derive from our ability to acquire knowledge from others and to use that communal store of experience to devise novel solutions to life's challenges.

Other species innovate, too. Chimps open nuts with stone hammers. Dolphins use a tool to flush out hidden prey.

Our uniqueness has to do with a capacity to teach skills to others over the generations with enough precision for building skyscrapers or going to the moon.

The density of human populations far exceeds what would be typical for an animal of our size. We live across an extraordinary geographical range and control unprecedented flows of energy and matter: our global impact is beyond question. When one also considers our intelligence, powers of communication, capacity for knowledge acquisition and sharing—along with magnificent works of art, architecture and music we create—humans genuinely do stand out as a very different kind of animal. Our culture seems to separate us from the rest of nature, and yet that culture, too, must be a product of evolution.

The challenge of providing a satisfactory scientific explanation for the evolution of our species' cognitive abilities and their expression in our culture is what I call "Darwin's Unfinished Symphony." That is because Charles Darwin began the investigation of these topics some 150 years ago, but as he himself confessed, his understanding of how we evolved these attributes was in his own words "imperfect" and "fragmentary." Fortunately, other scientists have taken up the baton, and there is an increasing feeling among those of us who conduct research in this field that we are closing in on an answer.

The emerging consensus is that humanity's accomplishments derive from an ability to acquire knowledge and skills from other people. Individuals then build iteratively on that reservoir of pooled knowledge over long periods. This communal store of experience enables creation of ever more efficient and diverse solutions to life's challenges. It was not our large brains, intelligence or language that gave us culture but rather our culture that gave us large brains, intelligence and language. For our species and perhaps a small number of other species, too, culture transformed the evolutionary process.

The term "culture" implies fashion or haute cuisine, but boiled down to its scientific essence, culture comprises behavior patterns shared by members of a community that rely on socially transmitted information. Whether we consider automobile designs, popular music styles, scientific theories or the foraging of small-scale societies, all evolve through endless rounds of innovations that add incremental refinements to an initial baseline of knowledge. Perpetual, relentless copying and innovation—that is the secret of our species' success.

ANIMAL TALENTS

COMPARING HUMANS with other animals allows scientists to determine the ways in which we excel, the qualities we share with other species and when particular traits evolved. A first step to understanding how humans got to be so different, then, is to take this comparative perspective and investigate the social learning and innovation of other creatures, a search that leads ultimately to the subtle but critical differences that make us unique.

Many animals copy the behavior of other individuals and in this way learn about diet, feeding techniques, predator avoidance, or calls and songs. The distinctive tool-using traditions of different populations of chimpanzees throughout Africa is a famous example. In each community, youngsters learn the

FOLLOWING in the steps of others—social learning—has been a key to the success of *Homo sapiens* as long as it has existed as a separate species. Here members of the San group in Namibia walk the dunes single file.

KERSTIN GEIER *Getty Images*

local behavior—be it cracking open nuts with a stone hammer or fishing for ants with a stick—by copying more experienced individuals. But social learning is not restricted to primates, large-brained animals or even vertebrates. Thousands of experimental studies have demonstrated copying of behavior in hundreds of species of mammals, birds, fishes and insects. Experiments even show that young female fruit flies select as mates males that older females have chosen.

A diverse range of behaviors are learned socially. Dolphins possess traditions for foraging using sea sponges to flush out fish hiding on the ocean floor. Killer whales have seal-hunting traditions, including the practice of knocking seals off ice floes by charging toward them in unison and creating a giant wave. Even chickens acquire cannibalistic tendencies through social learning from other chickens. Most of the knowledge transmitted through animal populations concerns food—what to eat and where to find it—but there are also extraordinary social conventions. One troop of capuchin monkeys in Costa Rica has devised the bizarre habit of inserting fingers into the eye sockets or nostrils of other monkeys or hands into their mouths, sitting together in this manner for long periods and gently swaying—conventions that are thought to test the strength of social bonds.

Animals also "innovate." When prompted to name an innovation, we might think of the invention of penicillin by Alexander Fleming or the construction of the World Wide Web by Tim Berners-Lee. The animal equivalents are no less fascinating. My favorite concerns a young chimpanzee called Mike, whom primatologist Jane Goodall observed devising a noisy dominance display that involved banging two empty kerosene cans together. This exhibition thoroughly intimidated Mike's rivals and led to him shooting up the social rankings to become alpha male in record time. Then there is the invention by Japanese carrion crows of using cars to crack open nuts. Walnuts shells are too tough for crows to crack in their beaks, but they nonetheless feed on these nuts by placing them in the road for cars to run over, returning to retrieve their treats when the lights turn red. And a group of starlings—birds famously fond of shiny objects used as nest decorations—started raiding a coin machine at a car wash in Fredericksburg, Va., and made off with, quite literally, hundreds of dollars in quarters. [For further examples of how animals adjust to urban environments, see "Darwin in the City," on page 82.]

Such stories are more than just enchanting snippets of natural history. Comparative analyses reveal intriguing patterns in the social learning and innovation exhibited by animals. The most significant of these discoveries finds that innovative species, as well as animals most reliant on copying, possess unusually large brains (both in absolute terms and relative to body size). The correlation between rates of innovation and brain size was initially observed in birds, but this research has since been replicated in primates. These findings support a hypothesis known as cultural drive, first proposed by University of California, Berkeley, biochemist Allan C. Wilson in the 1980s.

Kevin Laland is a professor of behavioral and evolutionary biology at the University of St. Andrews in Scotland and author of *Darwin's Unfinished Symphony: How Culture Made the Human Mind* (Princeton University Press, 2017).

Wilson argued that the ability to solve problems or to copy the innovations of others would give individuals an edge in the struggle to survive. Assuming these abilities had some basis in neurobiology, they would generate natural selection favoring ever larger brains—a runaway process culminating in the huge organs that orchestrate humans' unbounded creativity and all-encompassing culture.

Initially scientists were skeptical of Wilson's argument. If fruit flies, with their tiny brains, could copy perfectly well, then why should selection for more and more copying generate the proportionately gigantic brains seen in primates? This conundrum endured for years, until an answer arose from an unexpected source.

COPYCATS

THE SOCIAL LEARNING STRATEGIES TOURNAMENT was a competition that my colleagues and I organized that was designed to work out the best way to learn in a complex, changing environment. We envisaged a hypothetical world in which individuals—or agents as they are called—could perform a large number of possible behaviors, each with its own characteristic payoff that changed over time. The challenge was to work out which actions would give the best returns and to track how these changed. Individuals could either learn a new behavior or perform a previously learned one, and learning could occur through trial-and-error or through copying other individuals. Rather than trying to solve the puzzle ourselves, we described the problem and specified a set of rules, inviting anyone interested to have a go at solving it. All the entries—submitted as software code that specified how the agents should behave—competed against one another in a computer simulation, and the best performer won a €10,000 prize. The results were highly instructive. We found a strong positive relation between how well an entry performed and how well it required agents to learn socially. The winning entry did not require agents to learn often, but when they did, it was almost always through copying, which was always performed accurately and efficiently.

Brains are energetically costly organs, and social learning is paramount to animals that need to gather the resources necessary to grow and maintain a large brain efficiently.

The tournament taught us how to interpret the positive relation between social learning and brain size observed in primates. The results suggested that natural selection does not favor more and more social learning but rather a tendency toward better and better social learning. Animals do not need a big brain to copy, but they do need a big brain to copy well.

This insight stimulated research into the empirical basis of the cultural drive hypothesis. It led to the expectation that natural selection ought to favor anatomical structures or functional capabilities in the primate brain that promote accurate, efficient copying. Examples might include better visual perception if that allows copying over greater distances or imitating fine-motor actions. In addition, selection should foster greater connections between perceptual and motor structures in the brain, helping individuals to translate the sight of others performing a skill into their producing a matching performance by moving their body in a corresponding way.

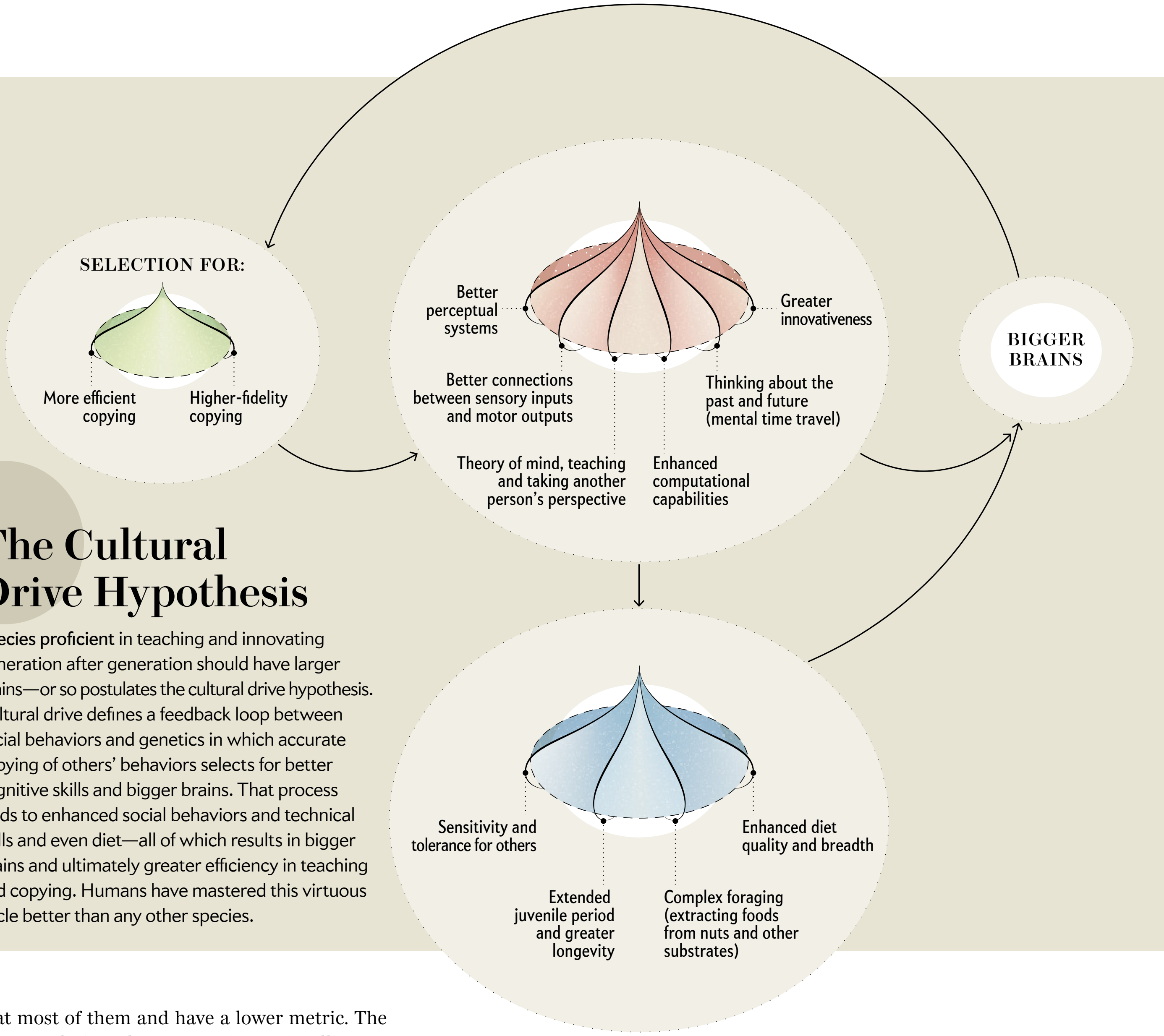
The same cultural drive hypothesis also predicted that selection for improved social learning should have influenced other aspects of social behavior and life history, including living in social groups and using tools. The reasoning was that the bigger the group and the more time spent in the company of others, the greater the opportunities for effective social learning. Through copying, monkeys and apes acquire diverse foraging skills ranging from extractive foraging methods such as digging grubs out of bark to sophisticated tool-using techniques such as fishing for termites with sticks. If social learning is what allows primates to pick up difficult-to-learn but productive food-procurement methods, any species proficient in social learning should show elevated levels of extractive foraging and tool use. They should possess a richer diet and have longer lives, if that gives more time for learning new skills and passing them on to descendants. In sum, cultural drive predicts that rates of social learning will correlate not only with brain size but also with a host of measures related to cognitive performance.

Rigorous comparative analyses have borne out these predictions. Those primates that excel at social learning and innovation are the same species that have the most diverse diets, use tools and extractive foraging, and exhibit the most complex social behavior. In fact, statistical analyses suggest that these abilities vary in lockstep so tightly that one can align primates along a single dimension of general cognitive performance, which we call primate intelligence (loosely analogous to IQ in humans).

Chimpanzees and orangutans excel in all these performance measures and have high primate intelligence, whereas some nocturnal prosimians are

The Cultural Drive Hypothesis

Species proficient in teaching and innovating generation after generation should have larger brains—or so postulates the cultural drive hypothesis. Cultural drive defines a feedback loop between social behaviors and genetics in which accurate copying of others' behaviors selects for better cognitive skills and bigger brains. That process leads to enhanced social behaviors and technical skills and even diet—all of which results in bigger brains and ultimately greater efficiency in teaching and copying. Humans have mastered this virtuous circle better than any other species.



poor at most of them and have a lower metric. The strong correlations between primate intelligence and both brain size measures and performance in laboratory tests of learning and cognition validate the use of the metric as a measure of intelligence. The interpretation also fits with neuroscientific analyses showing that the size of individual brain components can be accurately predicted with knowledge of overall brain size. Associated with the evolution of large primate brains are bigger and better-connected regions—neocortices and cerebellums—that allow executive control of actions and increased cortical projections to the motor neurons of the limbs, facilitating controlled and precise movements. This helps us to understand why big-brained animals show complex cognition and tool use. [For more on primate brains, see "Are We Wired Differently?" on page 60.]

Plotting the intelligence measure on a primate family tree reveals evolution for higher intelligence taking place independently in four distinct primate groups: the capuchins, macaques, baboons and great apes—precisely those species renowned for their social learning and traditions. This finding is exactly the pattern expected if cultural processes really were driving the evolution of brain and cognition. Further analyses, using better data and cutting-edge statistical methods, reinforce these conclusions, as do models that make quantitative predictions for brain and body size based on estimates of the brain's metabolic costs.

Cultural drive is not the only cause of primate brain evolution: diet and sociality are also important because fruit-eating primates and those living in large, complex groups possess large brains. It is difficult, however, to escape the conclusion that high intelligence and longer lives co-evolved in some primates because their cultural capabilities allowed them to exploit high-quality but difficult-to-access food resources, with the nutrients gleaned "paying" for brain growth. Brains are energetically costly organs, and social learning is paramount to animals gathering the resources necessary to grow and maintain a large brain efficiently.

Graphic by Federica Fragapane

NO CHIMP MOBILES

WHY, THEN, DON'T OTHER PRIMATES have complex culture like us? Why haven't chimpanzees sequenced genomes or built space rockets? Mathematical theory has provided some answers. The secret comes down to the fidelity of information transmission from one member of a species to another, the accuracy with which learned information passes between transmitter and receiver. The size of a species' cultural repertoire and how long cultural traits persist in a population both increase exponentially with transmission fidelity. Above a certain threshold, culture begins to ratchet up in complexity and diversity. Without accurate transmission, cumulative culture is impossible. But once a given threshold is surpassed, even modest amounts of novel invention and refinement lead rapidly to massive cultural change. Humans are the only living species to have passed this threshold.

Our ancestors achieved high-fidelity transmission through teaching—behavior that functions to facilitate a pupil's learning. Whereas copying is widespread in nature, teaching is rare, and yet teaching is universal in human societies once the many subtle forms this practice takes are recognized. Mathematical analyses reveal tough conditions that must be met for teaching to evolve, but they show that cumulative culture relaxes these conditions. The modeling implies that teaching and cumulative culture co-evolved in our ancestors, creating for the first time in the history of life on our planet a species whose members taught their relatives a broad range of skills, perhaps cemented through goal-oriented "deliberate" practice [see "Inside Our Heads," on page 42].

The teaching of cultural knowledge by hominins (humans and their extinct close relatives) included foraging, food processing, learned calls, toolmaking, and so forth and provided the context in which language first appeared. Why our ancestors alone evolved language is one of the great unresolved questions. One possibility is that language developed to reduce the costs, increase the accuracy and expand the domains of teaching. Human language may be unique, at least among extant species, because only humans constructed a sufficiently diverse and dynamic cultural world that demanded talking about. This explanation has the advantage that it accounts for many of the characteristic properties of language, including its distinctiveness, its power of generalization and why it is learned [see "Talking through Time," on page 54].

Language began as just a handful of shared symbols. But once started, the use of protolanguage imposed selection on hominin brains for language-learning skills and on languages themselves to favor easy-to-learn structures. That our ancestors' cultural activities imposed selection on their bodies and minds—a process known as gene culture co-evolution—is now well supported. Theoretical, anthropological and genomic analyses all demonstrate how socially transmitted knowledge, including that expressed in the manufacture and use of tools, generated natural selection that transformed human anatomy and cognition. This evolutionary feedback shaped the emergence of the modern human mind, generating an evolved psychology that spurred a motivation to teach, speak, imitate, emulate, and share the goals and intentions of others. It also produced enhanced learning and computational abilities. These capabilities evolved with cumulative culture because they enhance the fidelity of information transmission.

Teaching and language were evolutionary game changers for our lineage. Large-scale cooperation arose in human societies because of our uniquely

CHIMPS AND HUMANS are both toolmakers. Chimpanzees use sticks to hunt for a meal of termites and pass this technique along to their kin. Unlike chimps, humans transmit cultural knowledge to offspring with a high degree of precision that enables the making of sophisticated technologies.

STEVE BLOOM *Alamy (chimpanzees)*; CHRIS GUNN NASA *(telescope mirror)* potent capacities for social learning and teaching, as theoretical and experimental data attest. Culture took human populations down novel evolutionary pathways, both by creating conditions that promoted established mechanisms for cooperation witnessed in other animals (such as helping those that reciprocate) and by generating novel cooperative mechanisms not seen elsewhere. Cultural group selection—practices that help a group cooperate and compete with other groups (forming an army or building an irrigation system)—spread as they proved their worth [see "The Origins of Morality," on page 70].

Culture provided our ancestors with food-procurement and survival tricks, and as each new invention arose, a given population was able to exploit its environment more efficiently. This occurrence fueled not only brain expansion but population growth as well. Increases in both human numbers and societal complexity followed our domestication of plants and animals. Agriculture freed societies from the constraints that the peripatetic lives of hunter-gatherers imposed on population size and any inclinations to create new technologies. In the absence of this constraint, agricultural societies flourished, both because they outgrew hunter-gatherer communities through allowing an increase in the carrying capacity of a particular area for food production and because agriculture triggered a raft of associated innovations that dramatically changed human society. In the larger societies supported by increasing farming yields, beneficial innovations were more likely to spread and be retained. Agriculture precipitated a revolution not only by triggering the invention of related technologies—ploughs or irrigation technology, among others—but also by spawning entirely unanticipated initiatives, such as the wheel, city-states and religions.

The emerging picture of human cognitive evolution suggests that we are largely creatures of our own making. The distinctive features of humanity—our intelligence, creativity, language, as well as our ecological and demographic success—are either evolutionary adaptations to our ancestors' own cultural activities or direct consequences of those adaptations. For our species' evolution, cultural inheritance appears every bit as important as genetic inheritance.

We tend to think of evolution through natural selection as a process in which changes in the external environment, such as predators, climate or disease, trigger evolutionary refinements in an organism's traits. Yet the human mind did not evolve in this straightforward way. Rather our mental abilities arose through a convoluted, reciprocal process in which our ancestors constantly constructed niches (aspects of their physical and social environments) that fed back to impose selection on their bodies and minds, in endless cycles. Scientists can now comprehend the divergence of humans from other primates as reflecting the operation of a broad array of feedback mechanisms in the hominin lineage. Similar to a self-sustaining chemical reaction, a runaway process ensued that propelled human cognition and culture forward. Humanity's place in the evolutionary tree of life is beyond question. But our ability to think, learn, communicate and control our environment makes humanity genuinely different from all other animals. SA

A Visit from E.T.

Imagine an extraterrestrial intelligence studying Earth's biosphere. Which of all the species would it identify as differing from the rest? The answer is humanity. Here are a few reasons:

Population size. Our numbers are out of kilter with global patterns for vertebrate populations. There are several orders of magnitude more humans than expected for a mammal of our size.

Ecological range. Our species distribution is extraordinary. Humans have colonized virtually every region of the terrestrial globe.

Environmental regulation. Humans control vast and diverse flows of energy and matter on unprecedented scales.

Global impact. Human activities threaten and are driving extinct unmatched numbers of species while eliciting strong evolutionary change across the biosphere.

Cognition, communication and intelligence. Experiments demonstrate superior performance by humans across diverse tests of learning and cognition. Human language is infinitely flexible, unlike the communication of other animals.

Knowledge acquisition and sharing. Humans acquire, share and store information on never-before-seen scales and build on their pooled cultural knowledge cumulatively from generation to generation.

Technology. Humans invent and mass-produce infinitely more complex and diverse artifacts than other animals.

The extraterrestrials might well be charmed by the elephant's trunk and impressed by the giraffe's neck, but it is humans that they would single out. *—K.L.*

MORE TO EXPLORE

Social Intelligence, Innovation, and Enhanced Brain Size in Primates. Simon M. Reader and Kevin N. Laland in *Proceedings of the National Academy of Sciences USA*, Vol. 99, No. 7, pages 4436–4441; April 2, 2002.

Why Copy Others? Insights from the Social Learning Strategies Tournament. L. Rendell et al. in *Science*, Vol. 328, pages 208–213; April 9, 2010.

Identification of the Social and Cognitive Processes underlying Human Cumulative Culture. L. G. Dean et al. in *Science*, Vol. 335, pages 1114–1118; March 2, 2012.

FROM OUR ARCHIVES

The Morning of the Modern Mind. Kate Wong; June 2005.

scientificamerican.com/magazine/sa

TECHNO *SAPIENS*

TAKING APART THE INTERNAL-COMBUSTION ENGINE REVEALS OUR COLLECTIVE GENIUS

BY LEWIS DARTNELL

ILLUSTRATIONS BY JOSÉ MIGUEL MAYO (engine) AND MATTHEW TWOMBLY (insets)

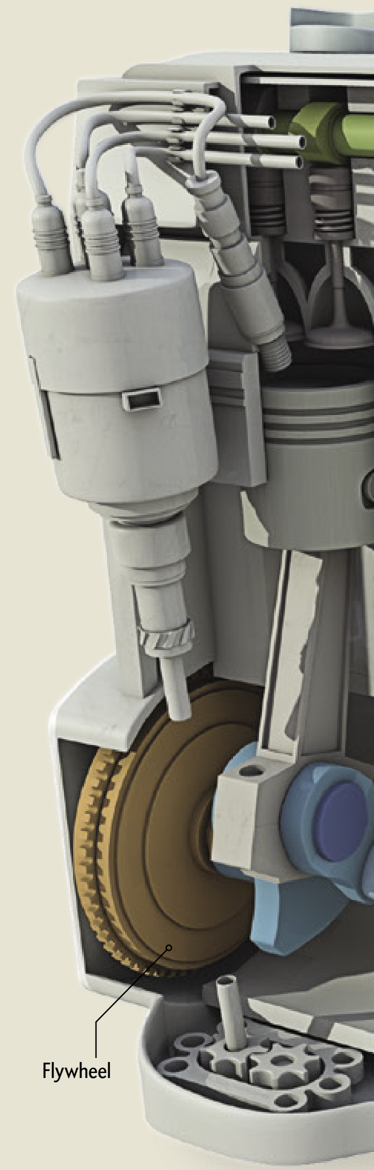
HUMANS DEMONSTRATE not only an extraordinary capacity for transferring knowledge from one generation to the next, they are also supremely skilled in building on this know-how to create novel technology, whether it be an Acheulean hand ax or the modern electrical grid. This vast web of interconnected knowledge and practical capability has required the labors of millions over the millennia. The subtleties of technologies from stone flaking to high-voltage transmission lines could take a substantial time to recover if humanity were ever forced to reboot civilization after a nuclear conflagration, an asteroid strike or some other global catastrophe.

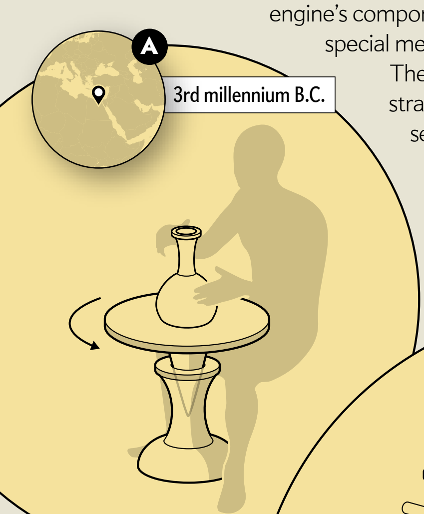
The power of teaching, copying and, especially, enhancing the creations of previous generations sets our species apart from all others. A new invention is rarely ever completely innovative: most often it is a rearrangement or embellishment of preexisting technologies. The internal-combustion engine presents a particularly clear example. It was invented by picking off-the-shelf-components from a library of existing mechanical modules. If you peel back the metallic skin of the hood and dissect the engine as you would an organism, you will find a compact organization of individual mechanisms, each performing its own function in precise coordination with the other components, each with its own centuries-long history.

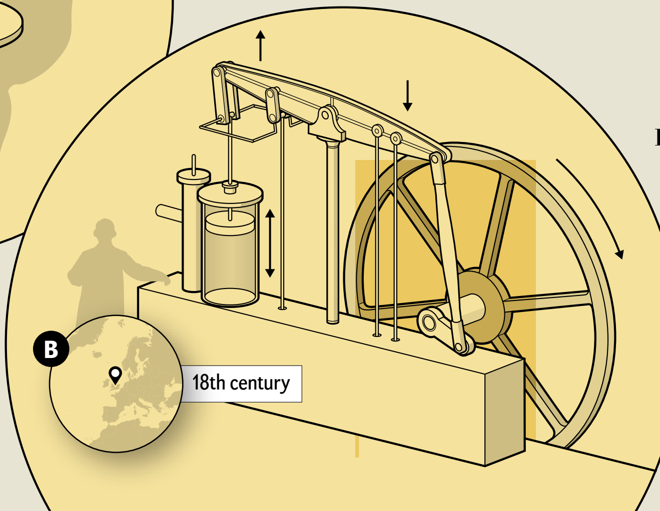
In aggregate, the internal-combustion engine almost miraculously transforms heat released by burning fuel into the smooth motion of the vehicle. The rapidly beating heart of a car is a set of engine cylinders and pistons, themselves essentially identical in form to ancient water pumps. The explosive expansion of hot gases produced by igniting fuel in the cylinders shunts out the pistons, but this back-and-forth movement must be translated into a rotation of the driveshaft and wheels. Three of the engine's components—the crank, camshaft and flywheel, all with ancient roots—deserve special mention in this process.

The story of these parts, illustrated here in a historical chronology, demonstrates that even though the purring engine in a brand-new sports car may seem like the height of modern technological sophistication, it is in fact a mishmash of components co-opted from ancient inventions. Some of them reach back to ancient China or even the very beginnings of civilization itself.

Lewis Dartnell is author of the *New York Times* best seller *The Knowledge: How to Rebuild Our World from Scratch* (Penguin Books, 2014).



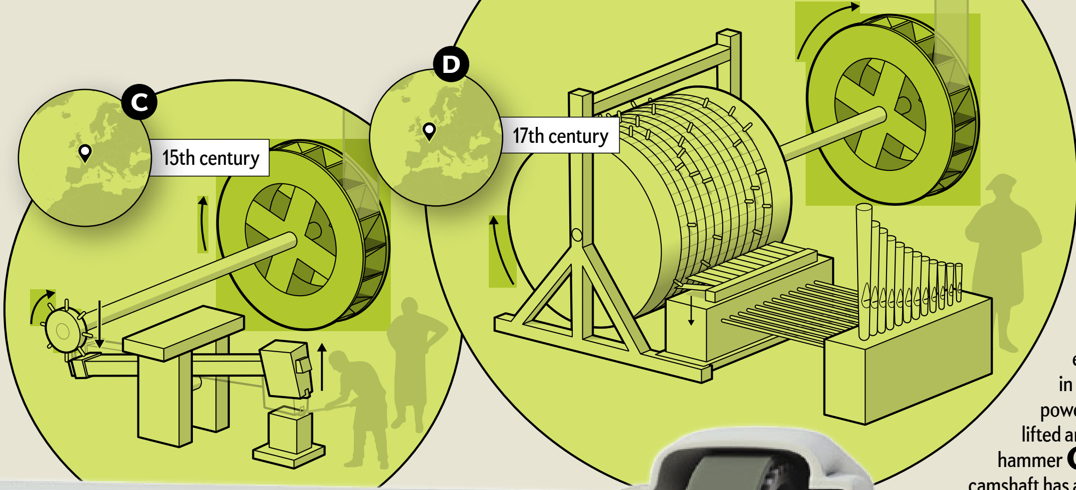




FLYWHEEL

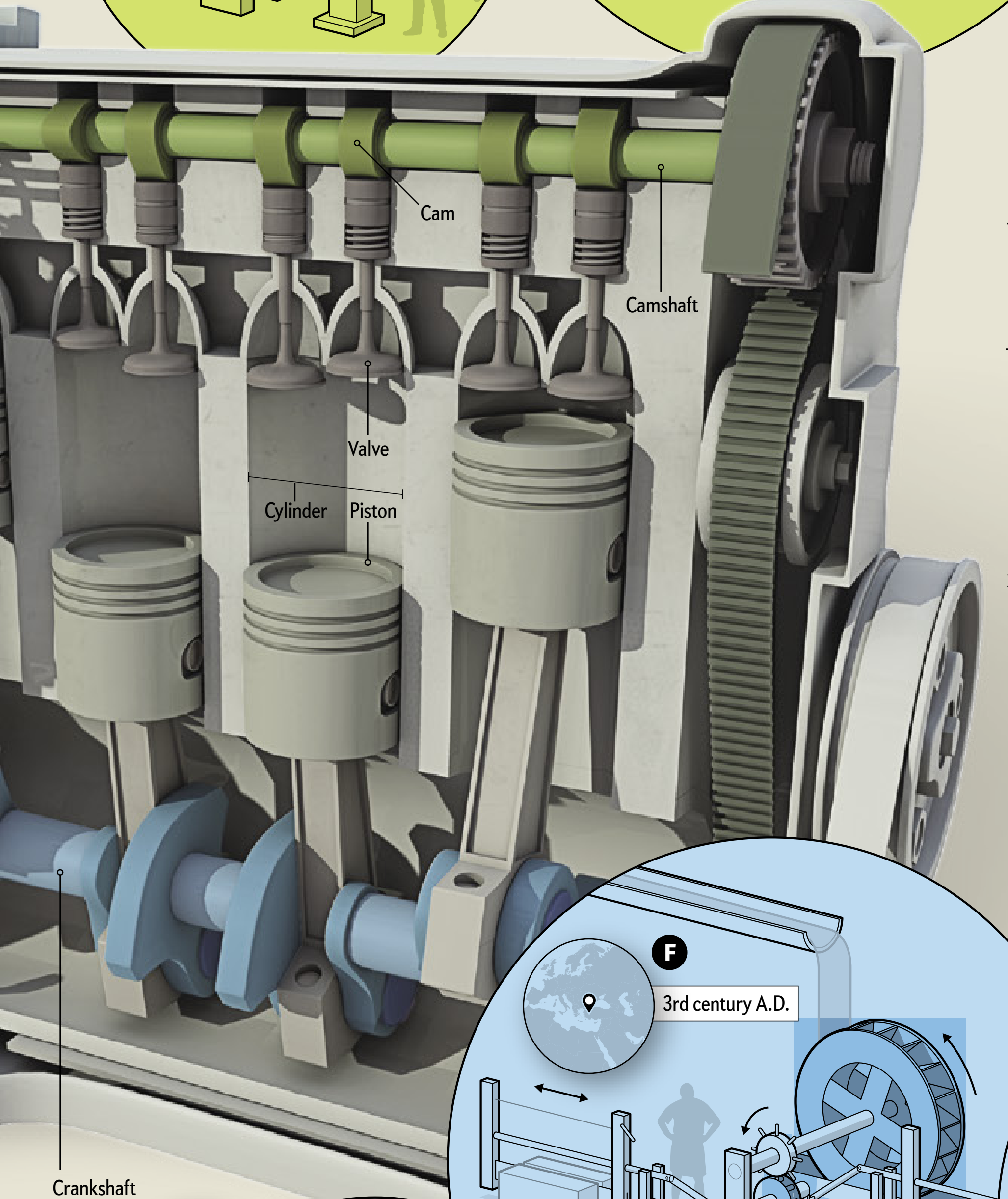
Pistons in an internal-combustion engine are orchestrated to fire in a staggered sequence, but the explosive impulses that turn the crankshaft are jerky, and a flywheel is needed to store rotational momentum and smooth out the shaft's spin.

The flywheel, an innovation dating back to potter's wheels in ancient Egypt **A**, became a standard fixture of the 18th-century steam engine **B**, a clear forerunner of the internal-combustion engine.



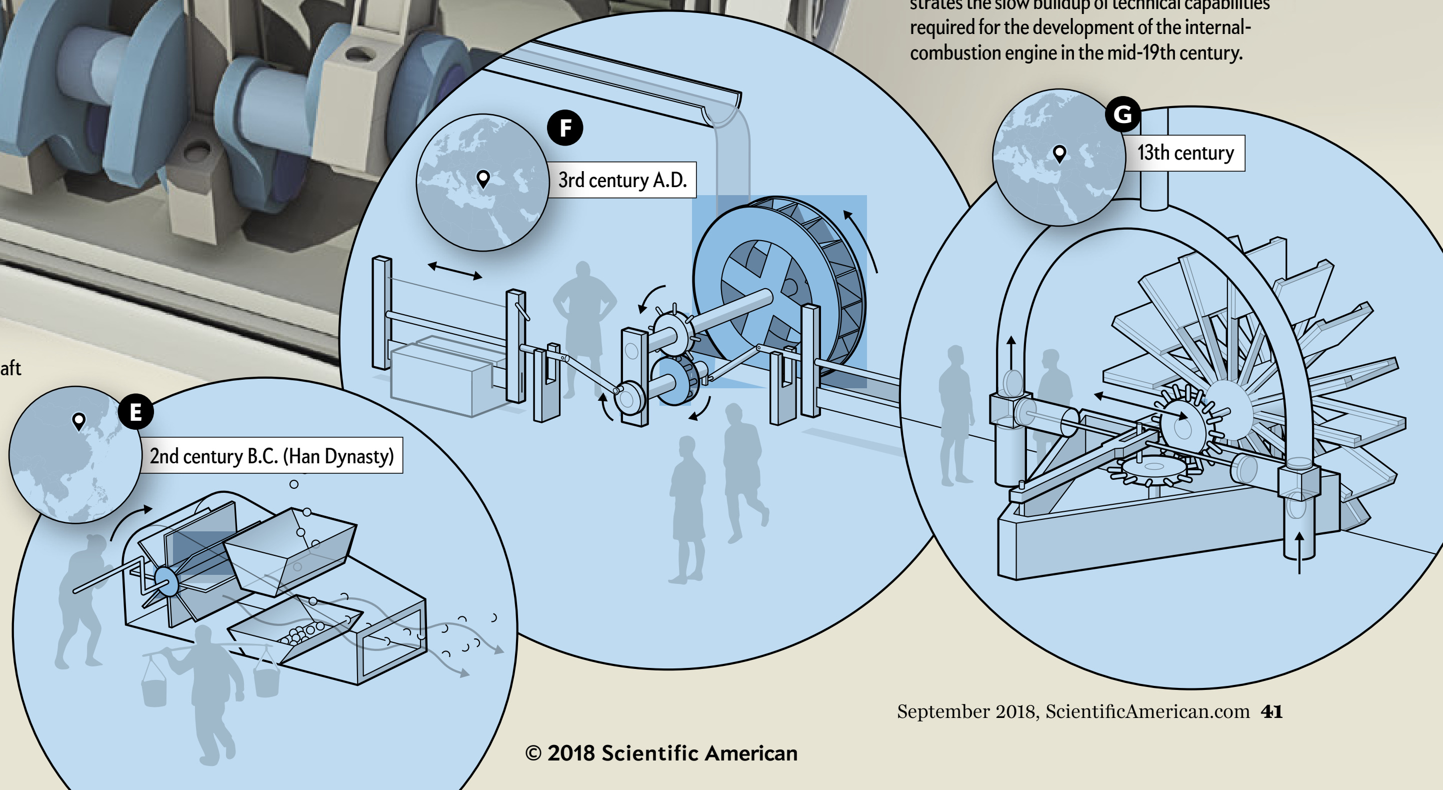
CAM

Protrusions known as cams situated on a rotating shaft drive the sequence of opening and closing of valves on engine cylinders to inject the fuel-air mixture, contain the blast and then expel the exhaust. Camshafts were used in 15th-century forges, where the power of a waterwheel repeatedly lifted and then dropped a heavy trip-hammer **C**. On a modern car engine, the camshaft has a line of cams at different angles on the shaft to operate the cylinder valves. The arrangement of cams functions as a mechanical program that physically encodes the correct sequence of valve openings. In fact, the camshaft reproduces the movements of the rotating pegged cylinder of musical automatons, such as 17th-century water organs **D**.



CRANK

The component that translates the up-and-down motion of the pistons into the rotary motion needed for transmission to the wheels is the crank. Early steam engines employed only one large cylinder and a single crank arm, but modern internal-combustion engines bring together the force of several pistons turning the same crankshaft—a spindle with several handlelike kinks along its length. The crank traces its roots back more than 2,000 years to the handles of Han Dynasty winnowing machines, whose manual turning motion created an "artificial wind" to separate grain from chaff **E**. In the third century A.D. the Hierapolis sawmill was the first to use a crank attached to a connecting rod to produce its requisite cutting motions **F**. In the 13th century polymath Ismail al-Jazari created a crankshaft accommodating twin pistons for use as a water pump **G**. Development of the crank demonstrates the slow buildup of technical capabilities required for the development of the internal-combustion engine in the mid-19th century.



TWO KEY FEATURES CREATED THE HUMAN MIND

PART 1

Why Us?

INSIDE OUR HEADS

BY THOMAS SUDDENDORF :: *ILLUSTRATION BY VICTO NGAI*

W HY ARE WE, AND NOT THE GORILLAS, RUNNING THE ZOOS? Other primates live inconspicuously in dwindling habitats, but humans have expanded and changed our surroundings to an astounding degree. Our dominance is obviously not the result of our physical ability; other animals are stronger and faster and have more acute senses. It is because of our mental abilities. Yet determining the cognitive traits that make us so special has turned out to be a devilishly complicated question to answer—one made more confusing by the frequent arrival of new studies that seem to show that animals from birds to chimpanzees can match many human cognitive skills.

Last year, to name just one example, a study published in *Science* boldly claimed that ravens can plan for the future just like humans do. Five birds learned to pick a stone and drop it into a box to get a reward. Subsequently, these ravens picked the rock from among distracting items minutes or even hours before the box was available to them. The researchers concluded from this achievement, along with a similar task in which the birds could exchange bottle tops for rewards, that the ravens were "thinking ahead" in flexible ways, an ability that is a key to human brainpower.

Yet the achievements of the ravens, as well as cognitive feats of apes in other studies, can be explained in simpler ways. It also turns out that animal and human cognition, though similar in many respects, differ in two profound dimensions. One is the ability to form nested scenarios, an inner theater of the mind that allows us to envision and mentally manipulate many possible situations and anticipate different outcomes. The second is our drive to exchange our thoughts with others. Taken together, the emergence of these two characteristics transformed the human mind and set us on a world-changing path.

BIRD BRAINS

LET US BEGIN by taking a harder look at that raven experiment. Even before the tests started, the birds had learned, over several trials, to recognize that the target item, the stone, led to rewards and that distractor items did not. So it is not really surprising that when the actual trials began, the ravens selected what had already been reinforced.

This is a good reason why scientists, before they jump to conclusions about "rich" animal capacities, need to carefully rule out more straightforward, or "lean," alternative explanations. They also need to conduct independent replications. In my laboratory, we have tried to do this by conducting studies with children that carefully limit the possibility of mistaking behavior actually driven by lean mechanisms for the products of rich cognition. We used single trials with novel tasks on our subjects to avoid giving them the learning opportunities that occur through repeated exposure. We also changed up the timing and spatial contexts of the tests to avoid cueing the children about the solution, and we concocted problems that involved the use of different skills to mitigate the effects of behavior that may result from a narrow innate predisposition.

For example, we showed the youngsters a puzzle box in one room before taking them to another room in which they were distracted with unrelated tasks. After 15 minutes, they were given the opportunity to pick one of several novel objects to take back to the first room. The three-year-olds picked randomly, but the four-year-olds tended to select the object that could later help solve the puzzle they were initially given. We have used this basic paradigm to assess the capacity for deliberate practice, which is the rehearsal of actions aimed at improving future performance [see "An Evolved Uniqueness," on page 32]. For instance, the children had the opportunity to practice catching a ball on a string with a cup in preparation for a return to the first room, where they could get a reward for success in a similar task.

IN BRIEF

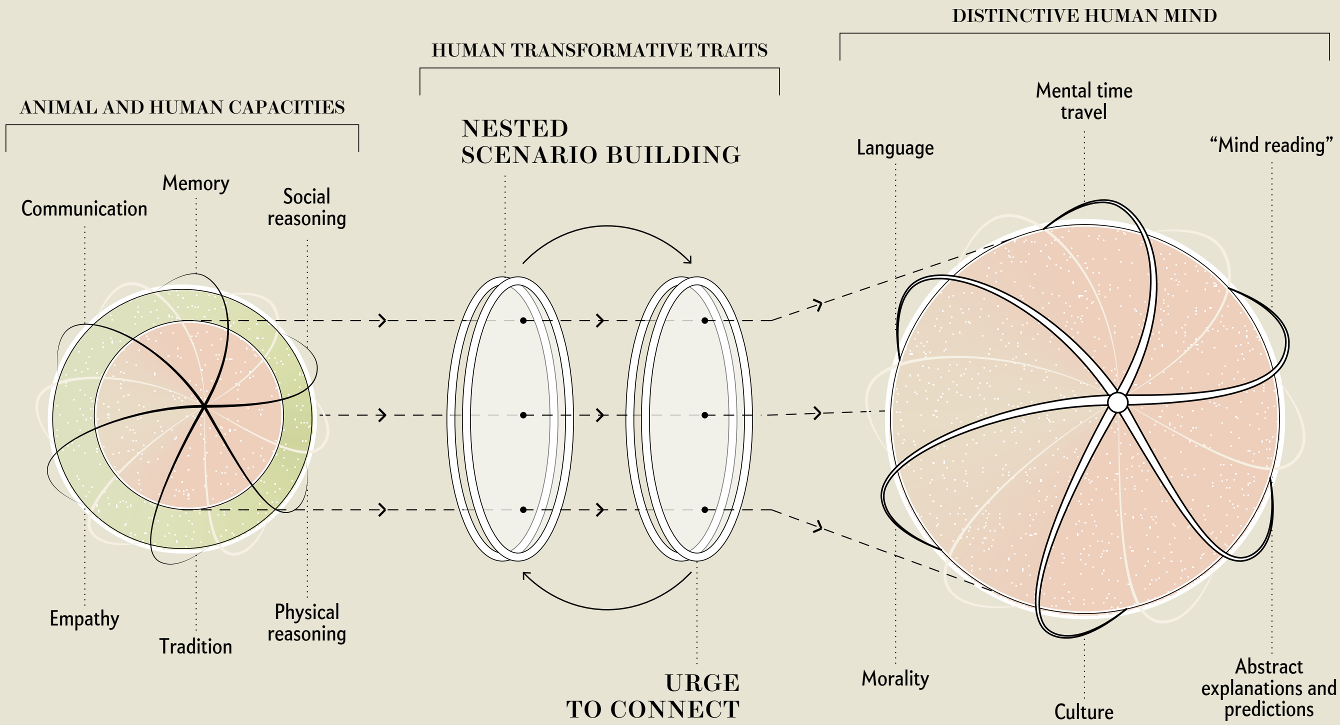
Humans clearly think differently than animals, but experiments that show *how* human cognition is unique have been hard to do.

Yet research has revealed two distinct human features: complex scenario building and exchanging thoughts with others.

Together these traits underlie critical human capacities such as language, culture, morality, foresight and even a kind of "mind reading."

Two Transformational Traits

Research in comparative psychology has identified several cognitive capacities shared by animals and humans, in domains such as communication, memory, social reasoning, physical reasoning, tradition and empathy. But two unique human features helped transform these capacities into abilities of the mind that set us apart from the animal world. One feature, nested scenario building, allows us to imagine several alternative situations, some with different outcomes, and embed them into a larger narrative of connected events. The second feature is the urge to connect, the human drive to exchange thoughts with others, enabling achievements beyond the abilities of lone individuals. These two traits amplify each other and have altered our minds, leading to human language, mental time travel, morality, culture, "mind reading" (or discerning the thoughts of others), and the capacity to develop and share abstract explanations of the world around us.



We found that the children could intentionally shape their own future abilities—they would practice the relevant skill in room two—after around age four or five but not before.

These tasks are designed to show basic capacities in areas such as foresight, and they do not map the upper limits of those abilities. When my son was four years old, for instance, we gave him a version of this task, and he succeeded. Later that day, when we were sitting on the bed back home, he put his hand on my thigh and said, "Papa, I don't want you to die." When I asked why he thought of that, he said that he would grow up, and I would become a granddad, and then I would die. He had a sophisticated capacity for envisioning the future that produced this unwelcome existential realization. Our study merely demonstrated that he had mental foresight and ruled out the leaner explanations.

The raven research and other animal studies have not met similar stringent criteria for establishing foresight, nor have they demonstrated deliberate practice. Does this mean we should conclude that animals do not have the relevant capacities at all? That would be premature. Absence of evidence is not evidence of absence, as the saying goes. Establishing competence in animals is difficult; establishing the absence of competence is even harder.

Consider the following study, in which my colleague Jon Redshaw of the University of Queensland in Australia and I tried to assess one of the most fundamental aspects of thinking about the future: the recognition that it is largely uncertain. When one realizes that events may unfold in more than one way, it makes sense to prepare for various possibilities and to make contingency plans. Human hunters demonstrate this when they lay a trap in front of all their prey's potential escape routes rather than just in front of one. Our simple test of this capacity was

Graphic by Federica Fragapane

to show a group of chimpanzees and orangutans a vertical tube and drop a reward at the top so they could catch it at the bottom. We compared the apes' performance with that of a group of human children aged two to four doing the same thing. Both groups readily anticipated that the reward would reappear at the bottom of the tube: they placed their hand under the exit to prepare for the catch.

Next, however, we made events a little harder to predict. The straight tube was replaced by an upside-down Y-shaped tube that had two exits. In preparation for the drop, the apes and the two-year-old children alike tended to cover only one of the potential exits and thus ended up catching the reward in only half of the trials. But four-year-olds immediately and consistently covered both exits with their hands, thus demonstrating the capacity to prepare for at least two mutually exclusive versions of an imminent future event. Between ages two and four, we could see this contingency planning increase in frequency. We saw no such ability among the apes.

This experiment does not prove, however, that apes and two-year-old humans have no understanding that the future can unfold in distinct ways. As I mentioned, there is a fundamental problem when it comes to showing the absence of a capacity. Perhaps the animals were not motivated, did not understand the basic task or could not coordinate two hands. Or maybe we simply tested the wrong individuals, and more competent animals might be able to pass.

To truly prove this ability is absent, a scientist would have to test all animals, at all times, on some fool-proof task. Clearly, that is not practical. All we can do is give individuals the chance to demonstrate competence. If they consistently fail, we can become more confident that they really do not have the capacity in question, but even then, future work may prove that wrong. The debates between rich and lean interpretations of animal behavior, coupled with this fundamental problem of proving that an ability is always missing, have made it difficult to establish what does and does not set humans apart.

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MIND THE GAP

DIFFICULT BUT NOT IMPOSSIBLE. In my book *The Gap: The Science of What Separates Us from Other Animals,* I surveyed the evidence for cognitive capacities most frequently assumed to be distinctly human and found that animals are smarter than widely thought. For instance, chimpanzees can solve problems through insight, console others in distress and maintain social traditions. Nevertheless, there is something profoundly distinct about human language, foresight, intelligence, culture and morality, and the ability to imagine the thoughts of another individual (we commonly speak about putting yourself in someone else's shoes). And in each of these domains, two underlying characteristics kept reemerging as making the critical human-animal difference. One is what I call "nested scenario building," which is our ability to imagine alternative situations, reflect on them and embed them into larger narratives of related events. The other is the "urge to connect," which is our deep-seated drive and capacity to exchange our thoughts with others, when we put our minds together to create something greater than what one individual can do alone.

Nested scenario building enables us to imagine other people's situations, moral conundrums or entirely fictional stories. In the context of thinking ahead, it allows us to picture potential future events, reflect on possibilities and embed them into larger stories of unfolding events. This, in turn, enables us to plan and prepare for opportunities and threats before they materialize.

Other animals, even bacteria, are attuned to long-term regularities such as day-night rhythms, and many can adjust to local patterns as well. Through associative learning, animals can predict that a reward or punishment is coming after a specific event. But people can mentally entertain situations, even entirely novel scenarios without external triggers, by combining and recombining in our mind basic elements, such as actors, actions and objects, and we can draw prudent conclusions from these mental exercises. A simple example: you can picture playing blindman's bluff on a busy street and figure out that it is a dangerous proposition even if you have never been in that situation. Nested scenario building depends on a host of sophisticated abilities working in concert, including imagination, memory, reflection and executive decision making.

Think of creating nested scenarios as an internal theater in which we can bring situations to life. Like a play, scenario building depends on certain components that have to come together. There is a "stage" to imagine events that are not actually occurring at that moment. Those events involve "actors" and their "set": individuals and objects that are linked in a narrative. We also employ capacities akin to a "director" who evaluates and manages the scenes and an "executive producer" who makes the final decisions about what to pursue. These components map onto psychological constructs such as working memory, recursive thought and executive function, features that develop at different rates during human childhood. As a result, competence at foresight emerges slowly as we mature. And as adults, we still frequently fail to anticipate future situations accurately—I most certainly do. We are not clairvoyants.

Thus, because nested scenario building is a risky way to reach decisions, humans need to pair it with that second characteristic: connecting our minds. Psychologist Michael Tomasello has described this ability as shared intentionality [see "The Origins of Morality," on page 70]. After all, the best way to find out about the future is to ask someone who has already been there, as it were.

If you really want to know what a holiday in New Zealand is like or what a career in psychology entails, you can envision all the scenarios you want, but your best bet is to ask someone who has been to that country or has pursued such a career. Human language is ideally suited for such exchanges; most of our conversations are about events displaced in time. In this way, we can learn from one another's experiences, reflections and plans. We ask questions and give advice, and we build deep bonds in the process. What is more, we can also shape the future in more deliberate ways by coordinating our actions in the pursuit of shared goals. We often do this by commenting on a companion's strategy, reviewing progress and then guiding the person to the next step.

Most of our extraordinary powers, when you think about it, derive from our collective wit. Consider that we all benefit from the tools and technologies other people invented. Many animals use tools, and some even make them, but to turn them into an innovation, one has to recognize that it will be useful again in the future. After that realization, one has a reason to retain the tool, to refine it further and to share it with others.

We can see this evolution in our inventions of increasingly effective ways to cause harm at a distance. This was probably a vital capacity for our early ancestors, who shared the land with dangerous saber-toothed cats. At first, our progenitors may have thrown rocks to drive away predators, but eventually they armed themselves with spears, then invented spear throwers, and then bows and arrows. New tools are only an advance, however, if one can use them effectively, which brings us back to deliberate practice. Chimpanzees in Senegal have been reported to make rudimentary spears that they thrust into tree hollows to kill bush babies. But there is as yet no observation that they practice thrusting, let alone throwing. Unlike humans, they could not benefit from the invention of a spear thrower. You can safely give them one of ours; they would not use it as we do.

The earliest evidence of deliberate practice is more than a million years old. The Acheulean stone tools of *Homo erectus* some 1.8 million years ago already suggest considerable foresight, as they appeared to have been carried from one place to another for repeated use. Crafting these tools requires considerable knowledge about rocks and how to work them. At some sites, such as Olorgesailie in Kenya, the ground is still littered with shaped stones, raising the question of why our ancestors kept making more tools when there were plenty lying around. The answer is that they were probably practicing how to manufacture those tools. Once they were proficient, they could wander the plains knowing they could make a new tool if the old one broke. These ancestors were armed and ready to reload.

Most animal species can be categorized as either specialists or generalists, but humans are both: we are capable of quickly adapting to local demands, even to anticipated demands, by acquiring relevant expertise. Moreover, through cooperation and division of labor, we can benefit from complementary skills, thereby enabling us to dominate most diverse habitats. We can keep even the fiercest predators in our zoos because we can foresee what they need and what they can and cannot do. So far there is no obvious evidence of other species engaging in such mental time travel nor in exchanging plots for a coordinated escape from the zoo when the conditions are right next summer.

With nested scenario building and the urge to wire their minds together, our ancestors eventually spawned civilizations and technologies that have changed the face of the earth. Science is the disciplined use of our collective wit, and we can deploy it to better understand the origin of our place in nature. We can further use it to model the future systematically and ever more clearly. By foreseeing the consequences of our actions, we are also confronted with moral choices between different options. We can predict the consequences of continuing pollution or destruction of animal habitats, inform others about them and, as the Paris climate agreement dramatically demonstrates, negotiate globally coordinated actions aimed at more desirable outcomes.

None of this is an excuse for arrogance. It is, in fact, a call for care. We are the only creatures on this planet with these abilities. As Spider-Man's Uncle Ben declared, communicating complex ideas in an urge to connect with his superhero nephew, "With great power comes great responsibility." SA

MORE TO EXPLORE

The Gap: The Science of What Separates Us from Other Animals. Thomas Suddendorf. Basic Books, 2013.

A Natural History of Human Thinking. Michael Tomasello. Harvard University Press, 2014.

Flexible Planning in Ravens? Jonathan Redshaw, Alex H. Taylor and Thomas Suddendorf in *Trends in Cognitive Sciences,* Vol. 21, No. 11, pages 821–822; November 2017.

Prospection and Natural Selection. T. Suddendorf, A. Bulley and B. Miloyan in *Current Opinion in Behavioral Sciences,* Vol. 24, pages 26–31; December 2018.

FROM OUR ARCHIVES

If I Had a Hammer. Ian Tattersall; September 2014.

scientificamerican.com/magazine/sa

DECODING THE PUZZLE OF HUMAN CONSCIOUSNESS

PART 1

Why Us?

THE HARDEST PROBLEM

BY SUSAN BLACKMORE :: *ILLUSTRATION BY VICTO NGAI*

MIGHT WE HUMANS BE THE ONLY SPECIES ON THIS PLANET TO BE truly conscious? Might lobsters and lions, beetles and bats be unconscious automata, responding to their worlds with no hint of conscious experience? Aristotle thought so, claiming that humans have rational souls but that other animals have only the instincts needed to survive. In medieval Christianity the "great chain of being" placed humans on a level above soulless animals and below only God and the angels. And in the 17th century French philosopher René Descartes argued that other animals have only reflex behaviors. Yet the more biology we learn, the more obvious it is that we share not only anatomy, physiology and genetics with other animals but also systems of vision, hearing, memory and emotional expression. Could it really be that we alone have an extra special something—this marvelous inner world of subjective experience?

IN BRIEF

Physiological and behavioral evidence indicates that humans are fundamentally similar to many other animals in their responses to painful and pleasurable stimuli.

Even so, scientists disagree on whether other creatures are conscious or can suffer.

Whether consciousness serves an evolutionary purpose and when it might have evolved are also hotly debated.

In fact, scholars dispute virtually every aspect of consciousness. Some contend that it can be measured, whereas others believe it is an illusion.

The question is hard because although your own consciousness may seem the most obvious thing in the world, it is perhaps the hardest to study. We do not even have a clear definition beyond appealing to a famous question asked by philosopher Thomas Nagel back in 1974: What is it like to be a bat? Nagel chose bats because they live such very different lives from our own. We may try to imagine what it is like to sleep upside down or to navigate the world using sonar, but does it feel like anything at all? The crux here is this: If there is nothing it is like to be a bat, we can say it is not conscious. If there is something (anything) it is like for the bat, it is conscious. So is there?

We share a lot with bats: we, too, have ears and can imagine our arms as wings. But try to imagine being an octopus. You have eight curly, grippy, sensitive arms for getting around and catching prey but no skeleton, and so you can squeeze yourself through tiny spaces. Only a third of your neurons are in a central brain; the rest are in the nerve cords in each of your eight arms, one for each arm. Consider: Is it like something to be a whole octopus, to be its central brain or to be a single octopus arm? The science of consciousness provides no easy way of finding out.

Even worse is the "hard problem" of consciousness: How does subjective experience arise from objective brain activity? How can physical neurons, with all their chemical and electrical communications, create the feeling of pain, the glorious red of the sunset or the taste of fine claret? This is a problem of dualism: How can mind arise from matter? Indeed, does it?

The answer to this question divides consciousness researchers down the middle. On one side is the "B Team," as philosopher Daniel C. Dennett described them in a heated debate. Members of this group agonize about the hard problem and believe in the possibility of the philosopher's "zombie," an imagined creature that is indistinguishable from you or me but has no consciousness. Believing in zombies means that other animals might conceivably be seeing, hearing, eating and mating "all in the dark" with no subjective experience at all. If that is so, consciousness must be a special additional capacity that we might have evolved either with or without and, many would say, are lucky to have.

On the other side is the A Team: scholars who reject the possibility of zombies and think the hard problem is, to quote philosopher Patricia Churchland, a "hornswoggle problem" that obfuscates the issue. Either consciousness just *is* the activity of bodies and brains, or it inevitably comes along with everything we so obviously share with other animals. In the A team's view, there is no point in asking when or why "consciousness itself" evolved or what its function is because "consciousness itself" does not exist.

WHAT IS IT LIKE TO BE A BAT? If it feels like something to be such a creature (in this case, a Geoffroy's tailless bat), then it is conscious.

NICOLAS REUSENS *Getty Images*

SUFFERING

WHY DOES IT MATTER? One reason is suffering. When I accidentally stamped on my cat's tail and she screeched and shot out of the room, I was sure I had hurt her. Yet behavior can be misleading. We could easily place pressure sensors in the tail of a robotic cat to activate a screech when stepped on—and we would not think it suffered pain. Many people become vegetarians because of the way farm animals are treated, but are those poor cows and pigs pining for the great outdoors? Are battery hens suffering horribly in their tiny cages? Behavioral experiments show that although hens enjoy scratching about in litter and will choose a cage with litter if access is easy, they will not bother to push aside a heavy curtain to get to it. So do they not much care? Lobsters make a terrible screaming noise when boiled alive, but could this just be air being forced out of their shells?

When lobsters or crabs are injured, are taken out of water or have a claw twisted off, they release stress hormones similar to cortisol and corticosterone. This response provides a physiological reason to believe they suffer. An even more telling demonstration is that when injured prawns limp and rub their wounds, this behavior can be reduced by giving them the same painkillers as would reduce our own pain.

The same is true of fish. When experimenters injected the lips of rainbow trout with acetic acid, the fish rocked from side to side and rubbed their lips on the sides of their tank and on gravel, but giving them morphine reduced these reactions. When zebra fish were given a choice between a tank with gravel and plants and a barren one, they chose the interesting tank. But if they were injected with acid and the barren tank contained a painkiller, they swam to the barren tank instead. Fish pain may be simpler or in other ways different from ours, but these experiments suggest they do feel pain.

Some people remain unconvinced. Australian biologist Brian Key argues that fish may respond as though they are in pain, but this observation does not prove they are consciously feeling anything. Noxious stimuli, he asserted in the open-access journal *Animal Sentience,* "don't feel like anything to a fish." Human consciousness, he argues, relies on signal amplification and global integration, and fish lack the neural architecture that makes these connections possible. In effect, Key rejects all the behavioral and physiological evidence, relying on anatomy alone to uphold the uniqueness of humans.

A WORLD OF DIFFERENT BRAINS

IF SUCH STUDIES CANNOT RESOLVE THE ISSUE, perhaps comparing brains might help. Could humans be uniquely conscious because of their large brains? British pharmacologist Susan Greenfield proposes that consciousness increases with brain size across the animal kingdom. But if she is right, then African elephants and grizzly bears are more conscious than you are, and Great Danes and Dalmatians are more conscious than Pekinese and Pomeranians, which makes no sense.

More relevant than size may be aspects of brain organization and function that scientists think are indicators of consciousness. Almost all mammals and most other animals—including many fish and reptiles and some insects—alternate between waking and sleeping or at least have strong circadian rhythms of activity and responsiveness. Specific brain areas, such as the lower brain stem in mammals, control these states. In the sense of being awake, therefore, most animals are conscious. Still, this is not the same as asking whether they have conscious content: whether there is something it is like to be an awake slug or a lively lizard.

Susan Blackmore is a psychologist and a visiting professor at the University of Plymouth in England. She has authored many books, most famously *The Meme Machine* (Oxford University Press, 2000).

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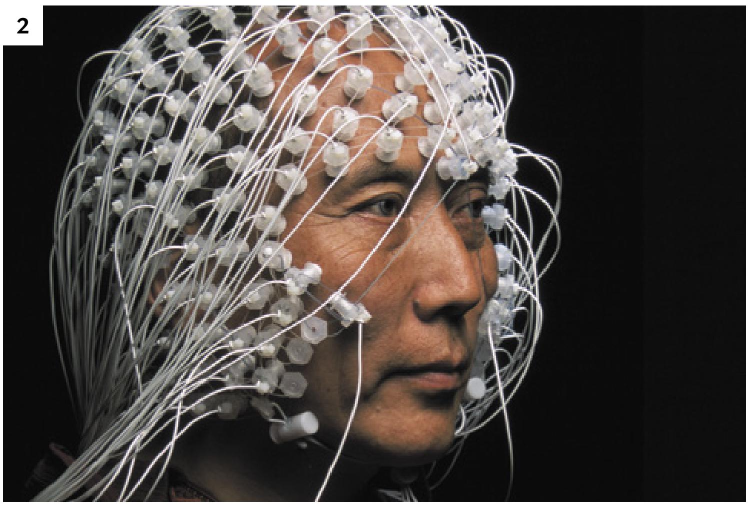


OCTOPUS (*1*) at Munich Zoo Hellabrunn in Germany opens a jar of tasty crabs. Only a third of its neurons are in its central brain, the rest being distributed in its arms. If it is conscious, where does that awareness reside? Sensors on the skull of a meditating monk (*2*) detect his brain activity, but how it creates his state of mind remains a mystery.

Many scientists, including Francis Crick and, more recently, British neuroscientist Anil Seth, have argued that human consciousness involves widespread, relatively fast, low-amplitude interactions between the thalamus, a sensory way station in the core of the brain, and the cortex, the gray matter at the brain's surface. These "thalamocortical loops," they claim, help to integrate information across the brain and thereby underlie consciousness. If this is correct, finding these features in other species should indicate consciousness. Seth concludes that because other mammals share these structures, they are therefore conscious. Yet many other animals do not: lobsters and prawns have no cortex or thalamocortical loops, for example. Perhaps we need more specific theories of consciousness to find the critical features.

Among the most popular is global workspace theory (GWT), originally proposed by American neuroscientist Bernard Baars. The idea is that human brains are structured around a workspace, something like working memory. Any mental content that makes it into the workspace, or onto the brightly lit "stage" in the theater of the mind, is then broadcast to the rest of the unconscious brain. This global broadcast is what makes individuals conscious.

This theory implies that animals with no brain, such as starfish, sea urchins and jellyfish, could not be conscious at all. Nor could those with brains that lack the right global workspace architecture, including fish, octopuses and many other animals. Yet, as we have already explored, a body of behavioral evidence implies that they are conscious.

Integrated information theory (IIT), originally proposed by neuroscientist Giulio Tononi, is a mathematically based theory that defines a quantity called Φ (pronounced "phi"), a measure of the extent to which information in a system is both differentiated into parts and unified into a whole. Various ways of measuring Φ lead to the conclusion that large and complex brains like ours have high Φ, deriving from amplification and integration of neural activity widely across the brain. Simpler systems have lower Φ, with differences also arising from the specific organization found in different species. Unlike global workspace theory, IIT implies that consciousness might exist in simple forms in the lowliest creatures, as well as in appropriately organized machines with high Φ.

Both these theories are currently considered contenders for a true theory of consciousness and ought to help us answer our question. But when it comes to animal consciousness, their answers clearly conflict.

THE EVOLVING MIND

THUS, OUR BEHAVIORAL, physiological and anatomical studies all give mutually contradictory answers, as do the two most popular theories of consciousness. Might it help to explore how, why and when consciousness evolved?

Here again we meet that gulf between the two groups of researchers. Those in the B Team assume

ALAMY (1); CARY WOLINSKY *Getty Images* (2) that because we are obviously conscious, consciousness must have a function such as directing behavior or saving us from predators. Yet their guesses as to when consciousness arose range from billions of years ago right up to historical times.

For example, psychiatrist and neurologist Todd Feinberg and biologist Jon Mallatt proffer, without giving compelling evidence, an opaque theory of consciousness involving "nested and nonnested" neural architectures and specific types of mental images. These, they claim, are found in animals from 560 million to 520 million years ago. Baars, the author of global workspace theory, ties the emergence of consciousness to that of the mammalian brain around 200 million years ago. British archaeologist Steven Mithen points to the cultural explosion that started 60,000 years ago when, he contends, separate skills came together in a previously divided brain. Psychologist Julian Jaynes agrees that a previously divided brain became unified but claims this happened much later. Finding no evidence of words for consciousness in the Greek epic the *Iliad,* he concludes that the Greeks were not conscious of their own thoughts in the same way that we are, instead attributing their inner voices to the gods. Therefore, Jayne argues, until 3,000 years ago people had no subjective experiences.

Are any of these ideas correct? They are all mistaken, claim those in the A Team, because consciousness has no independent function or origin: it is not that kind of thing. Team members include "eliminative materialists" such as Patricia and Paul Churchland, who maintain that consciousness just *is* the firing of neurons and that one day we will come to accept this just as we accept that light just *is* electromagnetic radiation. IIT also denies a separate function for consciousness because any system with sufficiently high Φ must inevitably be conscious. Neither of these theories makes human consciousness unique, but one final idea might.

This is the well-known, though much misunderstood, claim that consciousness is an illusion. This approach does not deny the existence of subjective experience but claims that neither consciousness nor the self are what they seem to be. Illusionist theories include psychologist Nicholas Humphrey's idea of a "magical mystery show" being staged inside our heads. The brain concocts out of our ongoing experiences, he posits, a story that serves an evolutionary purpose in that it gives us a reason for living. Then there is neuroscientist Michael Graziano's attention schema theory, in which the brain builds a simplified model of how and to what it is paying attention. This idea, when linked to a model of self, allows the brain—or indeed any machine—to describe itself as having conscious experiences.

By far the best-known illusionist hypothesis, however, is Dennett's "multiple drafts theory": brains are massively parallel systems with no central theater in which "I" sit viewing and controlling the world. Instead multiple drafts of perceptions and thoughts are continually processed, and none is either conscious or unconscious until the system is probed and elicits a response. Only then do we say the thought or action was conscious; thus, consciousness is an attribution we make after the fact. He relates this to the theory of memes. (A meme is information copied from person to person, including words, stories, technologies, fashions and customs.) Because humans are capable of widespread generalized imitation, we alone can copy, vary and select among memes, giving rise to language and culture. "Human consciousness is *itself* a huge complex of memes," Dennett wrote in *Consciousness Explained,* and the self is a "'benign user illusion."

More relevant than size may be aspects of brain organization and function that scientists think are indicators of consciousness.

This illusory self, this complex of memes, is what I call the "selfplex." An illusion that we are a powerful self that has consciousness and free will—which may not be so benign. Paradoxically, it may be our unique capacity for language, autobiographical memory and the false sense of being a continuing self that serves to increase our suffering. Whereas other species may feel pain, they cannot make it worse by crying, "How long will this pain last? Will it get worse? Why me? Why now?" In this sense, our suffering may be unique. For illusionists such as myself, the answer to our question is simple and obvious. We humans are unique because we alone are clever enough to be deluded into believing that there is a conscious "I." ■

MORE TO EXPLORE

The Character of Consciousness. David J. Chalmers. Oxford University Press, 2010.
Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts. Stanislas Dehaene. Viking, 2014.
From Bacteria to Bach and Back: The Evolution of Minds. Daniel C. Dennett. W. W. Norton, 2017.
Consciousness: An Introduction. Third edition. Susan Blackmore and Emily T. Troscianko. Routledge, 2018.

FROM OUR ARCHIVES

What Is Consciousness? Christof Koch; June 2018.

scientificamerican.com/magazine/sa

WHAT MAKES LANGUAGE DISTINCTLY HUMAN

PART 1

Why Us?

TALKING THROUGH TIME

BY CHRISTINE KENNEALLY :: *ILLUSTRATION BY VICTO NGAI*

DOLPHINS NAME ONE ANOTHER, AND THEY CLICK AND WHISTLE ABOUT their lives or the dangers posed by sharks and humans. They also pass on useful bits of know-how from mother to child, such as how to catch fish or how to flee. If they had language in the same sense that we do, however, they would not only pass down little bits of information but also aggregate them into a broad body of knowledge about the world. Over the span of generations clever practices, complex knowledge and technology based on two, three or several components would develop. Dolphins would have history—and with history, they would learn about the journeys and ideas of other dolphin groups, and any one individual could inherit a fragment of language, say, a story or poem, from another individual who had lived hundreds of years before. That dolphin would be touched, through language, by the wisdom of another dolphin, who was in every other way long gone.

IN BRIEF

Human communication is far more structured and complex than the gestures and sounds of other animals.

Scientists have, however, failed to find distinctive physiological, neurological or genetic traits that could explain the uniqueness of human language.

Language appears instead to arise from a platform of abilities, some of which are shared with other animals.

Intriguingly, the intricacy of human language may arise from culture: the repeated transmission of speech through many generations.

Only humans can perform this spectacular time-traveling feat, just as only humans can penetrate the stratosphere or bake strawberry shortcake. Because we have language, we have modern technology, culture, art and scientific inquiry. We have the ability to ask questions such as, Why is language unique to humans? Despite the accumulated genius we inherit when we learn to speak or sign, we have yet to work out a good answer. But a diverse group of brain scientists, linguists, animal researchers and geneticists are tackling the question—so we are much closer to a real understanding than ever before.

AN UNANSWERABLE QUESTION

THAT LANGUAGE is uniquely human has been assumed for a long time. But trying to work out exactly how and why that is the case has been weirdly taboo. In the 1860s the Société de Linguistique de Paris banned discussion about the evolution of language, and the Philological Society of London banned it in the 1870s. They may have wanted to clamp down on unscientific speculation, or perhaps it was a political move—either way, more than a century's worth of nervousness about the subject followed. Noam Chomsky, the extraordinarily influential linguist at the Massachusetts Institute of Technology, was, for decades, rather famously disinterested in language evolution, and his attitude had a chilling effect on the field. Attending an undergraduate linguistics class in Melbourne, Australia, in the early 1990s, I asked my lecturer how language evolved. I was told that linguists did not ask the question, because it was not really possible to answer it.

Luckily, just a few years later, scholars from different disciplines began to grapple with the question in earnest. The early days of serious research in language evolution unearthed a perplexing paradox: Language is plainly, obviously, uniquely human. It consists of wildly complicated interconnecting sets of rules for combining sounds and words and sentences to create meaning. If other animals had a system that was the same, we would likely recognize it. The problem is that after looking for a considerable amount of time and with a wide range of methodological approaches, we cannot seem to find anything unique in ourselves—either in the human genome or in the human brain—that explains language.

To be sure, we have found biological features that are both unique to humans and important for language. For example, humans are the only primates to have voluntary control of their larynx: it puts us at risk of choking, but it allows us to articulate speech. But the equipment that seems to be designed for language never fully explains its enormous complexity and utility.

It seems more and more that the paradox is not inherent in language but in how we look at it. For a long time we have been in love with the idea of a sudden, explosive transformation that changed mere apes into us. The idea of metamorphosis has gone hand in hand with a list of equally dramatic ideas. For example: that language is a wholly discrete trait that has little in common with other kinds of mental activity; that language is the evolutionary adaptation that changed everything; and that language is wired into humanity's DNA. We have looked for a critical biological event that brought complex language into existence around 50,000 years ago.

Findings from genetics, cognitive science and brain sciences are now converging in a different place. It looks like language is not a brilliant adaptation. Nor is it encoded in the human genome or the inevitable output of our superior human brains. Instead language grows out of a platform of abilities, some of which are very ancient and shared with other animals and only some of which are more modern.

TALKING TO THE ANIMALS

ANIMAL RESEARCHERS were the first to challenge the definition of language as a discretely human attribute. As comparative psychologist Heidi Lyn has pointed out, the only way we can truly determine what is unique to human language is to explore the capacities of other animals. Interestingly, almost every time researchers have proposed that humans can do something that other animals cannot because humans have language, studies have shown that some animals can do some of those things, at least some of the time.

Take gestures, for example. Some are individual, but many are common to our language community and even to all humans. It is clear that language evolved as part of a communication system in which gesture also plays a role. But landmark work has shown that chimpanzees gesture in meaningful ways, too. Michael Tomasello, now emeritus at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, and his colleagues have shown that all species of great apes will wait until they have another ape's attention before they signal, and they repeat gestures that do not get the response they want. Chimpanzees slap the ground or clap their hands to get attention—and just as a belligerent human might raise a fist, they roll their arms over their head (normally a prelude to an attack) as a warning to rivals.

Even so, Tomasello's laboratory found that apes were very poor at understanding a human pointing gesture that conveyed information, such as, for example, the location of a hidden object. Does pointing—or rather the ability to fully understand it—represent a critical step in the evolution of language? The claim struck Lyn, who worked with bonobos that are now at the Ape Cognition and Conservation Initiative, as absurd. "My apes understood when I pointed to things all the time," she says. But when she set up pointing experiments with chimpanzees at the Yerkes National Primate Research Center at Emory University, she was surprised to find that the apes there did not understand her pointing well at all. Then she went back to the bonobos in her lab and tested them. All of them did.

The difference between the pointing apes and the nonpointing apes had nothing to do with biology, Lyn concluded. The bonobos had been taught to communicate with humans using simple visual symbols; the chimpanzees had not. "It's apes that haven't been around humans in the same way that can't follow pointing," she explains.

The fact that the bonobos were taught by humans has been used to dismiss their ability, according to Lyn, as if they were somehow tainted. Language research with parrots and dolphins and other animals has been discounted for the same reason. But Lyn argues that animals trained by humans provide valuable insights. If creatures with different brains and different bodies can learn some humanlike communicative skills, it means that language should not be defined as wholly human and disconnected from the rest of the animal world. Moreover, whereas language may be affected by biology, it is not necessarily determined by it. With the bonobos, it was culture, not biology, that made the critical difference.

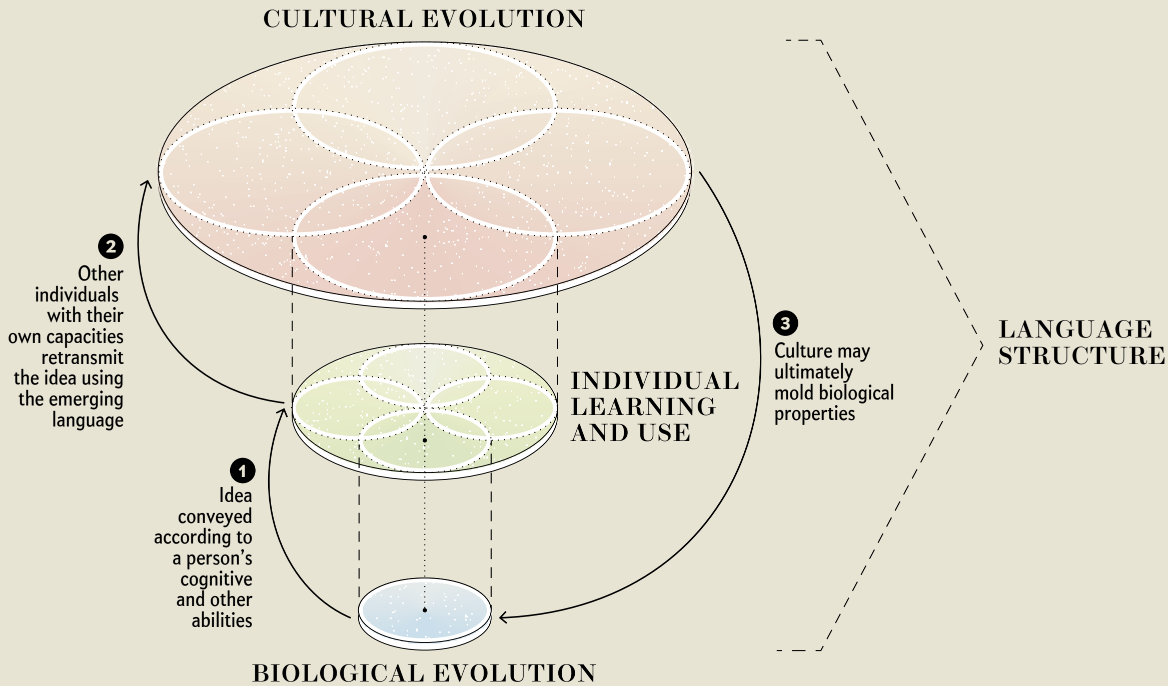
ALEX, a celebrated African grey parrot, could recognize and name some 100 different objects, along with their color, texture and shape, as well as convey his desires and intentions by means of sentences such as "Wanna go back." Chimpanzees can also be taught to use human language.

GETTY IMAGES

Christine Kenneally is an award-winning science journalist and author of two books, most recently *The Invisible History of the Human Race* (Viking, 2014).

Evolution of Language

Languages have complex structures, which enable, say, English speakers to guess what "blue giraffe" might mean even if they have never before encountered that particular combination of words. Extensive studies by Simon Kirby of the University of Edinburgh and other linguists suggest that language structure derives from repeatedly using words to convey ideas through many generations. In a circular process repeated innumerable times, one speaker, or agent, passes a concept on to others ❶ via whatever string of words she or he has thus far learned. The ability to transmit an idea coherently depends on cognitive capacities inherited from parents. The recipients of this utterance understand it as best they can and convey it to others ❷ within the community, along with their own modifications. These changes accumulate over generations in the culture. Someone who can better master the emerging discourse of the community is assumed to be more likely to pass on his or her genes. Therefore, with time the accumulated cultural refinements may influence biological properties ❸. Amazingly, from this babel eventually emerges order, as the speakers, all trying to learn the language as best they can, converge on a single, structured language that is both learnable and useful for conveying information. In sum, language in all its complexity emerges from culture.



GENETIC CODE

THE LIST OF ABILITIES that were formerly thought to be a unique part of human language is actually quite long. It includes parts of language, such as words. Vervet monkeys use wordlike alarm calls to signal a specific kind of danger. Another crucial aspect is structure. Because we have syntax, we can produce an infinite number of novel sentences and meanings, and we can understand sentences that we have never heard before. Yet zebra finches have complicated structure in their songs, dolphins can understand differences in word order and even some monkeys in the wild seem to use one type of call to modify another. The list extends to types of cognition, such as theory of mind, which is the ability to infer others' mental states. Dolphins and chimpanzees are excellent at guessing what an interlocutor wants. Even the supposedly unique ability to think about numbers falls by the wayside—bees can understand the concept of zero, bees and rhesus monkeys can count to four, and cormorants used for fishing in China reportedly count to seven.

The list includes genes. The famous *FOXP2* gene, once called a language gene, is indeed a gene that affects language—when it is mutated, it disrupts articulation—but it performs other roles as well. There is no easy way to tease out the different effects. Genes are critical for understanding how language evolved, says Simon Fisher, a geneticist at the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands, but "we have to think about what genes do." To put an incredibly complex process very briefly: genes code for proteins, which then affect cells, which may be brain cells that form neural circuits, and it is those circuits that are then responsible for behavior. "It may be that there is a network of genes that are important for syntactic processing or speaking proficiently," Fisher explains, "but there won't be a single gene that can magically code for a suite of abilities."

The list of no-longer-completely-unique human traits includes brain mechanisms, too. We are learn-

SOURCE: "CULTURE AND BIOLOGY IN THE ORIGINS OF LINGUISTIC STRUCTURE," BY SIMON KIRBY, IN *PSYCHONOMIC BULLETIN & REVIEW*, VOL. 24, NO. 1; FEBRUARY 2017

Graphic by Federica Fragapane

ing that neural circuits can develop multiple uses. One recent study showed that some neural circuits that underlie language learning may also be used for remembering lists or acquiring complicated skills, such as learning how to drive. Sure enough, the animal versions of the same circuits are used to solve similar problems, such as, in rats, navigating a maze.

Michael Arbib, a cognitive neuroscientist at the University of California, San Diego, notes that humans have created "a material and mental world of ever increasing complexity"—and yet whether a child is born into a world with the steam train or one with the iPhone, he or she can master some part of it without alterations in biology. "As far as we know," Arbib says, "the only type of brain on earth that can do that is the human brain." He emphasizes, however, that the brain is just one part of a complex system, which includes the body: "If dolphins had hands, maybe they could have evolved that world."

Indeed, making sense of the human world requires not only the brain in the body but also a group of brains interacting as part of the human social world. Arbib refers to this as an EvoDevoSocio approach. Biological evolution influences the development and learning of individuals, and individual learning shapes the evolution of culture; learning, in turn, can be shaped by culture. To understand language, the human brain has to be considered a part of those systems. The evolution of language was polycausal, Arbib says. No one switch was thrown: there were lots of switches. And it did not happen all at once but took a great deal of time.

CULTURAL REVOLUTION

CULTURE ALSO PLAYS A CRITICAL ROLE for Simon Kirby, a cognitive scientist who runs the Center for Language Evolution at the University of Edinburgh. From the beginning, Kirby was fascinated by the idea that not only is language something that we learn from others, but it is something that is passed down through generations of learners. What impact did the repeated act of learning have on language itself?

Kirby set out to test the question by fashioning a completely new method of exploring language evolution. Instead of looking at animals or humans, he built digital models of speakers, called agents, and fed them messy, random strings of language. His artificially intelligent agents had to learn the language from other agents, but then they had to teach other agents the language as well. Then Kirby rolled over generations of learners and teachers to see how the language might change. He likened the task to the telephone game, where a message is passed on from one person to the next and so on, with the final message often ending up quite different from the original.

Kirby found that his digital agents had a tendency to produce more structure in their output than they had received in their input. Even though the strings of language he initially gave them were random, sometimes by chance a string might appear to be slightly ordered. Critically, the agents picked up on that structure, and they generalized it. "The learners, if you like, hallucinated structure in their input," Kirby says. Having seen structure where there was none, the agents then reproduced more structure in what they said.

The changes might be very tiny, Kirby notes, but over the generations "the process snowballs." Excitingly, not only did the agents' language begin to look more and more structured after many generations, the kind of structure that emerged looked like a simple version of that which occurs in natural human language. Subsequently Kirby tried a variety of different models and gave them different kinds of data, but he found that "the cumulative accretion of linguistic structure seemed to always happen no matter how we built the models." It was the crucible of learning over and over again that created the language itself.

Now Kirby is re-creating his digital experiments in real life with humans and even animals by getting them to repeat things that they learn. He is finding that structure indeed evolves in this way. One of the more thrilling implications of this discovery is how it helps to explain why we can never pin down the right single gene or mutation or brain circuit to explain language: it is just not there. Language seems to emerge out of a combination of biology, individual learning and the transmission of language from one individual to another. The three systems run at entirely different timescales, but when they interlock, something extraordinary happens: language is born.

In the short time since the field of language evolution has been active, researchers may have not reached the holy grail: a definitive event that explains language. But their work makes that quest somewhat beside the point. To be sure, language is probably the most unique biological trait on the planet. But it is much more fragile, fluky and contingent than anyone might have predicted. SA

MORE TO EXPLORE

The First Word: The Search for the Origins of Language. Christine Kenneally. Viking, 2007.
How the Brain Got Language: The Mirror System Hypothesis. Michael A. Arbib. Oxford University Press, 2012.
Culture and Biology in the Origins of Linguistic Structure. Simon Kirby in *Psychonomic Bulletin & Review,* Vol. 24, No. 1, pages 118–137; February 2017.
The Question of Capacity: Why Enculturated and Trained Animals Have Much to Tell Us about the Evolution of Language. Heidi Lyn in *Psychonomic Bulletin & Review,* Vol. 24, No. 1, pages 85–90; February 2017.

FROM OUR ARCHIVES

Language in a New Key. Paul Ibbotson and Michael Tomasello; November 2016.

scientificamerican.com/magazine/sa

ARE WE WIRED DIFFERENTLY?

PARTS OF THE BRAIN INVOLVED IN LANGUAGE AND COGNITION HAVE ENLARGED GREATLY OVER AN EVOLUTIONARY TIMESCALE

BY CHET C. SHERWOOD

GRAPHICS BY MESA SCHUMACHER

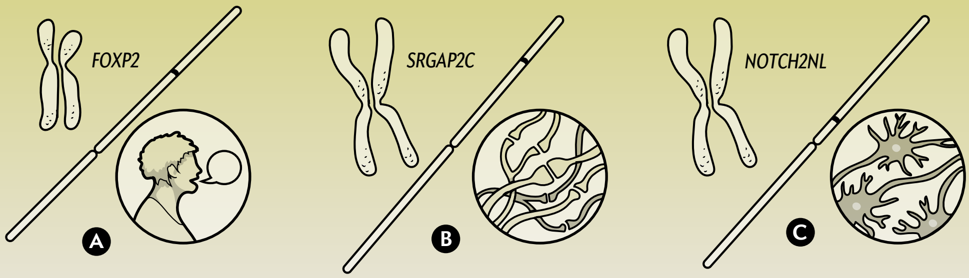
HUMANS ARE OFF THE SCALE. Modern human brains are about threefold larger than those of our earliest hominin ancestors and living great ape relatives. Across animals, brain size is tightly correlated with body size. But humans are the extreme outlier when gauged against this typical scaling relation. The average adult human brain is roughly three pounds, which is approximately 2 percent of body size. But it consumes an outsized 20 percent of the body's energy budget because of high levels of electrical activity by neurons and the metabolic fuel it takes to transmit chemical signals from one brain cell to the next.

Chet C. Sherwood is a professor of anthropology at the George Washington University. His work focuses on brain evolution in primates and other mammals.

Detailed comparisons of human brains with those of our close living primate relatives, including chimpanzees, have shown that the parts of the cerebral cortex involved in higher-order cognitive functions, such as creativity and abstract thinking, have become especially enlarged. These cortical areas, known as association regions, mature relatively late in postnatal development. Some of the long-range neural connections that link these association areas to one another and to the cerebellum (the latter plays a role in voluntary movement and learning new skills) are more numerous in human brains as compared with other primates. These human-enhanced networks are loci for language, toolmaking and imitation. Even ancient reward systems in a subcortical area called the striatum, a hub of activity for the brain-signaling molecule dopamine, appear to have been reshaped in human brain evolution. That change most likely increases attention to social signals and facilitates language learning.

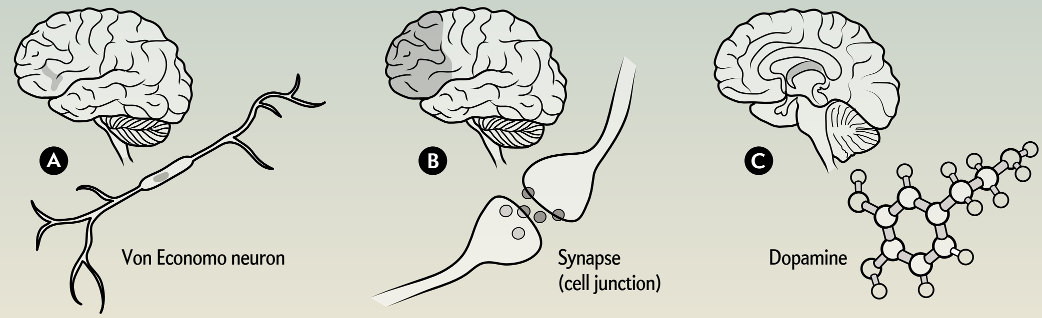
Where did our big brains come from? The hominin fossil record points to a general trend toward increased cranial capacity during the past six million years or so. That is when our lineage split from the last common ancestor we shared with chimpanzees and bonobos. Scientists consider a constellation of interrelated features of human biology to be associated with our large brains—slower growth through the stages of childhood, a longer life span, and more involvement in raising offspring by fathers and grandparents to assist mothers. Extended brain growth after birth means that significant events that lay the groundwork for cognition take place in a rich social and ecological context.

Another clue to what makes us different from chimpanzees and other intelligent species comes from compelling research that has uncovered genetic and molecular changes that occurred during the long course of the brain's evolution. A look at some of the distinctive features of the human brain follows.



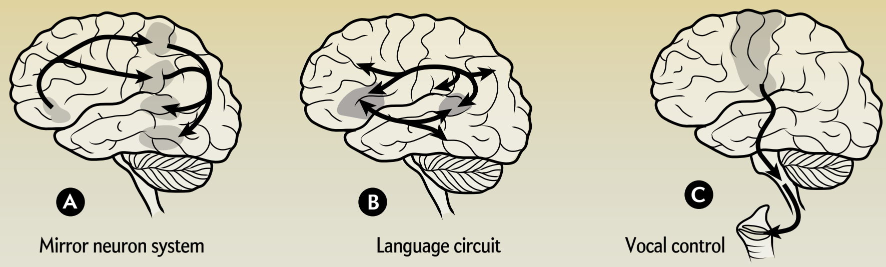
GENES

The variant of the *FOXP2* gene found in humans plays a role in vocal learning **A**. *SRGAP2C*, a unique duplicate of *SRGAP2* that is found only in humans, increases the density of neural connections **B**. A human version of a gene called *NOTCH*, known as *NOTCH2NL*, has three copies and aids in the production of neurons **C**.



CELLS

Von Economo neurons, which are pivotal in social-emotional brain circuits, are bigger in humans **A**. RNA that carries messages to instruct cells to make proteins is more active in the synapses of the prefrontal cortex (*dark area*) than it is in other primates **B**. Cells produce more of the neurotransmitter dopamine in the striatum. Dopamine is involved in various cognitive functions **C**.

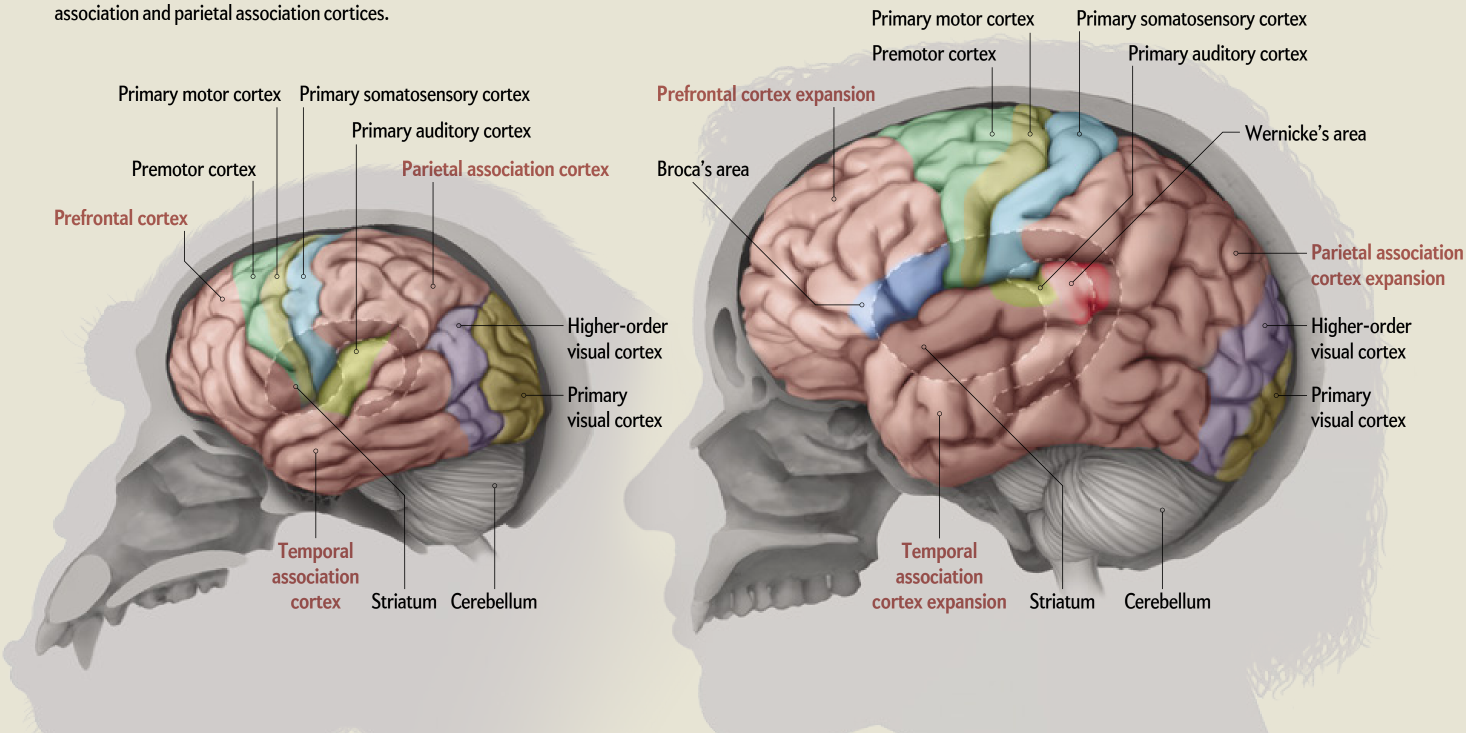


CIRCUITS

The mirror neuron system, activated when viewing the actions of others, has intricate circuitry in humans **A**. Expanded connections between two sites—Wernicke's and Broca's areas—form a vital circuit for language processing **B**. A link from the motor cortex to the brain stem coordinates the larynx muscles, a circuit absent in chimpanzees and macaques **C**.

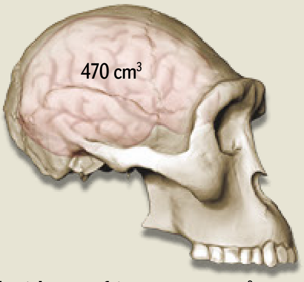
REGIONAL EXPANSION

Brain areas responsible for higher cognitive functions grew disproportionately in humans compared with the same regions in chimpanzees—among them, the prefrontal, temporal association and parietal association cortices.



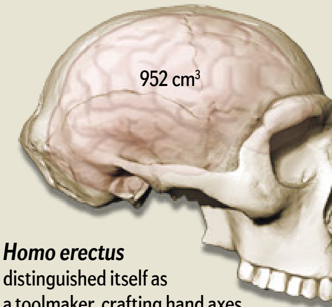
BIG BRAINS GOT US HERE

The last common ancestor that humans shared with chimpanzees and bonobos lived from six million to eight million years ago. After the two lines split, a number of evolutionary adaptations occurred: bipedalism, stone toolmaking and, notably, an increase in brain size in certain hominin species—a process that gained momentum as time passed.



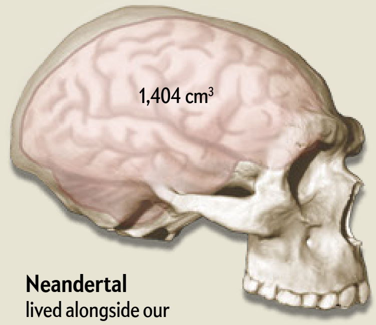
Australopithecus africanus combined human and ape features. Its brain volume of 470 cubic centimeters (cm³) was akin to that of chimpanzees.

3.3–2.1 million years ago (mya)



Homo erectus distinguished itself as a toolmaker, crafting hand axes and expanding its home environment outside of Africa.

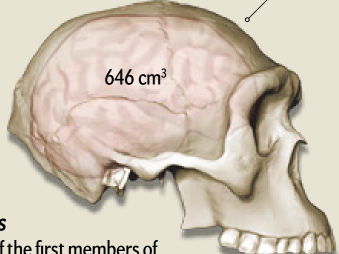
1.9 mya–143,000 years ago (143 kya)



Neandertal lived alongside our species and was an avid hunter, tool and fire user. Its braincase, at 1,404 cm³, was comparable in volume to our own.

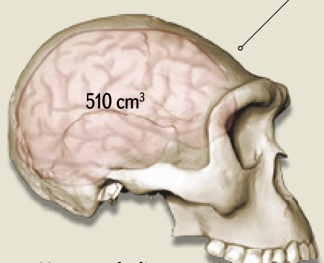
400–40 kya

2.1–1.6 mya



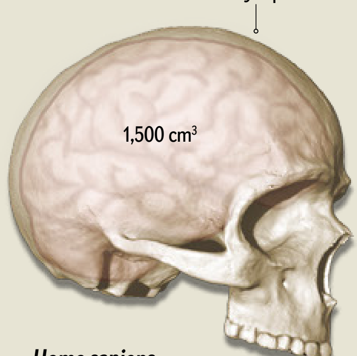
Homo habilis became one of the first members of the genus *Homo*. It had a smaller face than its ancestors and developed frontal areas linked to language.

335–236 kya



Homo naledi was a newer member of the human lineage whose story demonstrates that evolution does not always move in straight lines. Its smaller braincase was 510 cm³.

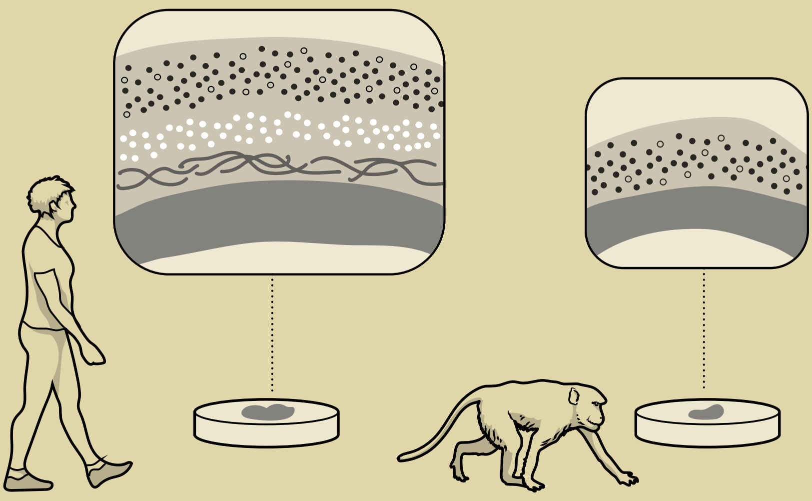
300 kya–present



Homo sapiens evolved some 300,000 years ago. Our brain shape is spherical, or globular, because of the rounded shape of the parietal area and the cerebellum.

MINI BRAINS

Supplying nutrients to groups of stem cells in a lab dish allows them to grow into mini brains. These cerebral organoids, as they are called, consist of entire brain regions, such as the cortex of a human or a monkey (*cross-sectional views*). These ingenious research tools afford an opportunity to compare the activity of genes and neural circuit development in organoids with the working of actual brains in humans, nonhuman primates and other species, ultimately providing a clearer picture of what makes us unique.



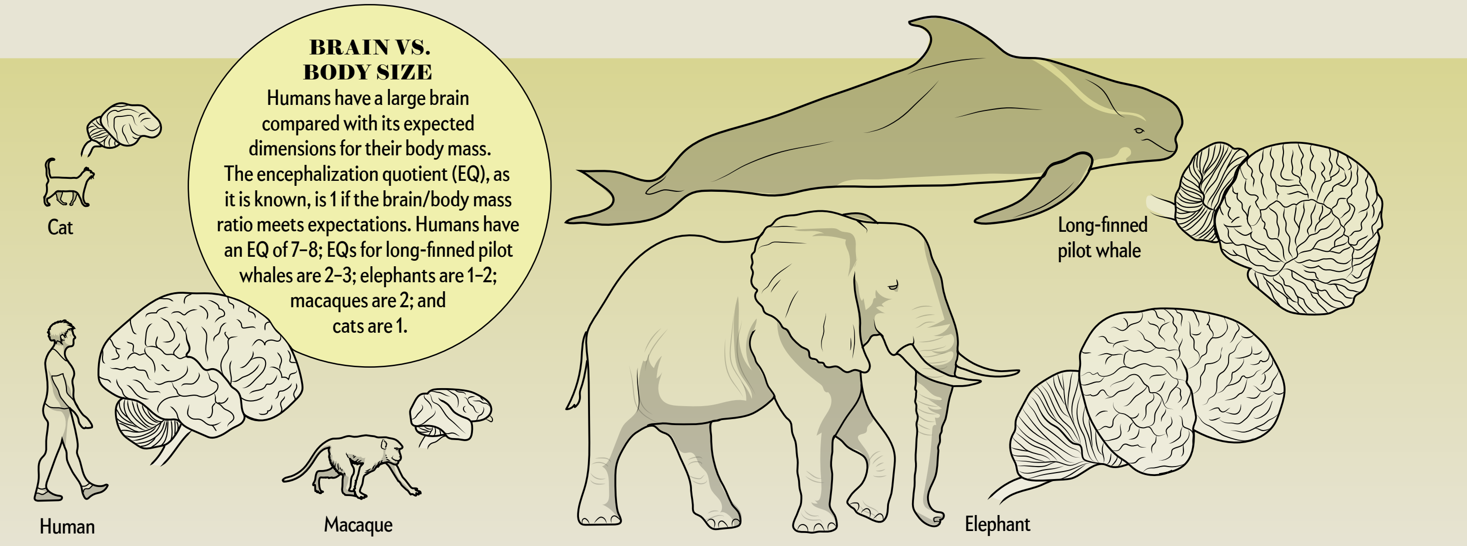
HOW OUR BRAINS GROW

Compared with other primates, human babies have brains that are underdeveloped, grow more rapidly in the first year after birth, and then level off years later with a volume about three times larger than that of a chimpanzee.

SOURCES: "Developmental Patterns of Chimpanzee Cerebral Tissues Provide Important Clues for Understanding the Remarkable Enlargement of the Human Brain," by T. Sakai et al., in *Proceedings of the Royal Society B,* Vol. 270; February 22, 2013 (*brain area expansion*); "Mammalian Brains Are Made of These: A Dataset of the Numbers and Densities of Neuronal and Nonneuronal Cells in the Brain of Glires, Primates, Scandentia, Eulipotyphlans, Afrotherians and Artiodactyls, and Their Relationship with Body Mass," by S. Herculano-Houzel et al., in *Brain, Behavior and Evolution,* Vol. 86, Nos. 3–4; December 2015 (*human* and *macaque neuron numbers*); "Dogs Have the Most Neurons, though Not the Largest Brain: Trade-Off between Body Mass and Number of Neurons in the Cerebral Cortex of Large Carnivoran Species," by D. Jardim-Messeder et al., in *Frontiers in Neuroanatomy,* Vol. 11, Article No. 118; December 2017 (*cat neuron number*); "Quantitative Relationships in Delphinid Neocortex," by H. S. Mortensen et al., in *Frontiers in Neuroanatomy,* Vol. 8, Article No. 132; November 2014 (*pilot whale neuron number*); "Cortical Cell and Neuron Density Estimates in One Chimpanzee Hemisphere," by C. E. Collins et al., in *PNAS,* Vol. 113, No. 3; January 19, 2016 (*chimpanzee neuron number*); "Human Evolutionary History," by E. K. Boyle and B. Wood, in *Evolution of Nervous Systems.* Second edition. Edited by J. H. Kaas. Academic Press, 2017 (*hominin evolution*); Smithsonian National Museum of Natural History *http://humanorigins.si.edu* (*hominin species time line*)

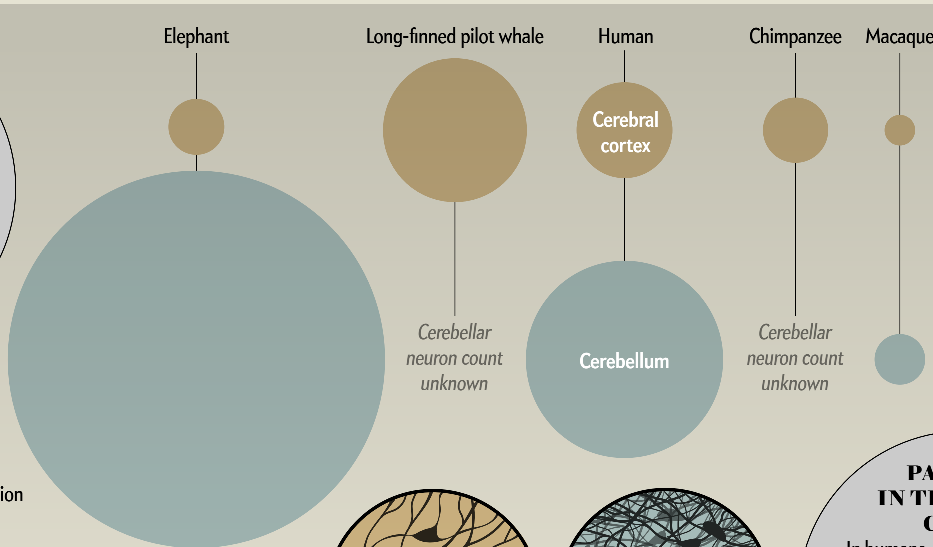
BRAIN VS. BODY SIZE

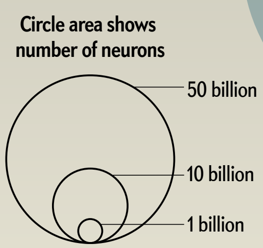
Humans have a large brain compared with its expected dimensions for their body mass. The encephalization quotient (EQ), as it is known, is 1 if the brain/body mass ratio meets expectations. Humans have an EQ of 7–8; EQs for long-finned pilot whales are 2–3; elephants are 1–2; macaques are 2; and cats are 1.

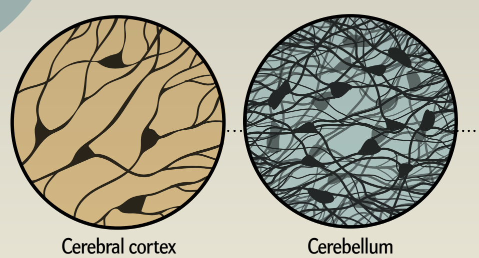


NEURON NUMBER

A much scrutinized measure of brainpower has to do with the number of an animal's neurons—and where they are located. Humans have more neurons in the cerebral cortex, 16 billion, than almost all other mammals, although the long-finned pilot whale has more.

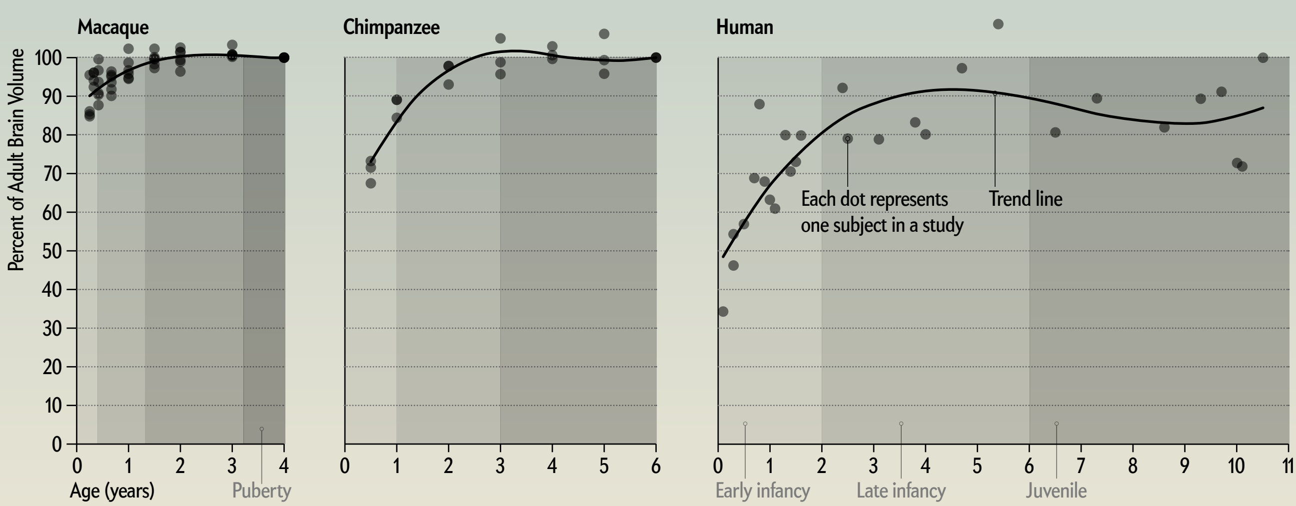






PACKING IN THE BRAIN CELLS

In humans, the cerebral cortex makes up 82 percent of the brain's mass but contains only 19 percent of the total neurons, whereas the cerebellum holds 80 percent or so of the neurons but only occupies 10 percent of its mass.



WHY DID *HOMO SAPIENS* ALONE SURVIVE TO THE MODERN ERA?

PART 2

Us and Them

LAST HOMININ STANDING

BY KATE WONG :: *ILLUSTRATION BY YUKO SHIMIZU*

AT THE DAWNING OF *HOMO SAPIENS,* OUR ANCESTORS WERE BORN INTO a world we would find utterly surreal. It's not so much that the climate and sea levels or the plants and the animals were different, although of course they were—it's that there were other kinds of humans alive at the same time. For most of *H. sapiens*' existence, in fact, multiple human species walked the earth. In Africa, where our species got its start, large-brained *Homo heidelbergensis* and small-brained *Homo naledi* also roamed. In Asia, there was *Homo erectus,* a mysterious group dubbed the Denisovans and, later, *Homo floresiensis*—a hobbitlike creature, tiny but for its large feet. The stocky, heavy-browed Neandertals, for their part, ruled Europe and western Asia. And there were probably even more forms, as yet undiscovered.

By around 40,000 years ago, based on current evidence, *H. sapiens* found itself all alone, the only remaining member of what was once an incredibly diverse family of bipedal primates, together known as hominins. (In this article, the terms "human" and "hominin" both refer to *H. sapiens* and its extinct relatives.) How did our kind come to be the last human standing?

Until a few years ago, scientists favored a simple explanation: *H. sapiens* arose relatively recently, in more or less its current form, in a single region of Africa and spread out from there into the rest of the Old World, supplanting the Neandertals and other archaic human species it encountered along the way. There was no appreciable interspecies fraternizing, just wholesale replacement of the old guards by the clever newcomer, whose ascendancy seemed inevitable.

Yet mounting evidence from fossil and archaeological discoveries, as well as DNA analyses, has experts increasingly rethinking that scenario. It now looks as though *H. sapiens* originated far earlier than previously thought, possibly in locations across Africa instead of a single region, and that some of its distinguishing traits—including aspects of the brain—evolved piecemeal. Moreover, it has become abundantly clear that *H. sapiens* actually did mingle with the other human species it encountered and that interbreeding with them may have been a crucial factor in our success. Together these findings paint a far more complex picture of our origins than many researchers had envisioned—one that privileges the role of dumb luck over destiny in the success of our kind.

IN BRIEF

Until recently, the dominant model of human origins held that *Homo sapiens* arose in a single region of Africa and replaced archaic human species throughout the Old World without interbreeding with them.

New findings from archaeology, paleontology and genetics are rewriting that story.

The latest research suggests that *H. sapiens* emerged from groups located across Africa and that interbreeding with other human species contributed to our success.

THEORY UNDER THREAT

DEBATE ABOUT THE ORIGIN of our species has traditionally focused on two competing models. On one side was the Recent African Origin hypothesis, championed by paleoanthropologist Christopher Stringer and others, which argues that *H. sapiens* arose in either eastern or southern Africa within the past 200,000 years and, because of its inherent superiority, subsequently replaced archaic hominin species around the globe without interbreeding with them to any significant degree. On the other was the Multiregional Evolution model, formulated by paleoanthropologists Milford Wolpoff, Xinzhi Wu and the late Alan Thorne, which holds that modern *H. sapiens* evolved from Neandertals and other archaic human populations throughout the Old World, which were connected through migration and mating. In this view, *H. sapiens* has far deeper roots, reaching back nearly two million years.

By the early 2000s the Recent African Origin model had a wealth of evidence in its favor. Analyses of the DNA of living people indicated that our species originated no more than 200,000 years ago. The earliest known fossils attributed to our species came from two sites in Ethiopia, Omo and Herto, dated to around 195,000 and 160,000 years ago, respectively. And sequences of mitochondrial DNA (the tiny loop of genetic material found in the cell's power plants, which is different from the DNA contained in the cell's nucleus) recovered from Neandertal fossils were distinct from the mitochondrial DNA of people today—exactly as one would expect if *H. sapiens* replaced archaic human species without mating with them.

Not all of the evidence fit with this tidy story, however. Many archaeologists think that the start of a cultural phase known as the Middle Stone Age (MSA) heralded the emergence of people who were beginning to think like us. Prior to this technological shift, archaic human species throughout the Old World made pretty much the same kinds of stone tools fashioned in the so-called Acheulean style. Acheulean technology centered on the production of hefty hand axes that were made by taking a chunk of stone and chipping away at it until it had the desired shape. With the onset of the MSA, our ancestors adopted a new approach to toolmaking, inverting the knapping process to focus on the small, sharp flakes they detached from the core—a more efficient use of raw material that required sophisticated planning. And they began attaching these sharp flakes to handles to create spears and other projectile weapons. Moreover, some people who made MSA tools also made items associated with symbolic behavior, including shell beads for jewelry and pigment for painting. A reliance on symbolic behavior, including language, is thought to be one of the hallmarks of the modern mind.

The problem was that the earliest dates for the MSA were more than 250,000 years ago—far older than those for the earliest *H. sapiens* fossils at less than 200,000 years ago. Did another human species invent the MSA, or did *H. sapiens* actually evolve far earlier than the fossils seemed to indicate?

In 2010 another wrinkle emerged. Geneticists announced that they had recovered nuclear DNA from Neandertal fossils and sequenced it. Nuclear DNA makes up the bulk of our genetic material. Comparison of the Neandertal nuclear DNA with that of living people revealed that non-African people today carry DNA from Neandertals, showing that *H. sapiens* and Neandertals did interbreed after all, at least on occasion.

Subsequent ancient genome studies confirmed that Neandertals contributed to the modern human gene pool, as did other archaic humans. Further, contrary to the notion that *H. sapiens* originated within the past 200,000 years, the ancient DNA suggested that Neandertals and *H. sapiens* diverged from their common ancestor considerably earlier than that, perhaps upward of half a million years ago. If so, *H. sapiens* might have originated more than twice as long ago as the fossil record indicated.

ANCIENT ROOTS

RECENT DISCOVERIES at a site called Jebel Irhoud in Morocco have helped bring the fossil, cultural and genetic evidence into better alignment—and bolstered a new view of our origins. When barite miners first discovered fossils at the site back in 1961, anthropologists thought the bones were around 40,000 years old and belonged to Neandertals. But over the years continued excavations and analyses led researchers to revise that assessment. In June 2017 paleoanthropologist Jean-Jacques Hublin of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, and his colleagues announced that they had recovered additional fossils from the site, along with MSA tools. Using two dating techniques, they estimated the remains to be roughly 315,000 years old. The researchers had found the oldest traces of *H. sapiens* to date, as well as the oldest traces of MSA culture—pushing back the fossil evidence of our species by more than 100,000 years and linking it to the earliest known appearance of the MSA.

Not everyone agrees that the Jebel Irhoud fossils belong to *H. sapiens*. Some experts think they may instead come from a close relative. But if Hublin and his collaborators are right about the identity of the bones, the constellation of skull traits that distinguish *H. sapiens* from other human species did not all emerge in lockstep at the inception of our kind, as supporters of the Recent African Origin theory had supposed. The fossils resemble modern humans in having a small face, for example. But the braincase is elongated like those of archaic human species rather than rounded like our own dome. This shape difference reflects differences in brain organization: compared with fully modern humans, the Jebel Irhoud individuals had smaller parietal lobes, which process sensory input, and a smaller cerebellum, which is involved in language and social cognition, among other functions.

Neither do the archaeological remains at Jebel Irhoud exhibit the full complement of MSA features. The people there made MSA stone tools for hunting and butchering gazelles that roamed the grasslands that once carpeted this now desert landscape. And they built fires, probably to cook their food and warm themselves against the chill of night. But they did not leave behind any traces of symbolic expression.

In fact, on the whole, they are not especially more sophisticated than the Neandertals or *H. heidelbergensis*. If you could journey back in time to our species' debut, you wouldn't necessarily pick it to win the evolutionary sweepstakes. Although early *H. sapiens* had some innovations, "there weren't any big changes at 300,000 years ago that indicate they were destined to be successful," observes archaeologist Michael Petraglia of the Max Planck Institute for the Science of Human History in Jena, Germany. "In the beginning with *sapiens*," Petraglia says, "it looks like anyone's game."

GARDENS OF EDEN

THE TOTAL *H. SAPIENS* PACKAGE, many researchers agree, did not coalesce until sometime between 100,000 and 40,000 years ago. So what happened in the intervening 200,000 years or more to transform our spe-

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cies from run-of-the-mill hominin to world-conquering force of nature? Scientists are increasingly thinking about how the size and structure of the early *H. sapiens* population might have factored into the metamorphosis. In a paper published online in July in *Trends in Ecology & Evolution,* archaeologist Eleanor Scerri of the University of Oxford and a large interdisciplinary group of co-authors, including Stringer, make the case for what they call the African Multiregionalism model of *H. sapiens* evolution. The scientists note that the earliest putative members of our species—namely, the Jebel Irhoud fossils from Morocco, the Herto and Omo Kibish fossils from Ethiopia, and a partial skull from Florisbad, South Africa—all look far more different from one another than people today do. So much so that some researchers have argued that they belong to different species or subspecies. "But maybe early *H. sapiens* was just ridiculously diverse," Scerri offers. And maybe looking for a single point of origin for our species, as many researchers have been doing, is "a wild goose chase," she says.

We may actually owe our extinct relatives a substantial debt of gratitude for our success.

When Scerri and her colleagues examined the latest data from fossils, DNA and archaeology, the emergence of *H. sapiens* began to look less like a single origin story and more like a pan-African phenomenon. Rather than evolving as a small population in a particular region of Africa, they propose, our species emerged from a large population that was subdivided into smaller groups distributed across the vast African continent that were often semi-isolated for thousands of years at a time by distance and by ecological barriers such as deserts. Those bouts of solitude allowed each group to develop its own biological and technological adaptations to its own niche, be it an arid woodland or a savanna grassland, a tropical rain forest or a marine coast. Every so often, however, the groups came into contact with one another, allowing for both genetic and cultural exchange that fed the evolution of our lineage.

Shifting climate could have fueled the fracturing and rejoining of the subpopulations. For instance, paleoenvironmental data have shown that every 100,000 years or so, Africa enters into a humid phase that transforms the forbidding Sahara Desert into a lush expanse of vegetation and lakes. These green Sahara episodes, as they are known, would have allowed populations formerly isolated by the harsh desert to link up. When the Sahara dried out again, populations would be sequestered anew and able to undergo their own evolutionary experiments for another stretch of time until the next greening.

A population subdivided into groups that each adapted to their own ecological niche, even as occasional migration between groups kept them connected, would explain not only the mosaic evolution of *H. sapiens*' distinctive anatomy but also the patchwork pattern of the MSA, Scerri and her co-authors argue. Unlike Acheulean tools, which look mostly the same everywhere they turn up throughout the Old World, MSA tools exhibit considerable regional variation. Sites spanning the time between 130,000 and 60,000 years ago in North Africa, for example, contain tool types not found at sites in South Africa from the same interval, including stone implements bearing distinctive stems that may have served as attachment points for handles. Likewise, South African sites contain slender, leaf-shaped tools made of stone that was heated to improve its fracture mechanics—no such implements appear in the North African record. Complex technology and symbolism become more common over time across the continent, but each group acts its own way, tailoring its culture to its specific niche and customs.

H. sapiens was not the only hominin evolving bigger brains and sophisticated behaviors, however. Hublin notes that human fossils from China dating to between 300,000 and 50,000 years ago, which he suspects belong to Denisovans, exhibit increased brain size. And Neandertals invented complex tools, as well as their own forms of symbolic expression and social connectedness, over the course of their long reign. But such behaviors do not appear to have become as highly developed or as integral to their way of life as they eventually did in ours, observes archaeologist John Shea of Stony Brook University, who thinks that advanced language skills allowed *H. sapiens* to prevail.

"All these groups are evolving in the same direction," Hublin says. "But our species crosses a threshold before the others in terms of cognitive ability, social complexity and reproductive success." And when it does—around 50,000 years ago, in Hublin's estimation—"the boiling milk escapes the saucepan." Forged and honed in Africa, *H. sapiens* could now enter virtually any environment on the earth and thrive. It was unstoppable.

CLOSE ENCOUNTERS

HUNDREDS OF THOUSANDS of years of splitting up from and reuniting with members of our own species might have given *H. sapiens* an edge over other members of the human family. But it was not the only factor in our rise to world domination. We may actually owe our extinct relatives a substantial debt of gratitude for their contributions to our success. The archaic human species that *H. sapiens* met as it migrated within Africa and beyond its borders were not merely competitors—they were also mates. The proof lies in the DNA of people today: Neandertal DNA makes up some 2 percent of the genomes of Eurasians; Denisovan DNA composes up to 5 percent of the DNA of Melanesians. And a recent study by Arun Durvasula and Sriram Sankararaman, both at the University of California, Los Angeles, published on the preprint server bioRxiv in March, found that nearly 8 percent of the genetic ancestry of the West African Yoruba population traces back to an unknown archaic species (researchers have yet to recover DNA from any archaic African fossils for comparison).

Some of the DNA that *H. sapiens* picked up from archaic hominins may have helped our species adapt to the novel habitats it entered on its march across the globe. When geneticist Joshua Akey of Princeton University and his colleagues studied the Neandertal sequences in modern human populations, they found 15 that occur at high frequencies, a sign that they had beneficial consequences. These high-frequency sequences cluster into two groups. About half of them influence immunity. "As modern humans dispersed into new environments, they were exposed to new pathogens and viruses," Akey says. Through interbreeding, "they could have picked up adaptations from Neandertals that were better able to fight off those new pathogens," he explains.

The other half of the Neandertal sequences that Akey's team found at high frequency in modern human populations are related to skin, including genes that influence pigmentation levels. Researchers have previously theorized that *H. sapiens* individuals from Africa, who presumably had darker skin to protect against harmful ultraviolet radiation from the sun, would have had to evolve lighter skin as they entered northern latitudes to get enough vitamin D, which the body acquires mainly through sun exposure. Skin genes from Neandertals may have aided our predecessors in doing exactly that.

Neandertals are not the only archaic humans who gave us useful genes. For example, modern-day Tibetans have the Denisovans to thank for a gene variant that helps them cope with the low-oxygen environment of the high-altitude Tibetan plateau. And contemporary African populations have inherited from an unknown archaic ancestor a variant of a gene that may help fend off bad bacteria in the mouth.

Interbreeding with archaic humans who had millennia to evolve adaptations to local conditions may well have allowed invading *H. sapiens* to adjust to novel environments faster than if it had to wait for favorable mutations to crop up in its own gene pool. But it's not all upside. Some of the genes we obtained from Neandertals are associated with depression and other diseases. Perhaps these genes were advantageous in the past and only began causing trouble in the context of modern ways of life. Or maybe, Akey suggests, the risk of developing these diseases was a tolerable price to pay for the benefits these genes conferred.

Archaic humans may have contributed more than DNA to our species. Researchers have argued that contact between divergent human groups probably led to cultural exchange and may have even spurred innovation. For example, the arrival of *H. sapiens* in western Europe, where the Neandertals long resided, coincided with an uncharacteristic burst of technological and artistic creativity in both groups. Previously some experts suggested that Neandertals were simply aping the inventive newcomers. But maybe it was the interaction between the two groups that ignited the cultural explosion on both sides.

In a sense, the fact that *H. sapiens* mixed with other human lineages should not come as a surprise. "We know from many animals that hybridization has played an important role in evolution," observes biological anthropologist Rebecca Rogers Ackermann of the University of Cape Town in South Africa. "In some cases, it can create populations, and even new species, that are better adapted to new or changing environments than their parents were because of novel traits or novel combinations of traits." Human ancestors show a similar pattern: the combination of different lineages resulted in the adaptable, variable species we are today. "*Homo sapiens* is the product of a complex interplay of lineages," Ackermann asserts, and it has flourished precisely because of the variation that arose from this interplay. "Without it," she says, "we simply wouldn't be as successful."

How often such mingling occurred and the extent to which it might have helped drive evolution in *H. sapiens* and other hominins remain to be determined. But it may be that the particular environmental and demographic circumstances in which our species found itself in Africa and abroad led to more opportunities for genetic and cultural exchange with other groups than our fellow hominins experienced. We got lucky—and are no less marvelous for it. SA

MORE TO EXPLORE

The Hybrid Origin of "Modern" Humans. Rebecca Rogers Ackermann et al. in *Evolutionary Biology,* Vol. 43, No. 1, pages 1–11; March 2016.

Did Our Species Evolve in Subdivided Populations across Africa, and Why Does It Matter? Eleanor M. L. Scerri et al. in *Trends in Ecology & Evolution.* Published online July 11, 2018.

FROM OUR ARCHIVES

Human Hybrids. Michael F. Hammer; May 2013.

scientificamerican.com/magazine/sa

HOW WE LEARNED TO PUT OUR FATE IN ONE ANOTHER'S HANDS

PART 2

Us and Them

THE ORIGINS OF MORALITY

BY MICHAEL TOMASELLO :: *ILLUSTRATION BY YUKO SHIMIZU*

IF EVOLUTION IS ABOUT SURVIVAL OF THE FITTEST, HOW DID HUMANS EVER BECOME MORAL creatures? If evolution is each individual maximizing their own fitness, how did humans come to feel that they really ought to help others and be fair to them?

There have traditionally been two answers to such questions. First, it makes sense for individuals to help their kin, with whom they share genes, a process known as inclusive fitness. Second, situations of reciprocity can arise in which I scratch your back and you scratch mine and we both benefit in the long run.

But morality is not just about being nice to kin in the manner that bees and ants cooperate in acts of inclusive fitness. And reciprocity is a risky proposition because at any point one individual can benefit and go home, leaving the other in the lurch. Moreover, neither of these traditional explanations gets at what is arguably the essence of human morality—the sense of obligation that human beings feel toward one another.

Recently a new approach to looking at the problem of morality has come to the fore. The key insight is a recognition that individuals who live in a social group in which everyone depends on everyone else for their survival and well-being operate with a specific kind of logic. In this logic of interdependence, as we may call it, if I depend on you, then it is in my interest to help ensure your well-being. More generally, if we all depend on one another, then we must all take care of one another.

How did this situation come about? The answer has to do with the particular circumstances that forced humans into ever more cooperative ways of life, especially when they are acquiring food and other basic resources.

THE ROLE OF COLLABORATION

OUR CLOSEST LIVING RELATIVES—chimpanzees and bonobos—forage for fruit and vegetation in small parties, but when resources are found, each individual scrambles to obtain food on its own. If any conflict arises, it is solved through dominance: the best fighter wins. In the closest thing to collaborative foraging among apes, a few male chimpanzees may surround a monkey and capture it. But this approach to hunting resembles more closely what lions and wolves do than the collaborative form of foraging undertaken by humans. Each chimpanzee maximizes its own chances in the situation by trying to block one possible avenue of the monkey's escape. The captor chimp will try to consume the entire carcass alone but typically cannot. Then all the individuals in the area converge on the captured prey and begin grabbing at it. The captor must allow this to happen or else fight the others, which would likely mean losing the food in the melee; thus, a small amount of food sharing takes place.

For a long time humans have done things differently. Around two million years ago the genus *Homo* emerged, with larger brains and new skills in making stone tools. Soon after, a global cooling and drying period led to a proliferation of terrestrial monkeys, which competed with *Homo* for many resources.

Early humans needed new options. One alternative involved scavenging carcasses killed by other animals. But then, according to an account from anthropologist Mary C. Stiner of the University of Arizona, some early humans—the best guess is *Homo heidelbergensis* some 400,000 years ago—began obtaining most of their food through active collaboration in which individuals formed joint goals to work together in hunting and gathering. Indeed, the collaboration became obligate (compulsory) in that it was essential to their survival. Individuals became interdependent with one another in immediate and urgent ways to obtain their daily sustenance.

An essential part of the process of obligate collaborative foraging involved partner choice. Individuals who were cognitively or otherwise incompetent at collaboration—those incapable of forming joint goals or communicating effectively with others—were not chosen as partners and so went without food. Likewise, individuals who were socially or morally uncooperative in their interactions with others—for example, those who tried to hog all the spoils—were also shunned as partners and so doomed. The upshot: strong and active social selection emerged for competent and motivated individuals who cooperated well with others.

The key point for the evolution of morality is that early human individuals who were socially selected for collaborative foraging through their choice of partners developed new ways of relating to others. Most important, they had strong cooperative motives, both to work together to achieve common

IN BRIEF

Seeds of human morality were planted some 400,000 years ago, when individuals began to collaborate in hunting-and-gathering exploits.

Cooperative interaction cultivated respect and fairness for other group members.

Later, growing population sizes cemented a sense of collective group identity that fostered a set of cultural practices and social norms.

goals and to feel sympathy for and help existing or prospective partners. If an individual depended on partners for foraging success, then it made good evolutionary sense to help them whenever necessary to make sure they were in good shape for future outings. In addition, one's own survival depended on others seeing you as a competent and motivated collaborative partner. Thus, individuals became concerned with how others evaluated them. In experiments from our laboratory, even young children care about how they are being evaluated by others, whereas chimpanzees seemingly do not.

Absent a historical record and, in many cases, even evidence from fossil remains and archaeological artifacts, our lab in Leipzig, Germany, and others have investigated the origins of human thinking and morality by comparing the behaviors of our close primate relatives with those of young children who have yet to integrate the norms of their culture.

From these studies we have surmised that early humans who engaged in collaborative foraging developed a new kind of cooperative reasoning that led them to treat others as equally deserving partners—that is, not just with sympathy but also with a sense of fairness (based on an understanding of the equivalence between oneself and others). Partners understood that they could, in principle, take on any role in a collaboration and that both of them needed to work together for combined success. Moreover, as two individuals collaborated repeatedly with one another as foragers, they developed an understanding—a mental "common ground"—that defined the ideal way that each partner needed to fulfill a role for mutual success. These role-specific standards shaped the expectation of what each partner should do: for example, in hunting antelopes, the chaser must do X, and the spearer must do Y. These idealized standards were impartial in that they specified what either partner had to do to fulfill the role "properly" in a way that ensured joint success. The roles—each of which had mutually known and impartial standards of performance—were, in fact, interchangeable. As such, each partner on the hunt was equally deserving of the spoils, in contrast to cheats and free riders who did not lend a hand.

In choosing a partner for a collaborative effort, early humans wanted to pick an individual who would live up to an expected role and divide the spoils fairly. To reduce the risk inherent in partner choice, individuals who were about to become partners could use their newfound skills of cooperation to make a joint commitment, pledging to live up to their roles, which required a fair division of the spoils. As part of this commitment, the would-be partners also could pledge implicitly that whoever might renege on a commitment would be deserving of censure. (The box on the next page explains the evolution of morality within the framework of the philosophical concept of intentionality.)

Anyone who deviated from what was expected and wanted to stay in good cooperative standing would willingly engage in an act of self-condemnation—internalized psychologically as a sense of guilt. A "we is greater than me" morality emerged. During a collaboration, the joint "we" operated beyond the selfish individual level to regulate the actions of the collaborative partners "I" and "you."

The outcome of early humans' adaptations for obligate collaborative foraging, then, became what is known as a second-personal morality—defined as the tendency to relate to others with a sense of respect and fairness based on a genuine assessment of both self and others as equally deserving partners in a collaborative enterprise. This sense of fairness was heightened by the feeling of obligation, the social pressure to cooperate and respect one's partner. That is, whereas all primates feel pressure to pursue their individual goals in ways they believe will be successful, the interdependency that governed social life for early humans meant that individuals felt pressures to treat others as they deserve to be treated and to expect others to treat them in this same way. This second-personal morality did not have all the defining attributes of modern human morality, but it already had the most important elements—mutual respect and fairness—in nascent form.

THE BIRTH OF CULTURAL NORMS

THE SECOND CRITICAL STEP in the evolution of human morality came when the small-scale collaborative foraging of early humans was eventually destabilized by two demographic factors that gave rise to modern humans more than 200,000 years ago. This new era came about because of competition among human groups. The struggles meant that loosely structured populations of collaborators had to turn into more tightly knit social groups to protect themselves from outside invaders. Each of these groups developed internal divisions of labor, all of which led to a collective group identity.

At the same time, population sizes were increasing. As numbers grew within these expanding tribal groups, the larger entities split into smaller subunits that still felt bound to the supergroup—or what might be characterized as a distinctive "culture." Finding ways to recognize members of one's own cultural group who were not necessarily next of kin—and then to separate them from members of other tribal groups—became essential. This type of recognition was important because only members of one's own cultural group could be counted on to share one's skills and values and be trustworthy partners,

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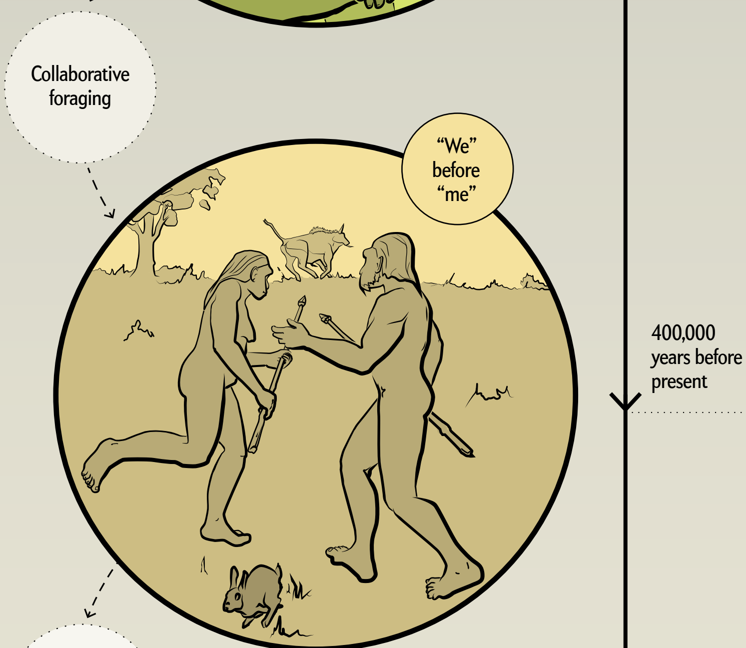
Evolution of Modern Human Morality

Animals often cooperate with others of their own species. But the way humans do so is different. The human form of cooperation—known simply as morality—distinguishes itself in two related ways. One person may help another based on unselfish motives driven by compassion, concern and benevolence. Also, members of a group might seek means for all to benefit through enacting norms to promote fairness, equity and justice. These capacities evolved over hundreds of thousands of years as humans began to work together out of a basic need for survival. The cognitive and social aspects of this process may be understood through the philosophical concept of intentionality: the ways individuals interpret the world and pursue their goals.

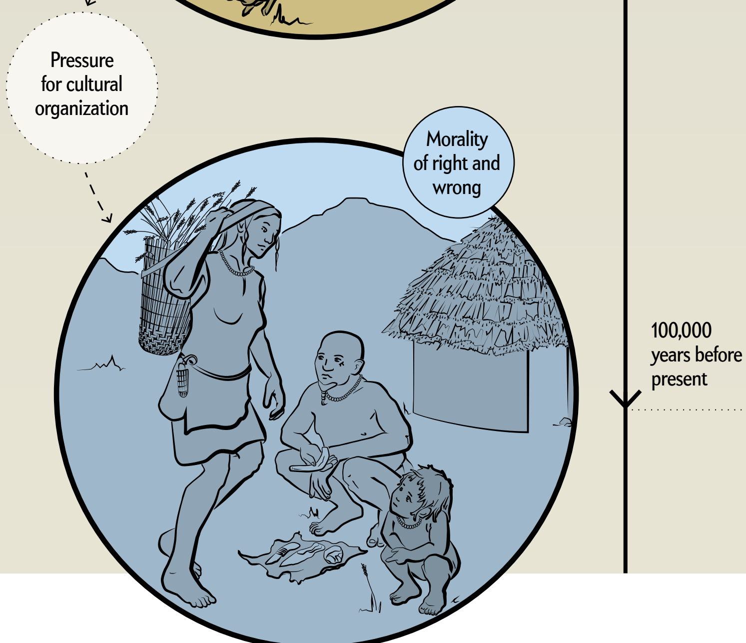
Individual Intentionality

An ability to flexibly change behavior to achieve a particular goal—usually for the purposes of competing with others—characterizes individual intentionality. Chimpanzee behavior is largely spurred by this self-interested perspective, as was that of the common ancestor of humans and chimpanzees—and perhaps it motivated early members of the hominin line as well. An example of this behavior occurs when chimpanzees forage for plants. A small group of animals searches together, but once they find fruit, each gathers its own stash and eats separately without interacting with other group members. A similar set of relatively self-centered behaviors are exhibited when hunting prey.



Joint Intentionality

Some 400,000 years ago a direct human ancestor—*Homo heidelbergensis*—began looking for better food sources. Hunting aurochs or other large game, as opposed to hares, required heightened cooperation, a joint intentionality, focusing on common goals. This type of teamwork contrasted with chimpanzees' every-animal-for-itself scramble during a monkey hunt. If the Paleolithic hunter-gatherers were to survive, their foraging practices became "obligate," not just a matter of discretion. Individuals chosen for the hunt were selected because they understood implicitly the need to cooperate and not hog the resulting spoils. A "second-personal morality" emerged in which it was understood that a "me" had to be subordinated to a "we."



Collective Intentionality

As groups grew in size beginning 150,000 years ago, the smaller bands that made up a tribe developed a set of common practices that represented the formal beginnings of human cultures. A set of norms, conventions and institutions grew up to define the group's goals and establish divisions of labor that set roles for each of its members—a collective intentionality that distinguished a tribe. These goals were internalized by each tribe member as an "objective morality" in which everyone knew immediately the difference between right and wrong as determined by the group's set of cultural practices.

Illustration by Portia Sloan Rollings

particularly for group defense. The dependence of individuals on the group thus led to a sense of collective identity and loyalty. A failure, meanwhile, to display this group identity and loyalty could result in being ostracized or dying in clashes with rivals.

Contemporary humans have many diverse ways of marking group identity, but the original ways were mainly behavioral ones and based on a number of assumptions: people who talk like me, prepare food like me and otherwise share my cultural practices are very likely members of my cultural group. And so from these suppositions emerged modern humans' tendency toward conformity to the group's cultural practices. Teaching one's children to do things in the conventional way defined by the group became mandatory for survival.

Teaching and conformity lay the foundations as well for cumulative cultural evolution—in which a practice or an artifact that had been in place for a long time could be improved on and that innovation could then be passed along to subsequent generations as part of a group's conventions, norms and institutions. Individuals were born into these collaborative social structures and had no choice but to conform to them. The key psychological characteristic of individuals adapted for cultural life was a group-mindedness, whereby people took the cognitive perspective of the group as a whole to care for its welfare and to conform to its ways—an inference derived from studies of the behavior of three-year-olds published in the late 2000s.

Individuals who belonged to a cultural group had to conform to the prevailing cultural practices and social norms to advertise that they identified with the group and its way of doing things. Some social norms were about more than conformity and group identity. They touched on a sense of sympathy and fairness (inherited from early humans), which became moral norms. Thus, just as some norms codified the right and wrong way of doing things in hunting or making tools, moral norms categorized the proper way of treating other people. Because the collective group goals and cultural common ground of human groups created an "objective" perspective—not "me" but "we" as a people—modern human morality came to be characterized as an objective form of right and wrong.

Of course, any individual could choose to act against a moral norm. But when called to task by other group members, the options were limited: one could ignore their criticism and censure and so place oneself outside the practices and values shared by the culture, perhaps leading to exclusion from the group. Modern humans thought of the cultural norms as legitimate means by which they could regulate themselves and their impulses and signal a sense of group identity. If a person did deviate from the group's social norms, it was important to justify uncooperativeness to others in terms of the shared values of the group ("I neglected my duties because I needed to save a child in trouble"). In this way, modern humans internalized not only moral actions but moral justifications and created a reason-based moral identity within the community.

THE PEOPLE OF WE

IN MY 2016 BOOK *A Natural History of Human Morality,* I proceed from the assumption that a major part of the explanation for human moral psychology comes from processes of evolution by means of natural selection. More important, though, the selecting is done not by the physical environment but rather by the social environment. In contrast to evolutionary approaches that base their arguments on reciprocity and the managing of one's reputation in the community, I emphasize that early human individuals understood that moral norms made them both judger and judged. The immediate concern for any individual was not just for what "they" think of me but rather for what "we," including "I," think of me. The essence of this account is thus a kind of "we is greater than me" psychological orientation, which gives moral notions their special powers of legitimacy in personal decision making.

The challenge in the contemporary world stems from an understanding that humans' biological adaptations for cooperation and morality are geared mainly toward small group life or cultural groups that are internally homogeneous—with out-groups not being part of the moral community. Since the rise of agriculture some 10,000 years ago, human societies have consisted of individuals from diverse political, ethnic and religious lines.

As a consequence, it becomes less clear who constitutes a "we" and who is in the out-group. The resulting potential for divisiveness leads to both internal social tensions within a society and, at the level of nations, to outright war—the ultimate example of in- and out-group conflicts. But if we are to solve our largest challenges as a species, which threaten all human societies alike, we had best be prepared to think of all of humanity as a "we." SA

MORE TO EXPLORE

Cooperative Hunting and Meat Sharing 400–200 Kya at Qesem Cave, Israel. Mary C. Stiner et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 106, No. 32, pages 13,207–13,212; August 11, 2009.

Why We Cooperate. Michael Tomasello et al. Boston Review Books, 2009.

Young Children Enforce Social Norms. Marco F. H. Schmidt et al. in *Current Directions in Psychological Science,* Vol. 21, No. 4, pages 232–236; July 25, 2012.

A Natural History of Human Morality. Michael Tomasello. Harvard University Press, 2016.

FROM OUR ARCHIVES

The "It" Factor. Gary Stix; September 2014.

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PART 2

Us and Them

WAR MAY NOT BE IN OUR NATURE AFTER ALL

WHY WE FIGHT

BY R. BRIAN FERGUSON :: *ILLUSTRATION BY YUKO SHIMIZU*

DO PEOPLE, OR PERHAPS JUST MALES, HAVE AN EVOLVED PREDISPOSITION to kill members of other groups? Not just a capacity to kill but an innate propensity to take up arms, tilting us toward collective violence? The word "collective" is key. People fight and kill for personal reasons, but homicide is not war. War is social, with groups organized to kill people from other groups. Today controversy over the historical roots of warfare revolves around two polar positions. In one, war is an evolved propensity to eliminate any potential competitors. In this scenario, humans all the way back to our common ancestors with chimpanzees have always made war. The other position holds that armed conflict has only emerged over recent millennia, as changing social conditions provided the motivation and organization to collectively kill. The two sides separate into what the late anthropologist Keith Otterbein called hawks and doves. (This debate also ties into the question of whether instinctive, warlike tendencies can be detected in chimpanzees [*see box on page 80*].)

IN BRIEF

Is war innate to the human species, or did it emerge after the organization of societies became increasingly complex?

Scholars split into two camps that might be labeled hawks and doves.

A close look at archaeological and other evidence suggests that collective killing resulted from cultural conditions that arose within the past 12,000 years.

If war expresses an inborn tendency, then we should expect to find evidence of war in small-scale societies throughout the prehistoric record. The hawks claim that we have indeed found such evidence. "When there is a good archaeological picture of any society on Earth, there is almost always also evidence of warfare.... Twenty-five percent of deaths due to warfare may be a conservative estimate," wrote archaeologist Steven A. LeBlanc and his co-author Katherine E. Register. With casualties of that magnitude, evolutionary psychologists argue, war has served as a mechanism of natural selection in which the fittest prevail to acquire both mates and resources.

This perspective has achieved broad influence. Political scientist Francis Fukuyama wrote that the roots of recent wars and genocide go back for tens or hundreds of thousands of years among our hunter-gatherer ancestors, even to our shared ancestor with chimpanzees. Bradley Thayer, a leading scholar of international relations, argues that evolutionary theory explains why the instinctual tendency to protect one's tribe morphed over time into group inclinations toward xenophobia and ethnocentrism in international relations. If wars are natural eruptions of instinctive hate, why look for other answers? If human nature leans toward collective killing of outsiders, how long can we avoid it?

The anthropologists and archaeologists in the dove camp challenge this view. Humans, they argue, have an obvious capacity to engage in warfare, but their brains are not hardwired to identify and kill outsiders involved in collective conflicts. Lethal group attacks, according to these arguments, emerged only when hunter-gatherer societies grew in size and complexity and later with the birth of agriculture. Archaeology, supplemented by observations of contemporary hunter-gatherer cultures, allows us to identify the times and, to some degree, the social circumstances that led to the origins and intensification of warfare.

WHEN DID IT BEGIN?

IN THE SEARCH for the origins of war, archaeologists look for four kinds of evidence. The artwork on cave walls is exhibit one. Paleolithic cave paintings from Grottes de Cougnac, Pech Merle and Cosquer in France dating back approximately 25,000 years show what some scholars perceive to be spears penetrating people, suggesting that people were waging war as early as the late Paleolithic period. But this interpretation is contested. Other scientists point out that some of the incomplete figures in those cave paintings have tails, and they argue that the bent or wavy lines that intersect with them more likely represent forces of shamanic power, not spears. (In contrast, wall paintings on the eastern Iberian Peninsula, probably made by settled agriculturalists thousands of years later, clearly show battles and executions.)

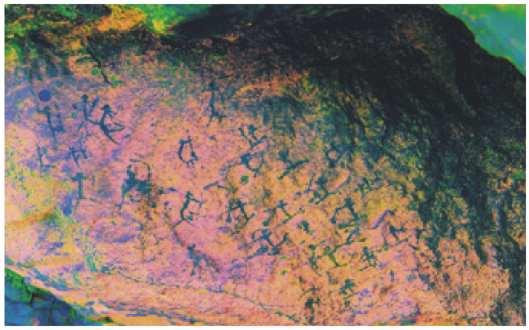
Weapons are also evidence of war, but these artifacts may not be what they seem. I used to accept maces as representing proof of war, until I learned more about Near Eastern stone maces. Most have holes for handles so narrow they could not survive one blow in battle. Maces also symbolize authority, and established rule can provide a way to resolve conflict without resorting to war. On the other hand, it is perfectly possible to go to war *without* traditional weapons: in southern Germany around 5000 B.C., villagers were massacred with adzes that were also used to work wood.

Beyond art and weapons, archaeologists look to settlement remains for clues. People who fear attack usually take precautions. In the archaeological record, we sometimes see people who lived in scattered homes on low flatlands shifted to nucleated defendable villages. Villages across Neolithic Europe were surrounded by mounded enclosures. But not all these enclosures seem designed for defense. Some may mark off distinct social groups.

Skeletal remains would seem ideal for determining when war began, but even these require careful assessment. Only one of three or four projectile wounds leaves a mark on bone. Shaped points made of stone or bone buried with a corpse are sometimes ceremonial, sometimes the cause of death. Unhealed wounds to a single buried corpse could be the result of an accident, an execution or a homicide. Indeed, homicide may have been fairly common in the prehistoric world—but homicide is not war. And not all fights were lethal. In some burial sites, archaeologists frequently find skulls with healed cranial depressions but few that caused death. The findings suggest fights with clubs or other nonlethal resolution of personal disputes, as is common in the ethnographic record. When the skulls are mostly from females, fractures may reflect domestic violence.

The global archaeological evidence, then, is often ambiguous and difficult to interpret. Often different clues must be pieced together to produce a suspicion or probability of war. But dedicated archaeological work—multiple excavations with good material recovery—should be able to conclude that war is at least suspected.

On balance, though, are there really indications that humans have been waging war for the entire history of the species? If your sample consists of cases known for high frequencies of perimortem wounds (those occurring at or near the time of death), the situation looks pretty bad. That is how figures such as 25 percent of deaths by violence are derived. Misconceptions result, however, because of cherry-picking by popular media. Any discovery of ancient killings grabs headlines. The news items ignore innumerable excavations that yield no signs of violence. And a comprehensive screening of reports from a particular area and time period, asking how many, if any, show even hints of war, paints an entirely different picture. War is hardly ubiquitous and does not go back endlessly in the archaeological record. Human warfare did indeed have a beginning.



TRACES of war more than 5,000 years ago appear in an enhanced image of rock-shelter art found on the Iberian Peninsula.

FROM "IDENTIFICATION OF PLANT CELLS IN BLACK PIGMENTS OF PREHISTORIC SPANISH LEVANTINE ROCK ART BY MEANS OF A MULTI-ANALYTICAL APPROACH: A NEW METHOD FOR SOCIAL IDENTITY MATERIALIZATION USING *CHAÎNE OPÉRATOIRE*," BY ESTHER LÓPEZ-MONTALVO ET AL., IN *PLOS ONE*, VOL. 1, NO. 2, ARTICLE NO. E0172225; FEBRUARY 16, 2017

THE FIRST HOSTILITIES

MANY ARCHAEOLOGISTS venture that war emerged in some areas during the Mesolithic period, which began after the last Ice Age ended around 9700 B.C., when European hunter-gatherers settled and developed more complex societies. But there really is no simple answer. War appeared at different times in different places. For half a century archaeologists have agreed that the multiple violent deaths at Jebel Sahaba along the Nile in northern Sudan occurred even earlier, around 12,000 B.C. There severe competition among settled hunter-gatherer groups in an area with once rich but declining food sources may have led to conflict.

At a slightly later time, settlements, weapons and burials in the northern Tigris suggest war involving settled villages of hunter-gatherers between 9750 and 8750 B.C. Nearby, the earliest known village fortifications occurred among farming people in the seventh millennium, and the first conquest of an urban center took place between 3800 and 3500 B.C. By that date, war was common across Anatolia, spread in part by conquering migrants from the northern Tigris.

In stark contrast, archaeologists have found no persuasive evidence in settlements, weapons or skeletal remains in the southern Levant (from Sinai to southern Lebanon and Syria) dating to before about 3200 B.C. In Japan, violent deaths from any cause are rare among hunter-gatherer groups from 13,000 to 800 B.C.

With the development of wet rice farming around 300 B.C., violent fatalities became apparent in more than one in 10 remains. In well-studied North American sites, some very early skeletal trauma seems the result of personal rather than collective conflicts. A site in Florida contained evidence of multiple killings about 5400 B.C. In parts of the Pacific Northwest, the same occurred by 2200 B.C., but in the southern Great Plains, only one violent death was recorded before A.D. 500.

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What about Our Chimp Cousins?

Anthropologists are looking at whether closely related primates show an instinctive propensity toward group killing

Delving into the question of human predisposition to war often involves looking beyond our species to examine the experiences of our chimpanzee relatives. This is a topic I have been studying for many years, and I am now finishing the writing of a book about it, *Chimpanzees, "War," and History.* I put quotes around "war" because intergroup conflict among chimps, though sometimes collective and deadly, lacks the social and cognitive dimensions essential to human war.

Human warfare involves opponents that often include multiple local groups that may be unified by widely varying forms of political organization. War is fostered by culturally specific systems of knowledge and values that generate powerful meanings of "us versus them." These social constructs have no primate analogies. Despite these distinctions, some scientists have argued that chimpanzees demonstrate an innate propensity to kill outsiders, inherited from the last common ancestor of chimps and people—an impulse that still subliminally pushes humans as well into deadly conflicts with those outside their communities.

My work disputes the claim that chimpanzee males have an innate tendency to kill outsiders, arguing instead that their most extreme violence can be tied to specific circumstances that result from disruption of their lives by contact with humans. Making that case has required my going through every reported chimpanzee killing. From this, a simple point can be made. Critical examination of a recent compilation of killings from 18 chimpanzee research sites—together amounting to 426 years of field observations—reveals that of 27 observed or inferred intergroup killings of adults and adolescents, 15 come from just two highly conflicted situations, which occurred at two sites in 1974–1977 and 2002–2006, respectively.

The two situations amount to nine years of observation, tallying a kill rate of 1.67 annually for those years. The remaining 417 years of observation average just 0.03 annually. The question is whether the outlier cases are better explained as evolved, adaptive behavior or as a result of human disruption. And whereas some evolutionary biologists propose that killings are explained as attempts to diminish the number of males in rival groups, those same data show that subtracting internal from external killings of males produces a reduction of outside males of only one every 47 years, fewer than once in a chimpanzee's lifetime.

From comparative case studies, I conclude that "war" among chimpanzees is not an evolved evolutionary strategy but an induced response to human disturbance. Case-by-case analyses will show that chimps, as a species, are not "killer apes." This research calls into question as well the idea that any human tendency toward bellicosity might be driven by an ancient genetic legacy from a distant ancestor of chimpanzees and humans. *—R.B.F.*

WHY DID IT HAPPEN?

THE PRECONDITIONS THAT MAKE war more likely include a shift to a more sedentary existence, a growing regional population, a concentration of valuable resources such as livestock, increasing social complexity and hierarchy, trade in high-value goods, and the establishment of group boundaries and collective identities. These conditions are sometimes combined with severe environmental changes. War at Jebel Sahaba, for one, may have been a response to an ecological crisis, as the Nile cut a gorge that eliminated productive marshlands, eventually leading to human abandonment of the area. Later, centuries after agriculture began, Neolithic Europe—to take one example—demonstrated that when people have more to fight over, their societies start to organize themselves in a manner that makes them more prepared to go ahead and embrace war.

There are limits, however, to what archaeology can show, and we must seek answers elsewhere. Ethnography—the study of different cultures, both living and past—illustrates these preconditions. A basic distinction is between "simple" and "complex" hunter-gatherer communities.

Simple hunting and gathering characterized human societies during most of humanity's existence dating back more than 200,000 years. Broadly, these groups cooperate with one another and live in small, mobile, egalitarian bands, exploiting large areas with low population density and few possessions.

Complex hunter-gatherers, in contrast, live in fixed settlements with populations in the hundreds. They maintain social rankings of kin groups and individuals, restrict access to food resources by lines of descent and have more developed political leadership. Signs of such social complexity first appeared during the Mesolithic. The appearance of complex hunter-gatherers can sometimes but not always mark a transitional stage to agriculture, the basis for the development of political states. These groups, moreover, often waged war.

The preconditions for war are only part of the story, however, and by themselves, they may not suffice to predict outbreaks of collective conflicts. In the Southern Levant, for instance, those preconditions existed for thousands of years without evidence of war.

Why, though, was there an absence of conflict? It turns out that many societies also have distinct preconditions for peace. Many social arrangements impede war, such as cross-group ties of kinship and marriage; cooperation in hunting, agriculture or food sharing; flexibility in social arrangements that allow individuals to move to other groups; norms that value peace and stigmatize killing; and recognized means for conflict resolution. These mechanisms do not eliminate serious conflict, but they do channel it in ways that either prevent killing or keep it confined among a limited number of individuals.

If this is so, why then are later archaeological findings, along with explorers' and anthropologists' reports, so full of deadly warfare? Over millennia preconditions of war became more common in more places. Once established, war has a tendency to spread, with violent peoples replacing less violent ones. States evolved around the world, and states are capable of militarizing peoples on their peripheries and trade routes. Environmental upheavals such as frequent droughts aggravate and sometimes generate conditions that lead to war, and peace may not return when conditions ease. Particularly notable was the intensification of the Medieval Warm period, from roughly A.D. 950 to 1250, and its rapid transformation into the Little Ice Age beginning around A.D. 1300. In that period war increased in areas across the Americas, the Pacific and elsewhere. In most of the world, war was long established, but conflicts worsened, with mounting casualties tallied.

Then came European global expansion, which transformed, intensified and sometimes generated indigenous war around the world. These confrontations were not just driven by conquest and resistance. Local peoples began to make war on one another, drawn into new hostilities by colonial powers and the commodities they provided.

Interaction between ancient and recent expanding states, and the ensuing conflicts, encouraged formation of distinctive tribal identities and divisions. Areas still beyond colonial control underwent changes impelled by longer-distance effects of trade, disease and population displacement—all of which led to wars. States also stirred up conflict among local peoples by imposing political institutions with clear boundaries rather than the amorphous local identities and limited authorities they often encountered in their colonial forays.

Scholars often seek support for the idea that human willingness to engage in deadly group hostilities predated the rise of the state by looking for evidence of hostilities in "tribal zones," where "savage" warfare seems endemic and is often seen as an expression of human nature. But a careful examination of ethnographically known violence among local peoples in the historical record provides an alternative perspective.

Hunter-gatherers of northwestern Alaska from the late 18th through the 19th centuries demonstrate the fallacy of projecting ethnography of contemporary peoples into humanity's distant past. Intense war involving village massacres lingers in detailed oral traditions. This deadly violence is cited as evidence of war by hunter-gatherers before disruption by expanding states.

Archaeology, however, combined with the history of the region, provides a very different assessment. There are no hints of war in early archaeological remains in the simple cultures of Alaskan hunter-gatherers. The first signs of war appear between A.D. 400 to 700, and they are probably the result of contact with immigrants from Asia or southern Alaska, where war was already established. But these conflicts were limited in size and probably intensity.

With favorable climatic conditions by A.D. 1200, a growing social complexity developed among these whale hunters, with denser, more settled populations and expanding long-distance trade. After a couple of centuries, war became common. War in the 19th century, however, was much worse, so severe that it caused decline of the regional population. These later conflicts—the ones that show up in oral histories—were associated with state expansion as a massive trade network developed out of new Russian entrepôts in Siberia, and they led to extreme territoriality and centralization of complex tribal groups across the Bering Strait.

NOT A FACT OF LIFE

DEBATE OVER WAR AND HUMAN NATURE will not soon be resolved. The idea that intensive, high-casualty violence was ubiquitous throughout prehistory has many backers. It has cultural resonance for those who are sure that we as a species naturally tilt toward war. As my mother would say: "Just look at history!" But doves have the upper hand when all the evidence is considered. Broadly, early finds provide little if any evidence suggesting war was a fact of life.

People are people. They fight and sometimes kill. Humans have always had a capacity to make war, if conditions and culture so dictate. But those conditions and the warlike cultures they generate became common only over the past 10,000 years—and, in most places, much more recently than that. The high level of killing often reported in history, ethnography or later archaeology is contradicted in the earliest archaeological findings around the globe. The most ancient bones and artifacts are consistent with the title of Margaret Mead's 1940 article: "Warfare Is Only an Invention—Not a Biological Necessity." SA

MORE TO EXPLORE

War in the Tribal Zone: Expanding States and Indigenous Warfare. Edited by R. Brian Ferguson and Neil L. Whitehead. School of American Research Press, 1992.

Beyond War: The Human Potential for Peace. Douglas P. Fry. Oxford University Press, 2007.

FROM OUR ARCHIVES

Tribal Warfare. R. Brian Ferguson; January 1992.

scientificamerican.com/magazine/sa

PART 3

Beyond Us

HUMANS ARE CHANGING THE COURSE OF EVOLUTION

DARWIN IN THE CITY

BY MENNO SCHILTHUIZEN :: *ILLUSTRATION BY ARMANDO VEVE*

W HOOSH!" EXCLAIMS MY FRIEND FRANK, AS HE THRUSTS HIS CUPPED hands upward, nearly knocking over his drink on the table between us. We are sitting in my backyard in Leiden, the Netherlands. Frank is demonstrating how, once or twice each day, a peregrine falcon swoops upward past his hospital office window with a freshly killed pigeon in its talons, headed for its lair underneath the giant illuminated logo at the top of the building. A few seconds later plucked feathers come drifting down.

Peregrine falcons are one of many bird species that have recently taken up an urban lifestyle. They traditionally hunt medium-sized birds around rocky cliffs, but as humans worldwide have filled the environment with an artificial cliff-scape of churches, chimneys and office buildings, the birds have happily exchanged escarpments for skyscrapers and jays for pigeons. In some parts of Europe and North America the majority of peregrine falcons nest in cities.

IN BRIEF

Species as varied as snails, dandelions and fish are adapting to urban environments in surprisingly novel ways.

In many cases, the speed of evolution is faster than would have occurred in natural settings.

Because cities worldwide present similar evolutionary pressures, species there may become more alike.

Many species will never be able to adapt to what are often extreme conditions, so they still need protections.

Such accidental similarities between urban and natural environments are attracting more fauna and flora to the metropolis. Cave cockroaches are preadapted to live in our dark, dank homes. Beach plants readily sprout along the briny edges of roads that are salted in winter. Raccoons, with their nimble, handlike forepaws, are eminently suited to manipulate garbage and compost bins strewn across the man-made landscape. *Homo sapiens* have established extensive settlements on nearly every continent, and by 2030 more than 600 cities will each be home to greater than one million people. No single species has ever produced new conditions for other species to live in, on such a global scale.

Something even more surprising is going on as well. The city—with its countenance of brick, glass and steel, the racing pulse of its vehicle-filled veins, its luminescent artificial light and the chemicals emanating from its pores—is an extreme yet bountiful environment. Although the conditions can be harsh, they can also provide many benefits, notably all the food and resources that humans accumulate. As in naturally extreme environments, such as deserts, sulfur springs and deep caves, this combination of risk and opportunity is driving the evolution of animals and plants that venture there. As my colleagues worldwide and I are discovering, cities have become pressure cookers of evolution—places that force adaptation to happen quickly and pervasively.

STREET-SMART SNAILS

YOU CAN WITNESS urban evolution on a field trip that begins right outside your door. My own small backyard is a good example. I must admit that, for a biologist, my garden is an embarrassment (as Frank keeps reminding me). All kinds of weeds are sprouting between old pavement tiles on the ground. There is a neglected rose bush in one corner and a potted hydrangea in another. That's about it, except for the sprawling hop plants that relentlessly scale the wall looming over my yard.

The hop leaves shroud one of my favorite examples of urban evolution. I carefully peel them away from the wall, showing Frank grove snails nibbling at the dead branches of previous years. The snails, *Cepaea nemoralis,* native to Europe and introduced across North America, can have a variety of shell colors and patterns. The variations are coded in their DNA. My snails are pale yellow, adorned with up to five black spiral bands.

Why yellow? The answer has to do with the heat island effect. Cities tend to be hotter than the countryside around them because the buildings and streets absorb the sun's heat. That absorption, plus added heat generated by the activities of millions of people and their machines, creates a bubble of hot air. In a modest municipality such as Leiden, the air in the city center is on average two to three degrees Celsius warmer than it is in the surrounding area. In big cities such as New York or Tokyo, the difference can be more than 10 degrees C. For snails, which are sometimes forced to spend weeks of summer drought clinging to a wall, the extra heat can become fatal—more so if they have a dark shell, which absorbs the energy. Natural selection is causing grove snail shells in my city and others to become lighter in color. Outside the city perimeter they are more likely to be red or brown.

As Frank and I pass through my garden gate into the alley, we stumble across a second example of urban evolution: dandelions! They are pushing up from cracks in the pavement. Some are in full yellow bloom; others sport a head of fluffy, umbrellalike seeds. Under natural conditions, the seeds, suspended from feathery parachutes, are supposed to drift in the wind and eventually land and germinate far away from their parents and siblings. This system prevents competition. But in the city, the strategy is not likely to work, because the stamp-sized bit of soil where the parent grows is often the only fertile spot around. Seeds that blow far in the wind will likely land on barren asphalt or concrete. It would be better to have a heavy seed that drops straight down to the soil at the parent's feet. That is exactly what Arathi Seshadri of Colorado State University discovered in 2012. The parachutes of urban dandelion seeds, she found, are more elongated and drop up to twice as fast as the parachutes holding dandelion seeds out in traditional meadows.

Ironically, this adaptation is similar to what a relative of the dandelion, cat's ear (*Hypochaeris radicata*), has undergone in a natural, extreme environment. On tiny islets off the Canadian western coast, cat's ear has evolved seeds that descend faster than those of plants on the mainland. Here the risk of being blown out to sea drove the modification.

DOWNTOWN ADAPTERS: Dandelions in cities are reshaping their seeds so they drop straight down into precious small patches of soil. Bridge spiders, which usually avoid sunlight, are bravely spinning webs under streetlights.

MARCEL VAN DEN BERGH

BRIGHT LIGHTS, BIG CITY

CONTINUING OUR FIELD TRIP to uncover urban evolution, Frank and I emerge from the alley and cross the main street to reach the river, *Galgenwater* (Gallows' Water). A cluster of houseboats hugs the embankment where Rembrandt's birthplace once stood. As we approach a suspension bridge, we notice spider webs everywhere: between bars on the bridge railings, against the windows of the houseboats. Large circular webs, ranging in size from dessert plates to bicycle wheels, glisten in the sun. The sucked-dry corpses of midges and moths hang from the threads, a reminder of the gallows that once stood here.

The bridge spiders (*Larinioides sclopetarius*) themselves are nowhere to be seen. The species is nocturnal, hiding in crevices that block daylight, waiting for night to venture to the web hubs to snare prey. Yet these webs are constructed right below the bridge lights. This now urban spider has

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SURVIVAL SKILLS: Pigeons, unafraid of the author, must learn to hide from the rising number of urban peregrine falcons that hunt them. Snails that live on city walls are evolving lighter shells to absorb less heat.

MARCEL VAN DEN BERGH

thrown tradition to the wind because the lights attract insects. In the 1990s Austrian arachnologist Astrid Heiling determined that urban bridge spiders are born with a love for artificial light, even though they still avoid sunlight.

Interestingly, an opposite evolution is happening in at least one species of the spiders' prey. For insects, the lure of a lightbulb is often fatal. They get fried by the heat, exhaust themselves circling the lamp when they should be feeding or mating, or end up in a bridge spider's jaws. Many entomologists believe the attraction to light is so hardwired in an insect's brain that it cannot switch off, even in the face of a severe death toll.

But Swiss entomologist Florian Altermatt was not convinced. He targeted the small ermine moth (*Yponomeuta cagnagella*). He collected hundreds of the caterpillars in the illuminated center of Basel and a similar number in dark forests outside the city. He reared them all in the lab and gave each moth a little paint mark to denote its urban or rural origin. Then he released more than 1,000 of them in a large dark cage that had a single fluorescent tube at one end. True to form, the rural moths tended to hover near the lamp, but the urban ones were more likely to ignore the light and settle elsewhere in the cage. Apparently, Altermatt concluded, the urban moths had evolved a resistance to artificial light.

RAPID EVOLUTION

THE HANDFUL OF EXAMPLES of urban Darwinism that Frank and I encountered on our brief stroll represent a ubiquitous process under way in city ecosystems around the globe. In addition to the heat island effect, impervious surfaces and light pollution, urban wildlife faces a panoply of other challenges: noise, chemical pollution and traffic, to name but a few. Urban evolutionary biologists have found many instances of wildlife adapting to such stressors. Some creatures can even overcome the seemingly insurmountable obstacle of heavy toxic pollution. Andrew Whitehead of the University of California, Davis, and his colleagues found that little estuarine fishes on the U.S. East Coast, called mummichogs, have developed tolerance to PCB concentrations up to 8,000 times higher than what is normally lethal for them.

Perhaps even more important than physical and chemical factors are the biological ones. The new city dwellers rub shoulders with a motley crew of foreign species, brought in accidentally or intentionally: ornamental plants, agricultural crops and pests, domesticated pets, and all the insects and weeds that people unwittingly carry in on their clothes and vehicles. Together these organisms form an ecosystem of species that cohabit willy-nilly, without ever having had the opportunity to adapt to one another. This unorthodox mix sets the stage for the mutual evolution of new attack and defense abilities: exotic parakeets might adapt to feed on native city seeds, whereas native city birds could evolve immunities against foreign parasites.

All these challenges and opportunities create a powerful mix in which urban species evolve rapidly. Substantial adaptation often happens in a couple of decades, sometimes only a few years. Mummichogs evolved their PCB tolerance in just a few dozen fish generations; theoretical models show that is about as fast as evolution could take place for them.

Many people doubt evolution can really happen so quickly. After all, Darwin wrote: "We see nothing of these slow changes in progress, until the hand of time has marked the long lapse of ages." Yet under strong natural selection pressure, evolution can proceed much more rapidly than Darwin thought possible. This is especially true for organisms that can reproduce multiple times in a year.

In a meta-analysis of more than 1,600 case studies, published last year in the *Proceedings of the National Academy of Sciences USA,* a group of researchers led by Marina Alberti of the University of Washington found a clear signal that urbanization does speed up evolution, in some cases as much as double the rate. One of the strongest drivers of greater speed was the introduction of exotic species into an environment.

Given that rapid urban evolution is happening all around us, does that mean everything is fine? Will all species simply adapt to the human-altered habitats that will increasingly dominate Earth in our current geologic epoch, the Anthropocene? Sadly, no. Only certain species will be able to colonize, survive and thrive in cities. For each success story, there may be a dozen cases of urban extinction: species that simply could not adapt and therefore disappear. Many, many species will continue to need the reserves, protected areas, laws and other safeguards that allow pristine habitats to survive in the citified future.

Nevertheless, urban ecosystems expanding around the world do represent an exciting new phase in the history of life on Earth. Never before has an extreme habitat had such a global presence. Cities everywhere share a suite of common features that flora and fauna will adapt to in similar ways. Perhaps spare-time naturalists can help the full-timers track the extent and pace of change. Many urban species, such as city pigeons, white clover and dandelions, are prevalent across the planet; a global community of citizen scientists could effectively monitor how they are changing. (Indeed, the evolution of yellow-shelled grove snails was revealed by volunteers using the smartphone app SnailSnap, which has yielded data on more than 12,000 snails in Dutch cities.)

Never before has an extreme habitat had such a global presence. It may turn out that all the intrepid creatures adapting in parallel to cityscape conditions could become more alike, coming up with the same solutions for the many pressures.

It may turn out that all those intrepid creatures adapting in parallel to comparable cityscape conditions could become more alike, coming up with the same solutions for the many pressures. Global homogenization could be the characteristic that actually sets urban evolution apart from "natural" evolution and become the hallmark of human influence on other species. Because such a situation is unprecedented ecologically, we can only guess what the future will hold. SA

MORE TO EXPLORE

Darwin Comes to Town: How the Urban Jungle Drives Evolution. Menno Schilthuizen. Picador, 2018.
The Influence of Human Disturbance on Wildlife Nocturnality. Kaitlyn M. Gaynor et al. in *Science,* Vol. 360, pages 1232–1235; June 15, 2018.

FROM OUR ARCHIVES

Urban Monkeys. Sheo Dan Singh; July 1969.

scientificamerican.com/magazine/sa

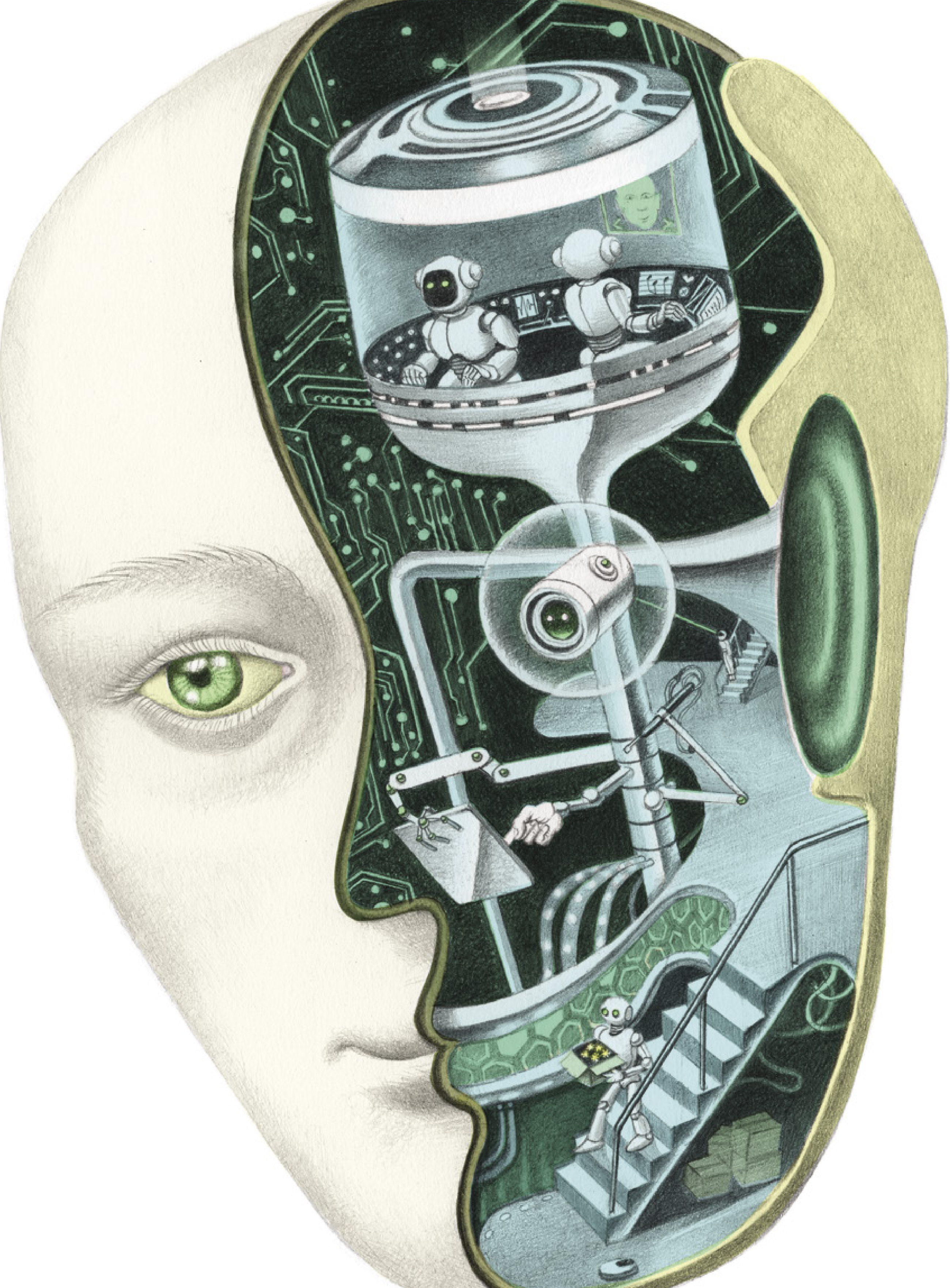
AI WILL SERVE OUR SPECIES, NOT CONTROL IT

PART 3

Beyond Us

OUR DIGITAL DOUBLES

BY PEDRO DOMINGOS :: *ILLUSTRATION BY ARMANDO VEVE*



HUMANS ARE THE ONLY ANIMALS THAT BUILD MACHINES. BY DOING SO, we expand our capabilities beyond our biological limits. Tools turn our hands into more versatile appendages. Cars let us travel faster, and airplanes give us wings. Computers endow us with bigger brains and memory capacity, and smartphones orchestrate daily life. Now we are creating technology that can evolve on its own by encoding into it an ability to learn through data and effort. Will it ultimately supplant us? Or will it augment our abilities, enhancing our humanness in unprecedented ways?

IN BRIEF

The pursuit of artificial intelligence can be seen as part of human evolution. The next stage of automation will require the creation of a so-called master algorithm. It would integrate the five main ways that machines currently learn into a single, unified paradigm.

Technology is simply an extension of human capabilities. Machines do not have free will, only goals that we give to them. It is the misuse of the technology by people that we should be worried about, not a robot takeover.

A more plausible near-term scenario for AI is the proliferation of "digital doubles"—virtual models of ourselves that will interact with each other in countless simulations to help us make faster, more informed choices in our daily lives.

Machine learning started in the 1950s with the work of pioneering scientists such as Frank Rosenblatt, who built an electronic neuron that learned to recognize digits, and Arthur Samuel, whose checkers program learned by playing against itself until it could beat some humans. But it is only in the past decade that the field has truly taken off, giving us self-driving cars, virtual assistants that understand our commands (up to a point) and countless other applications.

Every year we invent thousands of new algorithms, which are sequences of instructions telling a computer what to do. The hallmark of learning machines, however, is that instead of programming them in detail, we give them general goals such as "learn to play checkers." Then, like humans, they improve with experience. These learning algorithms tend to fall into five main categories, each inspired by a different scientific field. Unsurprisingly, one way that machines learn is by mimicking natural selection, through evolutionary algorithms. In the Creative Machines Lab at Columbia University, primitive robots try to crawl or fly, and the specifications of those that perform best are periodically mixed and mutated to 3-D print the next generation. Starting with randomly assembled bots that can barely move, this process eventually produces creatures such as robot spiders and dragonflies after thousands or tens of thousands of generations.

But evolution is slow. Deep learning, currently the most popular machine-learning paradigm, takes inspiration from the brain. We start with a highly simplified mathematical model of how a neuron works and then build a network from thousands or millions of these units and let it learn by gradually strengthening the connections between neurons that fire together when looking at data. These neural networks can recognize faces, understand speech and translate languages with uncanny accuracy. Machine learning also draws on psychology. Like humans, these analogy-based algorithms solve new problems by finding similar ones in memory. This ability allows for the automation of customer support, as well as e-commerce sites that recommend products based on your tastes.

Machines may also learn by automating the scientific method. To induce a new hypothesis, symbolic learners invert the process of deduction: If I know that Socrates is human, what else do I need to infer that he is mortal? Knowing that humans are mortal would suffice, and this hypothesis can then be tested by checking if other humans in the data are also mortal. Eve, a biologist robot at the University of Manchester in England, has used this approach to discover a potential new malaria drug. Starting with data about the disease and basic knowledge of molecular biology, Eve formulated hypotheses about what drug compounds might work, designed experiments to test them, carried out the experiments in a robotic lab, revised or discarded the hypotheses, and repeated until it was satisfied.

Finally, learning can rely purely on mathematical principles, the most important of which is Bayes's theorem. The theorem says that we should assign initial probabilities to hypotheses based on our knowledge, then let the hypotheses that are consistent with the data become more probable and those that are not become less so. It then makes predictions by letting all the hypotheses vote, with the more probable ones carrying more weight. Bayesian learning machines can do some medical diagnoses more accurately than human doctors. They are also at the heart of many spam filters and of the system that Google uses to choose which ads to show you.

Each of these five kinds of machine learning has its strengths and weaknesses. Deep learning, for example, is good for perceptual problems such as vision and speech recognition but not for cognitive ones such as acquiring commonsense knowledge and reasoning. With symbolic learning, the reverse is true. Evolutionary algorithms are capable of solving harder problems than neural networks, but it can take a very long time to solve them. Analogical methods can learn from just a small number of instances but are liable to get confused when given too much information about each. Bayesian learning is most useful for dealing with small amounts of data but can be prohibitively expensive with big data.

These vexing trade-offs are why machine-learning researchers are working toward combining the best elements of all the paradigms. In the same way that a master key opens all locks, our goal is to create a so-called master algorithm—one that can learn everything that can be extracted from data, deriving all possible knowledge from it.

The challenge on us now is similar to the one faced by physicists: quantum mechanics is effective at describing the universe at the smallest scales and general relativity at the largest scales, but the two are incompatible and need to be reconciled. And in the same way that James Clerk Maxwell first unified light, electricity and magnetism before the Standard Model of particle physics could be developed, different research groups, including mine at the University of Washington, have proposed ways to unify two or more of the machine-learning paradigms. Because scientific progress is not linear and instead happens in fits and starts, it is difficult to predict when the full unification of the master algorithm might be complete. Regardless, achieving this goal will not usher in a new, dominant race of machines. Rather, it will accelerate human progress.

MACHINE TAKEOVER?

ONCE WE ATTAIN THE MASTER ALGORITHM and feed it the vast quantities of data each of us produce, artificial-intelligence systems will potentially be able to learn very accurate and detailed models of individual people: our tastes and habits, strengths and weaknesses, memories and aspirations, beliefs and personalities, the people and things we care about, and how we will respond in any given situation. That models of us could essentially predict the choices we will make is both exciting and disquieting.

Many worry that machines with these capabilities will use their newfound knowledge to take all our jobs, enslave us or even exterminate us. But that is unlikely to happen because they have no will of their own. Essentially all AI algorithms are driven by goals that we program, such as "find the shortest route from the hotel to the airport." What distinguishes these algorithms from ordinary ones is that they have a lot of flexibility in figuring out how to reach the goals we set for them rather than needing to execute a predefined series of steps. Even as they get better at the task with experience, the goals remain unchanged. Solutions that do not make progress toward the goal are automatically discarded. Plus, humans get to check that what the machines produce does indeed satisfy our objectives. We are also able to verify that the machines do not violate any of the constraints we put on them, such as "obey the rules of the road."

When we envision an AI, though, we tend to project onto it human qualities such as volition and consciousness. Most of us are also more familiar with humanlike AIs, such as home robots, than with the myriad other types that do their work behind the scenes. Hollywood compounds this perception by depicting robots and AIs as humans in disguise—an understandable tactic that makes for a more compelling story. Artificial intelligence is just the ability to solve hard problems—a task that does not require free will. It is no more likely to turn against us than your hand is to slap you. Like any other technology, AIs will always be extensions of us. The more powerful we can make them, the better.

What, then, might our AI-enabled future look like? Intelligent machines will indeed supplant many jobs, but the effects on society will likely be similar to previous forms of automation. Two hundred years ago the majority of Americans were farmers. Yet today machines have replaced almost all of them without causing massive unemployment. Doomsayers argue that this time is different because machines are replacing our brains, not just our brawn, leaving nothing for humans to do. But the day that AIs can carry out all the tasks we can is still very distant, if it ever comes. For the foreseeable future, AIs and humans will be good at different things. Machine learning's primary effect will be to greatly lower the cost of intelligence. This democratization will increase the variety of economically feasible uses of that intelligence, generating new jobs and transforming old ones to accomplish more with the same amount of human labor.

Then there is the "singularity" scenario, popularized by futurist Ray Kurzweil. It is one of ever accelerating technological progress: machines learn to make better machines, which in turn make even better ones, and so on. But we know that this cannot continue forever because the laws of physics place strict limits on how powerful even a quantum computer can be, and in some aspects, we are not far from hitting them. The progress of AI, like the progress of everything else, will eventually plateau.

Another vision popular among futurists is that

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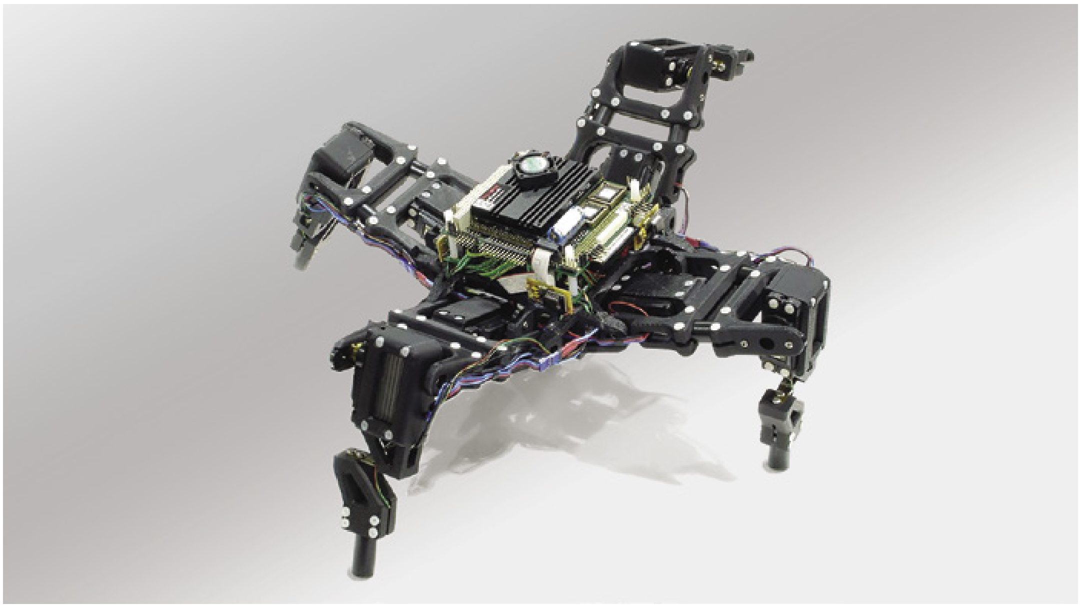
SMART BOT: This sea star uses evolutionary algorithms to learn how to simulate itself. These algorithms are one type of machine learning that could be unified with others into a "master algorithm," a singularly powerful human tool.



VICTOR ZYKOV AND JOSH BONGARD

computer models of us will become so good that they will be practically indistinguishable from the real thing. In this scenario, we could upload ourselves to the cloud and live on forever as pieces of software, free of the pesky constraints of the physical world. One problem with this scenario is that it may not be biologically feasible. To upload yourself, you would presumably need an accurate model of each of your neurons, complete with the memories they store. It would have to be captured so reliably that the model's predictions would not rapidly diverge from the behavior of the real neurons—a tall order indeed. But even if this were a realistic option, would you really upload yourself if you had the chance? How could you know for sure that your model was not missing some essential part of you—or that it was conscious at all? What if a thief stole your identity in the most absolute and complete sense of the word? I believe that people will opt to hang on to their squishy, carbon-based selves—the "wetware," as computer scientists jokingly call it—for as long as they can and then call it quits.

CHERCHEZ L'HUMAIN

AI—MACHINE LEARNING IN PARTICULAR—is really just the continuation of human evolution. In *The Extended Phenotype,* Richard Dawkins shows how common it is for animals' genes to control the environment beyond their bodies, from cuckoo eggs to beaver dams. (Dawkins serves on *Scientific American*'s board of advisers.) Technology is the extended phenotype of humans, and what we are building today is another layer of our technological exoskeleton. I think the most likely scenario for how humans will use AI is more fascinating than the usual speculations.

Within a decade each one of us will probably have a "digital double," an AI companion that will be even more indispensable than our smartphones are today. Your digital double will not need to physically move around with you; most likely it will live somewhere in the cloud, just as much of your data already does. We can see its beginnings in virtual assistants such as Siri, Alexa and Google Assistant. At the heart of your digital double will be a model of you, learned from all the data you have ever generated in your interactions with the digital world, from desktop computers and Web sites to wearable devices and sensors in the environment such as smart speakers, thermostats, cell-phone towers and video cameras.

The better our learning algorithms become and the more personal data we feed them, the more accurate our digital doubles will get. Once we have the master algorithm and then couple it with continuous capture of your sensorimotor stream via an augmented reality headset and other personal sensors, your double will grow to know you better than your best friend.

The model and data will be maintained by a "data bank," not unlike a traditional bank that stores and invests your money. Many existing companies would surely like to provide that service for you. Google cofounder Sergey Brin has said that Google wants to be "the third half of your brain," but you probably would not want part of your brain to subsist by showing you ads. You might be better served by a new kind of company with fewer conflicts of interest or by a data union you form with like-minded people.

After all, the central worry about AI is not that it will spontaneously turn evil but that the humans who control it will misuse it (*cherchez l'humain,* as the French might say—"look to the human"). So your data bank's first duty will be to ensure that your model is never used against your interests. Both you and the data bank must be vigilant about monitoring AI crime because this technology will empower bad actors as much as anyone. We will need AI police (the Turing police, as William Gibson called it in his 1984 book *Neuromancer*) to catch the AI criminals.

If you have the misfortune of living under an authoritarian regime, this scenario could usher in unprecedented dangers because it will allow the government to monitor and restrain you like never before. Given the speed at which machine learning is progressing and the predictive policing systems already in use, the *Minority Report* scenario—where people are preemptively arrested when they are about to commit a crime—no longer seems far-fetched. Then there are the implications of inequality as the world adapts to the speed of life with digital doubles before all of us are able to afford one.

Our first duty, as individuals, will be not to become complacent and trust our digital doubles beyond their years. It is easy to forget that AIs are like autistic savants and will remain so for the foreseeable future. From the outside, AIs may seem objective, even perfect, but inside they are as flawed as we are or more, just in different ways. For example, AIs lack common sense and can easily make errors that a human never would, such as mistaking a person crossing the street for a windblown plastic bag. They are also liable to take our instructions too literally, giving us precisely what we asked for instead of what we actually wanted. (So think twice before telling your self-driving car to get you to the airport on time at all costs.)

Practically speaking, your digital double will be similar enough to you to take your place in all kinds of virtual interactions. Its job will not be to live your life for you but rather to make all the choices you do not have the time, patience or knowledge for. It will read every book on Amazon and recommend the few that you are most likely to want to read yourself. If you need a car, it will research the options and haggle with the car dealer's bots. If you are job hunting, it will interview itself for all the positions that fit your needs and then schedule live interviews for you for the most promising ones. If you get a cancer diagnosis, it will try all potential treatments and recommend the most effective ones. (It will be your ethical duty to use your digital double for the greater good by letting it take part in medical research, too.) And if you are seeking a romantic partner, your double will go on millions of virtual dates with all eligible doubles. The pairs that hit it off in cyberspace can then go on a date in real life.

Essentially your double will live out countless

Your digital double will take your place in all kinds of virtual interactions.

probable lives in cyberspace so that the single one you live in the physical world is likely to be the best version. Whether your simulated lives are somehow "real" and your cyberselves have a kind of consciousness (as portrayed in the plots of some *Black Mirror* episodes, for instance) are interesting philosophical questions.

Some people worry that this means that we are handing over control of our lives to computers. But it actually gives us more control, not less, because it allows us to make choices we could not before. Your model will also learn from the results of each virtual experience (Did you enjoy the date? Do you like your new job?) so that over time, it will become better at suggesting the things you would choose for yourself.

In fact, we are already accustomed to most of our decision making taking place without our conscious intervention because that is what our brains do now. Your digital double will be like a greatly expanded subconscious, with one key difference: Whereas your subconscious lives alone inside your skull, your digital double will continuously interact with those of other people and organizations. Everyone's doubles will keep trying to learn models of one another, and they will form a society of models, living at computer speeds, branching out in all directions, figuring out what we would do if we were there. Our machines will be our scouts, blazing a trail into the future for us as individuals and as a species. Where will they lead us? And where will we choose to go? SA

MORE TO EXPLORE

The Master Algorithm: How the Quest for the Ultimate Learning Machine Will Remake Our World. Pedro Domingos. Basic Books, 2015.

The Digital Mind: How Science Is Redefining Humanity. Arlindo Oliveira. MIT Press, 2017.

FROM OUR ARCHIVES

Self-Taught Robots. Diana Kwon; March 2018.

scientificamerican.com/magazine/sa

WHY WE ARE PROBABLY THE ONLY INTELLIGENT LIFE IN THE GALAXY

PART 3

Beyond Us

ALONE IN THE MILKY WAY

BY JOHN GRIBBIN :: *ILLUSTRATION BY ARMANDO VEVE*

A

STRONOMERS HAVE NOW FOUND THOUSANDS OF PLANETS ORBITING OTHER stars in the Milky Way, and 100 billion more stars in the galaxy presumably host planets of their own. Given the sheer number of worlds out there, scientists find it easy to hope that some of them must be harboring sentient beings. After all, could Earth really be unique among so many planets?

IN BRIEF

With so many exoplanets out there in the galaxy, it seems reasonable to hope that life may be prevalent. But a series of unusual coincidences occurred to give rise to our intelligent civilization, and it is quite unlikely such serendipity has taken place elsewhere.

The timing of our solar system's birth in the history of the galaxy was fortuitous, for example, as is our location in the Milky Way. Furthermore, several features of our planet are very rare, and the conditions that sparked the evolution of life here might be irreproducible.

Perhaps most unlikely of all was the development of our technological species from those first sparks of life—a feat that is probably unique.

It could. Optimism about the possibilities of intelligent extraterrestrial life ignores what we know about how humans came to exist. We are here because of a long chain of implausible coincidences—many, many, many things had to go right to result in the situation in which we find ourselves. This chain is so implausible, in fact, that there is good reason to conclude that humans most likely are the only technological civilization in the galaxy. (Let us leave aside the other countless galaxies in the cosmos because, as the saying has it, "in an infinite universe, anything is possible.")

SPECIAL TIMING

THE COINCIDENCES BEGIN with the manufacture of heavy elements, which include everything heavier than hydrogen and helium. The first stars were born in clouds of these two lightest elements, the residue of the big bang, more than 13 billion years ago. They cannot have had planets, because there was nothing to make planets from—no carbon, oxygen, silicon, iron or any other metals (with cavalier disregard for chemical subtleties, astronomers call all elements heavier than hydrogen and helium metals).

Metals are created inside stars and spread through space when stars throw off material as they die, sometimes in spectacular supernova explosions. This material enriches interstellar clouds, so each successive generation of stars made from the clouds will have a greater metallicity than the one before it. When the sun came into being about 4.5 billion years ago, this enrichment had been going on for billions of years in our galactic neighborhood. Even so, the sun contains roughly 71 percent hydrogen, 27 percent helium and just 2 percent metals. Its composition mirrors that of the cloud that made the solar system, so the rocky planets, including Earth, formed from only that tiny amount of elemental construction material. Stars older than the sun have even fewer metals and, correspondingly, less chance of making rocky, Earth-like planets (giant gaseous planets, such as Jupiter, are easier to form but not as likely to host life). This means that even if we are not the only technological civilization in the galaxy, we must be one of the first.

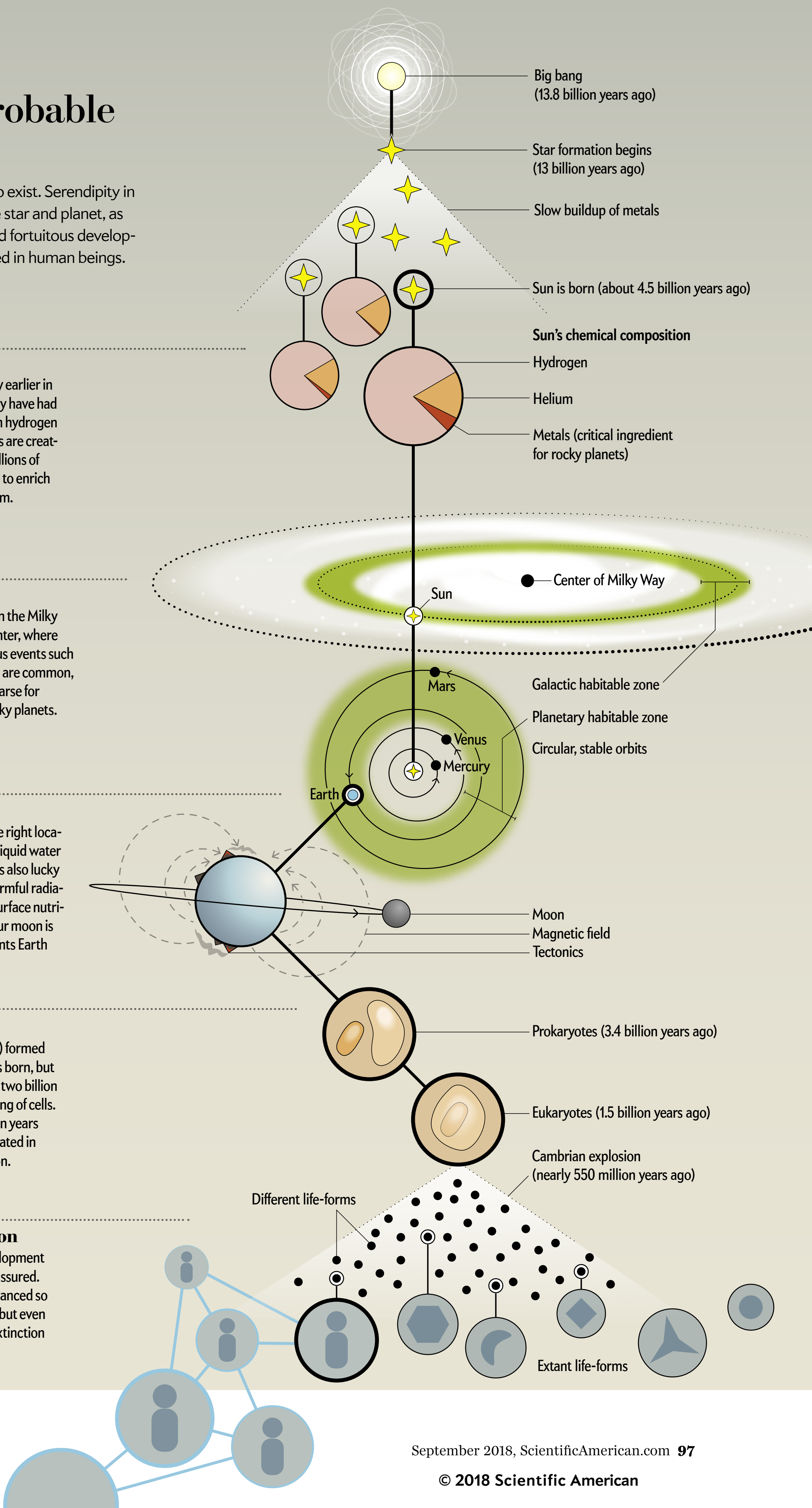
SPECIAL LOCATION

OUR PLACE IN THE MILKY WAY is also propitious. The sun is located in a thin disk of stars about 100,000 light-years across; it is roughly 27,000 light-years from the galactic center, a little more than halfway to the rim. By and large, stars closer to the center contain more metals, and there are more old stars there. This situation is typical of disk galaxies, which seem to have grown outward from the center.

More metals sounds like a good thing from the point of view of making rocky planets, but it may not be so good for life. One reason for the extra metallicity is that stars are packed more densely toward the center, so there are many supernovae, which produce energetic radiation—x-rays and charged particles known as cosmic rays—that is harmful to planets of nearby stars. The galactic center also is home

Chain of Improbable Coincidences

Many things had to go right for us to exist. Serendipity in the timing and location of our home star and planet, as well as lucky conditions on Earth and fortuitous developments in the evolution of life, resulted in human beings.



Timing

If the sun and Earth had been born any earlier in galactic history, our planet would likely have had too few metals (elements heavier than hydrogen or helium) to form life. These elements are created during stellar deaths, and it took billions of years for enough stars to form and die to enrich the materials that built our solar system.

Location

The sun lies in a Goldilocks zone within the Milky Way—not too close to the galactic center, where stars are more crowded and dangerous events such as supernovae and gamma-ray bursts are common, and not too far, where stars are too sparse for enough metals to build up to form rocky planets.

Planetary Conditions

Within our solar system, Earth is in the right location for hospitable temperatures and liquid water (the planetary habitable zone). Earth is also lucky to have a magnetic field that repels harmful radiation and plate tectonics to replenish surface nutrients and stabilize the temperature. Our moon is likely behind both boons; it also prevents Earth from tipping too far on its axis.

Early Life

Single-celled organisms (prokaryotes) formed just a billion years after our planet was born, but more complex cells (eukaryotes) took two billion years more to arise from a fluke merging of cells. Even then, it was almost another billion years before multicellular life-forms proliferated in an event called the Cambrian explosion.

Technological Civilization

Once multicellular life arose, the development of an intelligent species was far from assured. We still do not know how humans advanced so far beyond our close animal relatives, but even our species may have come close to extinction several times, DNA evidence shows.

Illustration by Jen Christiansen

to a very large black hole, Sagittarius A*, which produces intense outbursts of radiation from time to time.

Then there is the problem of even more energetic events called gamma-ray bursts. Using recent gravitational-wave studies, astronomers learned that some of these explosions are caused by merging neutron stars. Observations of gamma-ray bursts in other galaxies show that they are more common in the crowded inner regions of galaxies. A single burst could sterilize the core of the Milky Way, and statistics based on studies of other galaxies suggest that one occurs in ours every one million to 100 million years.

Farther from the center, all these catastrophic events have less impact, but stars are sparser and metallicity is lower, so there are fewer rocky planets, if any. Taking everything into account, astronomers such as Charles H. Lineweaver of the Australian National University infer that there is a "galactic habitable zone" extending from about 23,000 to 30,000 light-years from the galactic center—only about 7 percent of the galactic radius, containing fewer than 5 percent of the stars because of the way they are concentrated toward the core. That region still encompasses a lot of stars but rules out life for the majority of them in our galaxy.

The sun is close to the middle of the habitable zone, but other astronomical idiosyncrasies distinguish our solar system. For example, there is some evidence that an orderly arrangement of planets in nearly circular orbits providing long-term stability is uncommon, and most planetary systems are chaotic places, lacking the calm Earth has provided for life to evolve.

SPECIAL PLANET

ALL THE TALK OF EARTH-LIKE PLANETS obscures another critical distinction. Astronomers have found around 50 of these worlds, but when they say "Earth-like," all they mean is a rocky planet in the habitable zone that is about the same size as ours. By this criterion, the most Earth-like planet we know is Venus—but you could never live there. The fact that you can live on Earth is the result of fortuitous circumstances.

The two planets differ in several important ways. Venus has a thick crust, no sign of plate tectonics and essentially no magnetic field. Earth has a thin, mobile crust where tectonic activity, especially around plate boundaries, brings material to the surface through volcanism. Over Earth's long history, this activity has carried ores up to where humans can mine them to provide the raw materials for our technological civilization. Plate tectonics has also brought nutrients to the surface to replenish those that get depleted by the cells living there, and it is crucial for recycling carbon and stabilizing the temperature over long timescales. Earth also has a large metallic (in the everyday sense of the word) core that, coupled with its rapid rotation, produces a strong magnetic field to shield its surface from harmful cosmic radiation. Without this screen, our atmosphere would probably erode, and any living thing on the surface would get fried.

All these attributes of our planet are directly related to our moon—another feature that Venus and many other Earth-like planets lack. Scientists' best guess is that the moon formed early in the solar system's history, when a Mars-size object struck the nascent Earth a glancing blow that caused both protoplanets to melt. The metallic material from the two objects settled into Earth's center, and much of our planet's original lighter rocky material splashed out to become the moon, leaving Earth with a thinner crust than before. Without that impact, Earth would be a sterile lump of rock like Venus, lacking a magnetic field and plate tectonics. The presence of such a large moon has also acted as a stabilizer for our planet. Over the millennia Earth has wobbled on its axis as it goes around the sun, but thanks to the gravitational influence of the moon, it can never topple far from the vertical, as seems to have happened with Mars. It is impossible to say how often such impacts occur to form double systems such as Earth and its moon. But clearly they are rare, and without our satellite we would likely not be here.

SPECIAL LIFE

ONCE THE EARTH-MOON SYSTEM settled down, life emerged with almost indecent rapidity. Leaving aside controversial claims for evidence of even earlier creatures, scientists have found fossil remains of single-celled organisms in rocks 3.4 billion years old—just about a billion years younger than Earth itself. At first, this sounds like good news for anyone hoping to find extraterrestrials—surely if life got started on Earth so soon, it could arise with equal ease on other planets? The snag is that although it started, it did not do much for the next three billion years. Indeed, microbes that are essentially identical to those original bacterial cells still live on Earth today—arguably the most successful species in the history of life on our planet and a classic example of "if it ain't broke, don't fix it."

These simple cells, known as prokaryotes, are little more than bags of jelly, containing the basic molecules of life (such as DNA) but without the central nucleus and specialized structures such as mitochondria, which use chemical reactions to generate the energy needed by the cells in your body. The more complex cells, the stuff of animals and plants, are known as eukaryotes, and they are all descended from a single merging of cells that occurred about 1.5 billion years ago.

The merger involved two types of primordial single-celled organisms: bacteria and archaea. The latter

John Gribbin is a science writer, an astrophysicist and a visiting fellow in astronomy at the University of Sussex in England. He is author of *Alone in the Universe* (Wiley, 2011).

are so named because they were once thought to be older than bacteria. The evidence now suggests that both forms emerged at about the same time, when life first appeared on Earth—meaning that however life got started, it actually emerged twice. Once it was here, it went about its business largely unchanged for about two billion years. That business involved, among other things, "eating" other prokaryotes by engulfing them and using their raw materials.

Then came the dramatic turning point: An archaeon engulfed a bacterium but did not "digest" it. The bacterium became a resident of the new cell, the first eukaryote, and evolved to carry out specialized duties within it, leaving the rest of the host free to develop without worrying about where it got its energy. The cell then repeated the trick, becoming more complex.

The similarities between the cells of all advanced life-forms on Earth show that they are descended from a *single* single-celled ancestor—as biologists are fond of saying, at the level of a cell there is no difference between you and a mushroom. Of course, the trick might have happened more than once, but if it did, the other protoeukaryotes left no descendants (probably because they got eaten). It is a measure of how unlikely such a single fusion of cells was that it took two billion years of evolution to occur.

Even then, not much happened for another billion years or so. Early eukaryotes got together to make multicellular organisms, but at first these were nothing more than flat, soft-bodied creatures resembling the structure of a quilt. The proliferation of multicellular life-forms that led to the variety of life on Earth today only kicked off nearly 550 million years ago, in an outburst known as the Cambrian explosion. This was such a spectacular event that it is still the most significant one in the fossil record. But nobody knows why it happened—or how likely it is to happen elsewhere. Eventually that eruption of life produced a species capable of developing technology and wondering where it came from.

SPECIAL SPECIES

THE PROGRESSION from primitive to advanced species was not easy. The history of humanity is written in our genes, in such detail that it is possible to determine from DNA analysis not only where different populations came from but how many of them were around. One of the surprising conclusions from this kind of analysis is that groups of chimpanzees living close to one another in central Africa are more different genetically than humans living on opposite sides of the world. This can only mean that we are all descended from a tiny population of humans, possibly the survivors of some catastrophe or catastrophes.

DNA evidence pinpoints two evolutionary bottlenecks in particular. A little more than 150,000 years ago the human population was reduced to no more than a few thousand—perhaps only a few hundred—breeding pairs. And about 70,000 years ago the entire human population fell to about 1,000. Although this interpretation of the evidence has been questioned by some researchers, if it is correct, all the billions of people now on Earth are descended from this group, which was so small that a species diminished to such numbers today would likely be regarded as endangered.

> Even if we are not the only technological civilization in the galaxy, we must be one of the first. Is another such civilization likely to exist today? Almost certainly no.

That our species survived—and even flourished, eventually growing to number more than seven billion and advancing into a technological society—is amazing. This outcome seems far from assured.

As we put everything together, what can we say? Is life likely to exist elsewhere in the galaxy? Almost certainly yes, given the speed with which it appeared on Earth. Is another technological civilization likely to exist today? Almost certainly no, given the chain of circumstances that led to our existence. These considerations suggest we are unique not just on our planet but in the whole Milky Way. And if our planet is so special, it becomes all the more important to preserve this unique world for ourselves, our descendants and the many creatures that call Earth home. SA

MORE TO EXPLORE

The Galactic Habitable Zone and the Age Distribution of Complex Life in the Milky Way. Charles H. Lineweaver et al. in *Science,* Vol. 303, pages 59–62; January 2, 2004. Preprint available at https://arxiv.org/abs/astro-ph/0401024

Alone in the Universe: Why Our Planet Is Unique. John Gribbin. Wiley, 2011.

FROM OUR ARCHIVES

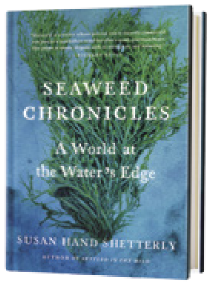
Cosmic (In)Significance. Caleb Scharf; August 2014.

scientificamerican.com/magazine/sa

By Andrea Gawrylewski

Seaweed Chronicles: A World at the Water's Edge

by Susan Hand Shetterly. Algonquin Books, 2018 ($24.95)

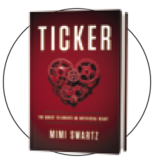


BLADDER WRACK seaweed on the Orkney Islands in Scotland.

With the word "weed" in its name, seaweed certainly seems like a resource as unnecessary as it is inexhaustible. But nature writer Shetterly details why this hardy alga deserves safeguarding. In evocative prose, she describes seaweed's role in the environment, especially in her coastal home of "Downeast Maine," and the people who study, harvest, sell, eat and protect it. She profiles fishers who because their fishery has been depleted have switched to gathering a variety known as rockweed for industrial and culinary uses, as well as activists fighting to regulate the harvest to prevent rockweed from disappearing as the fish did. Shetterly also takes a seaweed cooking class, visits a factory for "Kelp Krunch bars" and travels with a biologist who studies how baby eider ducks depend on seaweed to survive. *—Clara Moskowitz*

Ticker: The Quest to Create an Artificial Heart

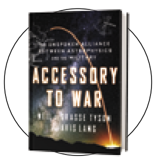
by Mimi Swartz. Crown, 2018 ($27)



It was 1963, and O. H. "Bud" Frazier, then a medical student, had his hands wrapped around a patient's heart—his forceful massage the sole act keeping the man alive. Journalist Swartz chronicles the decades-long evolution of top U.S. cardiac surgery programs through intimate profiles of the field's most prominent practitioners as they race to build an artificial heart. She captures details of the profession with panache: a split-second decision to put a sheep's heart into a human body, the challenge of engineering a device that can maintain blood temperature for hours. Ultimately, she contends, cardiology was at the mercy of outside forces. When the *Challenger* shuttle exploded in 1986, Swartz writes, that failure translated into more skepticism toward all technology-based fields and a long-term dip in funding for heart surgery programs. Even matters of the heart do not unfold in isolation. *—Maya Miller*

Accessory to War: The Unspoken Alliance between Astrophysics and the Military

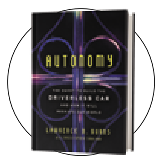
by Neil deGrasse Tyson and Avis Lang. W. W. Norton, 2018 ($30)



"The roster of nations that have wielded the most power on the world stage … are precisely those nations whose scientists knew the most about the universe at any given time," assert astrophysicist Tyson and writer Lang in this comprehensive exploration of the long-standing synergy between astronomy and warfare. The stars guided prophesying seers and bloodthirsty raiders in remote antiquity; telescopes were beloved tools in the academies and battlefields of Renaissance Europe; rockets and satellites are now vital for both generals and Nobel Prize–winning academics. Understanding how and why "the soft power of cosmic discovery" promotes military might, the authors contend, is crucial for stimulating further progress in space science—and perhaps even lasting peace on Earth. *—Lee Billings*

Autonomy: The Quest to Build the Driverless Car—And How It Will Reshape Our World

by Lawrence D. Burns, with Christopher Shulgan. Ecco, 2018 ($27.99)



Self-driving cars, once heroic engineering prototypes confined to desert race courses, are now being tested around the Phoenix, Ariz., metropolitan area—arguably, the greatest transition in mobility since the automobile began. Burns, who led R&D at General Motors for years and consulted on Google's autonomous car project, is an unabashed booster for the technology. But he and writer Shulgan vividly recount the painful birth of the first robotic racers and highlight the missteps, egos and legal battles that have hampered its progress. Insider drama aside, they present a compelling vision of a future with many fewer cars, less pollution, less congestion—and more freedom to move than ever before. *—W. Wayt Gibbs*

IAIN SARJEANT *Getty Images*

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

Abortion Facts

Education and birth control are slowly making the politics less relevant

By Michael Shermer

In May of this year the pro-life/pro-choice controversy leapt back into headlines when Ireland overwhelmingly approved a referendum to end its constitutional ban on abortion. Around the same time, the Trump administration proposed that Title X federal funding be withheld from abortion clinics as a tactic to reduce the practice, a strategy similar to that of Texas and other states to shut down clinics by burying them in an avalanche of regulations, which the U.S. Supreme Court struck down in 2016 as an undue burden on women for a constitutionally guaranteed right. If the goal is to attenuate abortions, a better strategy is to reduce unwanted pregnancies. Two methods have been proposed: abstinence and birth control.

Abstinence would obviate abortions just as starvation would forestall obesity. There is a reason no one has proposed chastity as a solution to overpopulation. Sexual asceticism doesn't work, because physical desire is nearly as fundamental as food to our survival and flourishing. A 2008 study published in the *Journal of Adolescent Health* entitled "Abstinence-Only and Comprehensive Sex Education and the Initiation of Sexual Activity and Teen Pregnancy" found that among American adolescents ages 15 to 19,

"abstinence-only education did not reduce the likelihood of engaging in vaginal intercourse" and that "adolescents who received comprehensive sex education had a lower risk of pregnancy than adolescents who received abstinence-only or no sex education." A 2011 *PLOS ONE* paper analyzing "Abstinence-Only Education and Teen Pregnancy Rates" in 48 U.S. states concluded that "increasing emphasis on abstinence education is positively correlated with teenage pregnancy and birth rates," controlling for socioeconomic status, educational attainment and ethnicity.

Most telling, a 2013 paper entitled "Like a Virgin (Mother): Analysis of Data from a Longitudinal, US Population Representative Sample Survey," published in *BMJ* reported that 45 of the 7,870 American women studied between 1995 and 2009 said they become pregnant *without sex.* Who were these immaculately conceiving parthenogenetic Marys? They were twice as likely as other pregnant women to have signed a chastity pledge, and they were significantly more likely to report that their parents had difficulties discussing sex or birth control with them.

When women are educated and have access to birth-control technologies, pregnancies and, eventually, abortions decrease. A 2003 study on the "Relationships between Contraception and Abortion," published in *International Family Planning Perspectives,* concluded that abortion rates declined as contraceptive use increased in seven countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Bulgaria, Turkey, Tunisia and Switzerland). In six other nations (Cuba, Denmark, the Netherlands, Singapore, South Korea and the U.S.), contraceptive use and abortion rates rose simultaneously, but overall levels of fertility were falling during the period studied. After fertility levels stabilized, contraceptive use continued to increase, and abortion rates fell.

Something similar happened in Turkey between 1988 and 1998, when abortion rates declined by almost half when unreliable forms of birth control (for one, the rhythm method) were replaced by more modern technologies (for example, condoms). Public health consultant Pinar Senlet, who conducted the 2001 study published in *International Family Planning Perspectives,* and her colleagues reported that "marked reductions in the number of abortions have been achieved in Turkey through improved contraceptive use rather than increased use."

To be fair, the multivariable mesh of correlations in all these studies makes inferring direct causal links difficult for social scientists to untangle. But as I read the research, when women have limited sex education and no access to contraception, they are more likely to get pregnant, which leads to higher abortion rates. When women are educated about and have access to effective contraception, as well as legal and medically safe abortions, they initially use both strategies to control family size, after which contraception alone is often all that is needed and abortion rates decline.

Admittedly, deeply divisive moral issues are involved. Abortion does end a human life, so it should not be done without grave consideration for what is at stake, as we do with capital punishment and war. Likewise, the recognition of equal rights, especially reproductive rights, should be acknowledged by all liberty-loving people. But perhaps progress for all human life could be more readily realized if we were to treat abortion as a problem to be solved rather than a moral issue over which to condemn others. As gratifying as the emotion of moral outrage is, it does little to bend the moral arc toward justice. 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.

Furry Business

Castor canadensis constructed a continent

By Steve Mirsky

The Hoover Dam on the border of Nevada and Arizona is 726 feet high and 1,244 feet across. But another dam in Michigan's Upper Peninsula is more impressive. Made of wood, mud, rocks and whatever other materials were available, this dam is six feet high and more than 260 feet long. And it's more impressive because the builders had no printed plans, heavy equipment or opposable thumbs. They lacked hard hats but had hard teeth. To accomplish the feat, they also relied on their feet, the rear two of which are webbed. And their determined brains come hardwired for aquatic architecture. You probably don't need to be slapped with its broad, flat tail to have by now sussed out that we're talking about *Castor canadensis,* aka the North American beaver.

The Michigan dam description comes from environmental journalist Ben Goldfarb's engrossing and elegantly written new book *Eager: The Surprising, Secret Life of Beavers and Why They Matter*. People have used them for food, currency and hat-making material—the human desire for warm and stylish chapeaus almost wiped beavers out. But their population is rebounding as we recognize that beavers can restore ecosystems. Goldfarb quotes one scientist's wise counsel: "Let the rodent do the work."

Before the near clear-cutting of the species, beavers engineered great swaths of North America: a study found that prior to the arrival of undocumented immigrants from Europe, the continent was the site of between 15 million and 250 million beaver ponds.

Goldfarb guesstimates, using midrange numbers and pond sizes, that beavers submerged some 234,000 square miles. Real estate busts don't leave that much property underwater. A lot of that saturated, wet, moist or merely damp land dried up after "trappers de-beavered North America," as Goldfarb puts it, which "left behind some of the finest soil a farmer could till." The bountiful agricultural output of the young U.S. and Canada rested on the shoulders of rodent giants.

The ghosts of beavers past still haunt New York City, where *Scientific American* is based. Our official city seal features two beavers. The walls of the Astor Place subway station include bas-relief beavers gnawing on terra-cotta tree trunks. (John Jacob Astor made his financial killing on beaver furs.) And a few short blocks north of our current offices, you can stroll down Beaver Street. Or flee down it, depending on the situation. What I didn't know until I read Goldfarb's book was that when the Dutch bought Manhattan from the Lenape in 1626, the island "was little more than a pot-sweetener: The real prizes were the 7,246 beaver skins that sailed to Europe." I now choose to think that self-portraits by the hatted Vermeer and Rembrandt include New York City beavers on the masters' heads.

Within its wide scope, *Eager* includes other nuggets sure to make you the most fascinating conversationalist at your next party. Which, if it's in Sweden, could include the drink brand BVR HJT (pronounced *bäverhojt* or called "beaver shout"). It's schnapps flavored with beaver musk. One blogger wrote that the drink wasn't strong, but the smell that soon seeped from her skin was.

Nugget: Beavers engage in "caecotrophy, eating their own pudding-like excretions to extract every last iota of nutrition." Goldfarb notes that after the second go-through, what comes out of the beaver is "nearly sawdust." Perhaps an enterprising ecology Ph.D. candidate can one day quantify "nearly."

Nugget: Beavers have a second set of lips behind their teeth, thereby "permitting them to chew and drag wood without drowning." Once exposed to that information, the reader will immediately recognize the necessity of that evolutionary innovation. The reader could also be creeped out.

Nugget: In 2016 canoeists noticed a prosthetic leg, presumably load-bearing, in a beaver dam in Wisconsin. They plucked it out, found the owner via a Craigslist ad and returned it. He'd lost it a few weeks earlier when his canoe tipped over. As he told a local news outlet, "I wasn't overly worried about it, because I use my older model for fishing and hunting.... It wasn't my everyday leg." Seems he took the whole episode in stride. SA

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Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

SEPTEMBER

1968 Advanced Lasers

"There are now hundreds of masers and lasers, generating frequencies over most of the electromagnetic spectrum, from the radio region far into the ultraviolet. Indeed, it seems that before long the art of stimulating emission will be extended into the X-ray region. Meanwhile the development of visible-light lasers is providing excitement enough. As we go to higher and higher powers, laser light is demonstrating extraordinary nonlinear phenomena in its interactions with matter. Some of the lasers now under development in the laboratory, such as the tunable and picosecond versions, are showing us that lasers so far have been rather simple devices. —Arthur Schawlow"

Schawlow shared the 1981 Nobel Prize in Physics for his work on laser light.

1918 Opposing the Sea

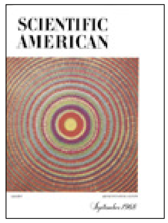
"After nearly 70 years of consideration, the people of the Netherlands are about to begin the partway draining of the Zuyder Zee in order to add quite 523,440 acres to Holland's present area of dry land. The stress of war and the task of harboring hundreds of thousands of refugees has brought Holland to a realization of her shortage of agricultural lands. Nothing less than a massive dike 18 miles long will suffice to shut in the Zuyder Zee and, at the same time, be sturdy enough to hold the North Sea at bay when in its angriest moods. The greatest height known to have been attained by waves along the coast of the Zuyder Zee was in December of 1883, when, owing to an exceptionally severe gale, the surf then mounted embankments fully 17 feet above normal high tide. The height of the dike above sea level will be 17.6 feet near the North Holland end."

War in the Air

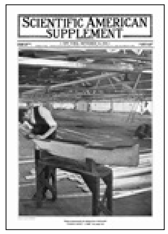
"Speed, climbing ability, and marksmanship are only three factors in aerial combat. It is safe to say that maneuvering skill is by far the most important factor. The aviator who knows every trick of his profession stands the best chance of winning or escaping. A 'stunt' frequently employed at the front is the upward swoop followed by a tail slide. When a machine is being pursued by another which is blazing away at the tail of the first, the usual maneuver for the first pilot is to pull the control stick backwards, heading his machine straight up until it attains a vertical position. Here it 'hangs' by its propeller for just an instant, as is strikingly shown in our cover sketch, when it slides back and is finally brought into the level position again. Now it is behind the opponent and possesses the advantage."

1918: Aerial combat was an evolving invention in the First World War. Here two airplanes fight it out in the sky.

SCIENTIFIC AMERICAN, VOL. CXIX, NO. 10; SEPTEMBER 7, 1918



1968



1918

1868

1868 Fashion Victims

"The medical journals are making a feeble crusade against the high-heeled and narrow-toed boots now in vogue. This fashion must be creating a rich harvest for the corn doctors, and it is sure to result in a greater or lesser degree of permanent deformity. When the heel is raised, as is the prevalent custom, the bones of the thigh, pelvis, and leg, as well as the foot, are thrown into abnormal positions; and the effect of such unnatural tension is sure to be perpetuated, in the shape of crooked shins, bandy legs, elephantine toe joints, and cramped ungraceful gait. Let us hope that before these evils shall have become greatly multiplied, fickle fashion may remove the cause, and give us something more sensible and endurable than these toe-screws."

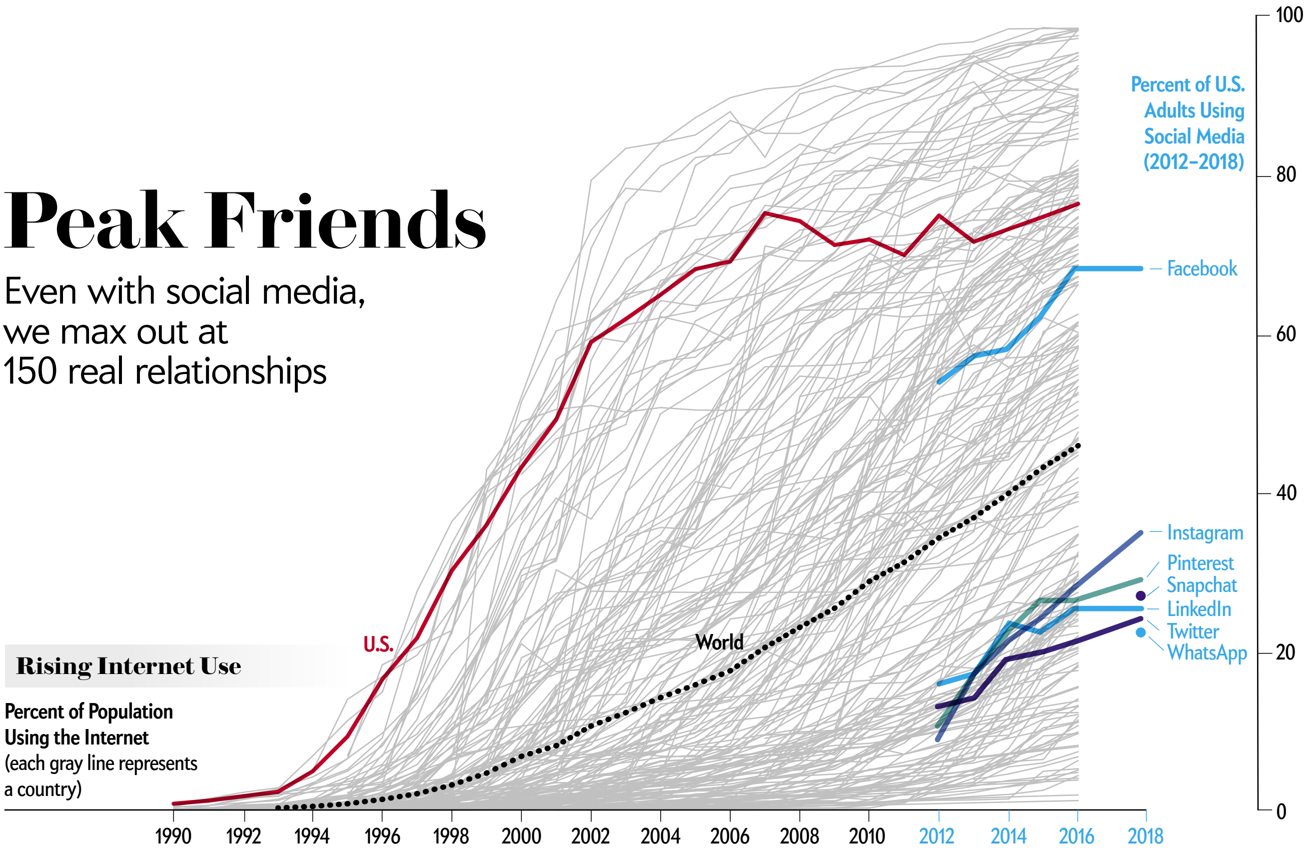
A Victorian Obsession

"The idea of being buried alive is one that fills the mind with horror, and the accounts which have from time to time appeared in the public prints, describing such occurrences, have always attracted the attention of a sensation-loving public. There are numerous and generally reliable tests for determining whether death has actually occurred previous to the commencement of decay, which are familiar to most people. Granted that in extremely rare cases, it is possible these should fail, it is difficult to perceive how Mr. Vester's patent burial-case is an improvement. It consists of an ordinary burial-case or coffin with a tube at the head, containing a ladder and a cord to enable the resuscitated individual to return to the upper air, provided he has strength to do it, which we think would in most cases be doubtful. The invention is claimed to be of inestimable service where parties have been interred while in a trance."

Text by Mark Fischetti | Graphic by Jen Christiansen

Peak Friends

Even with social media, we max out at 150 real relationships

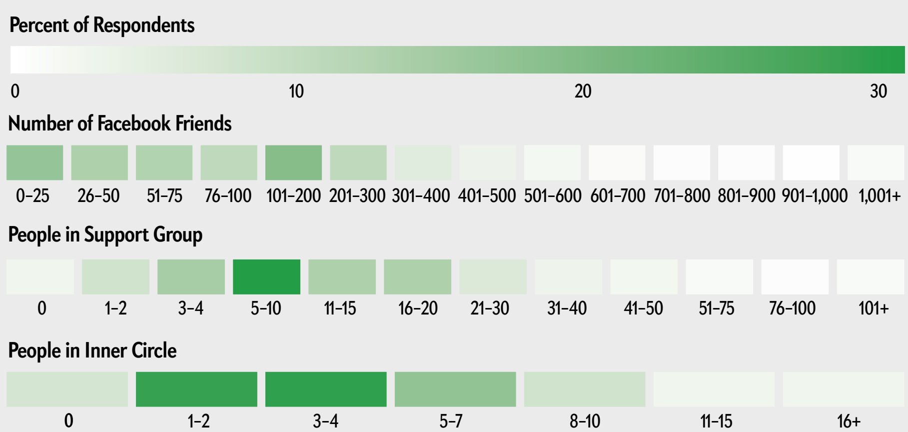


Humans are extremely social creatures. Anthropologists maintain that our hypersocial nature has helped us become a uniquely dominant species. Now social media allows a large percentage of people to communicate effortlessly worldwide (*large graph*), something no other animal can do.

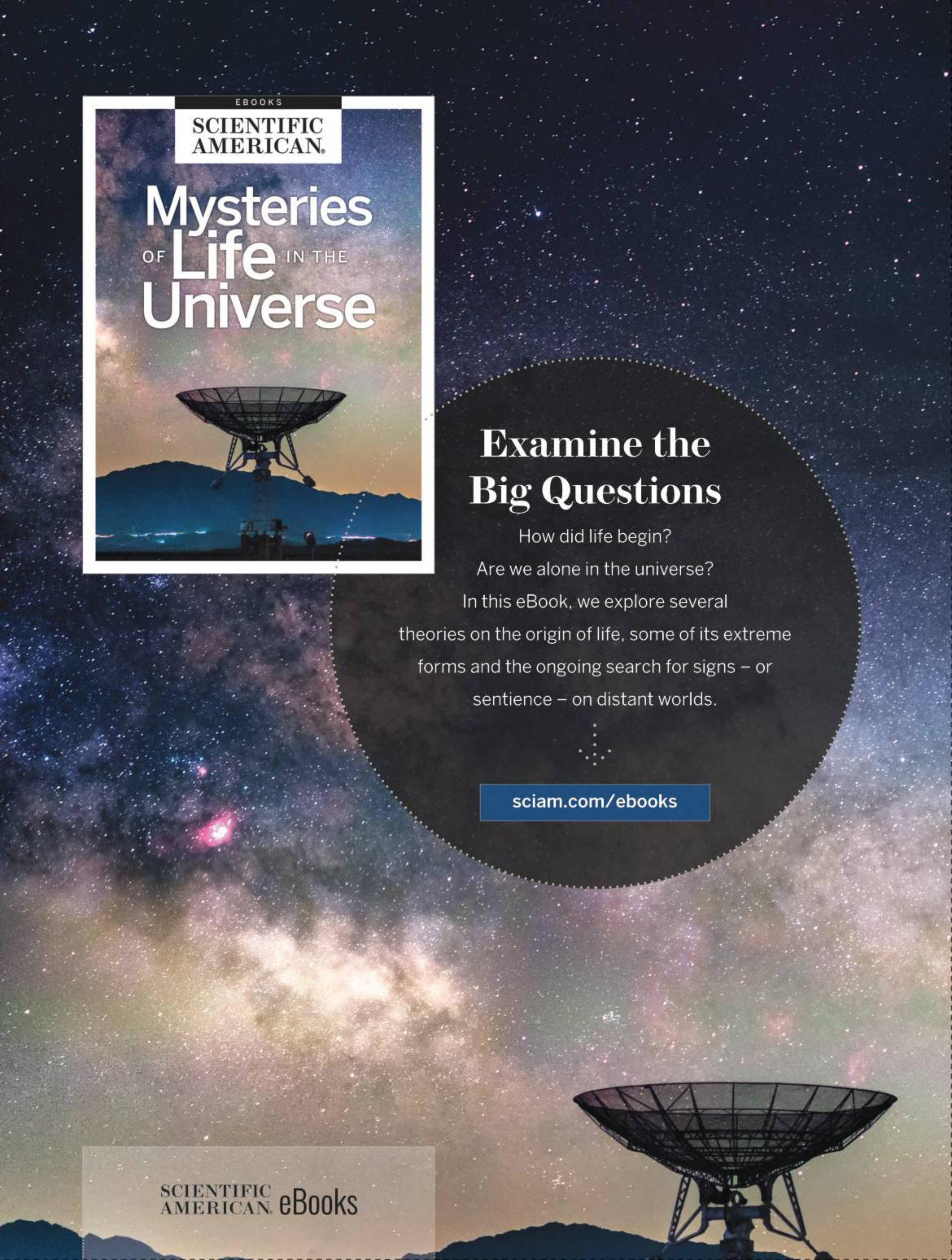
Yet despite running up hundreds of friends on Facebook and thousands of followers on Twitter, we are fooling ourselves, scientists say. We can really only maintain about 150 meaningful relationships at any time. Study after study confirms that most people have about five intimate friends, 15 close friends, 50 general friends and 150 acquaintances (*green bars*). Robin Dunbar, an evolutionary psychologist now at the University of Oxford, who had showed this pattern convincingly in the 1990s, revisited his old conclusions in a recent study of several thousand Facebook users. He found that despite social media's explosion, our network of significant contacts still maxes out at around 150. This threshold is imposed by brain size and chemistry, as well as the time it takes to maintain meaningful relationships, Dunbar says. "The time you spend," he adds, "is crucial."

The Facebook Test

In a 2016 study by Dunbar, 2,000 adults who said they use social media regularly were asked how many Facebook friends they had. They were then asked how many they would consider intimate friends (their inner circle) and how many they would go to for advice or sympathy in times of emotional stress (their support group). The replies mirror surveys from before social media's rise: most individuals have about five intimate friends, 15 people in their support group and 150 acquaintances.



SOURCES: INTERNATIONAL TELECOMMUNICATION UNION, WORLD TELECOMMUNICATION/ICT DEVELOPMENT REPORT AND DATABASE (*Internet use data*); PEW RESEARCH CENTER (*social media data*); "DO ONLINE SOCIAL MEDIA CUT THROUGH THE CONSTRAINTS THAT LIMIT THE SIZE OF OFFLINE SOCIAL NETWORKS?" BY R.I.M. DUNBAR, IN *ROYAL SOCIETY OPEN SCIENCE*, VOL. 3, ARTICLE NO. 150292; JANUARY 2016 (*Facebook friend survey data*)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