NAUTILUS

Playing War

GAMES, NOT MISSILES p.32

$12

SEPT/OCT 2015 Science Connected NAUTIL.US

Reimagining the Battlefield

War and gaming seem to be converging. Xbox controllers are being adapted for use in real weapons systems. A growing portion of United States Air Force pilots fly drones, manipulating joysticks from quiet suburbs. The U.S. military is experimenting with a gamified cyberwarfare platform called Plan X, complete with hit points and templates. Another of its platforms, called America's Army, has been a first-person-shooter recruiting tool for over a decade.

All of which gives us pause. Aren't death and destruction depersonalized when they are presented in the guise of a game? If war looks like Call of Duty, will we see war with the respect and caution it deserves?

On the other hand—what if gaming could avoid the need for war in the first place?

This was the hope of Buckminster Fuller, the American architect and inventor, when he proposed his "World Game" concept in the 1960s. Assets, troop deployments, and even ocean currents would be displayed on a map. An elaborate set of in-game negotiations would undercut the single-victor, zero-sum assumptions necessary for war. Lessons and conclusions from the game could be applied to the real world.

While Fuller's proposal wasn't taken up by Congress, it still serves as a remarkable (if virtual) endpoint for the long history of war games that preceded it. War games have been scaling up their realism for centuries, from early chess played with chariot and elephant pieces, through the numerical casualty tables of 19th-century Prussian *kreigsspiel*, to computerized Cold War simulations.

The first goal of these games has always been to increase the chances of victory on real battlefields. But they have also indicated when war might be unnecessary, or ineffective. At the beginning of the Vietnam War, for example, a U.S. military game predicted a physical stalemate on the battlefield, and significant public opposition.

America escalated anyway. After all, the warning had come from just a game. Would the warning have counted for more, if real military action looked like a game too?

Welcome to the September/October *Nautilus* print edition.

—*Michael Segal*
Editor in Chief

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—Alan Lightman, p. 84

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CONTACT

415 Madison Avenue, 13th Floor
New York, NY 10017
212 221 3870
info@nautil.us

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Nautilus has received financial support from:

John Templeton Foundation   SIMONS FOUNDATION   hhmi Howard Hughes Medical Institute

Published by

NAUTILUS *think*

Letters

Reader responses to the July/August 2015 print edition.

Nautilus *welcomes reader responses. Please email* letters@nautil.us. *All letters are subject to editing.*

"LIFE BEYOND THE PALE BLUE DOT"

It does seem remarkably anthropocentric to extrapolate our particular perceptions, born and evolved over a billion years in our specific natural environment, to the myriad of other worlds.

—George Gantz

"THE COLORS WE EAT"

Fascinating! It's all stuff I sort of knew in the back of my mind was true but seems absurd when actually confronted as fact. The idea that I'm so blindly swayed to taste and generally experience things differently by even tiny changes in their colour is so odd.

—Clem Mcculloch

"ABOUT YOUR SKIN"

Every racist in the universe needs to read this article.

—Anonymous

"THE LAST DROP OF WATER IN BROKEN HILL"

If they are still washing cars or watering plants outside at all, they are not even close to out of water.

—kgelner

"THE REINVENTION OF BLACK"

The later use of black in monochromes also relates to the more general developments in monochromatic art, minimalism in music, art, design, and perhaps also represents a revolt against both the sensory overstimulation and over-consumption of decadent modernity.

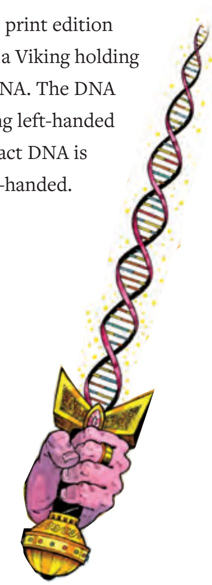
—Anonymous

CORRECTIONS

Due to an editorial error, "What's 250 Million Light-Years Big, Almost Empty, and Full of Answers?", which ran in the July/August 2015 print edition of *Nautilus*, incorrectly stated that it was proven "this year" that the gravitational signature of many voids together can be detected. It was proven in 2014.

The art on page 110 of the July/August 2015 print edition of *Nautilus* is © 2015 Artists Right Society (ARS), New York/ ADAGP, Paris. It was incorrectly credited.

The May/June 2015 print edition of *Nautilus* depicts a Viking holding double-stranded DNA. The DNA was drawn as having left-handed chirality, when in fact DNA is nearly always right-handed.

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Preludes

PSYCHOLOGY

Happiness Is Other People

In the future, a pill will make you happy. But not for long.

JAMES J. HUGHES HAS SEEN the future, and it smiled back. Hughes is a sociologist at Temple University, where he teaches public policy, and a former Buddhist monk. He is currently writing a book called *Cyborg Buddha* that delves into neurotechnologies that engineer our emotions. He has little doubt that we will soon be able to boost a host of happiness-causing compounds in our brains. Nanoscale technologies that marry robotics and pharmacology will give us mood bots that we ingest, which then travel to specific areas of the brain and turn happiness up or down. "We're going to be able to affect mood in increasingly precise ways in ordinary people," Hughes says.

This is just the beginning of the good news. Assuming we can navigate the challenges of climate change, wars, and stray asteroids whizzing past our planet, Hughes, executive director of the Institute for Ethics and Emerging Technologies, a think tank, believes new technologies will allow us to reduce poverty, hunger, and violence. "People are going to be happier and suffer from a lot less of the things that chronically screwed up the life of their ancestors," he says. "I see the end of a lot of diseases and cures for a lot of mental illnesses. Life expectancy will dramatically increase."

All of this might lead you to assume that Hughes sleeps well at night. If we feel a sense of well-being, and are not hungry, sick, or poor—if we can expect to live to be 200 without violence—what is there to worry about?

Actually, a lot. Hughes, and other researchers who think about the future, say we could engineer happiness, producing a hedonistic high, where we'd walk around in a great mood, shouting "Hello" to one another. But it's a fleeting sensation that can vary from moment to moment. Happiness through gene therapy is missing something essential.

Just listen to Nicholas A. Christakis, a Yale sociologist, who coauthored a seminal study showing that a significant boost in life satisfaction could be contributed to a particular gene (*5-HTTLPR*). "I'm very skeptical that technological advances will affect what I regard as foundational features of human nature," he says. "It's not just what the genes do inside our body, how they modify our neurophysiology or transmitters, but what the genes do outside our body, how they affect how many friends you make or whether you will pick happy or

Long-running Harvard study: Social connections keep you healthy and happy.

PHOTO BY BERNARD HOFFMAN/THE LIFE PICTURE COLLECTION/GETTY IMAGES

ILLUSTRATION BY NAFTALI BEDER

sad friends." What determines happiness, Christakis says, is "pretty constant across place and time": relationships.

What's the secret to happiness? Daniel Gilbert, a Harvard psychologist, and author of the best-selling book *Stumbling On Happiness*, has heard the question a hundred times. "That question could have been posed a few years ago, 300 years ago, 2,000 years ago," he says. "And it would never have been wrong to answer, 'You are the most social animal on earth. Invest in your social relationships; it will be a form of happiness.' "

George Vaillant is the former director of one of the longest and most comprehensive longitudinal studies on the development of healthy adults ever compiled: the Study of Adult Development at Harvard, previously known as The Grant Study in Social Adjustments. "The most important thing in happiness is to get the word out of your vocabulary," Vaillant says. "A great deal of happiness is simply hedonism: 'I feel OK because I've just had a Big Mac or a good bowel movement.' That has very little to do with a sense of wellbeing. The secret to wellbeing is experiencing positive emotions." And the secret to that, Vaillant says, might sound trite. But you can't argue with the facts. The secret is love.

"In the 1970s, I would have been laughed at" to suggest such a thing, Vaillant adds. "But here I was finding hard data to support the fact that your relationships are the most important thing in your wellbeing. It's been gratifying to find support for something as sentimental as love."

Robert Waldinger, a psychiatrist and Harvard Medical School professor who currently leads Harvard's Study of Adult Development, echoes his predecessor. "Close relationships and social connections keep you happy and healthy, and that is the bottom line. Humans are wired for personal connections."

Which brings us back to the future. Hughes worries that brain-boost happiness could remove us from relationships that benefit society and us. "It's not good to live in a land where everyone is walking around zoned out on bliss, having cranked their mood happiness up to 11," Hughes says. "We don't want people lying in the gutter saying, 'I'm happy here.' "

—Adam Piore

PSYCHOLOGY

The Lost Dream Journal of the Man Who Discovered Neurons

An exclusive look at the dreams Santiago Ramón y Cajal recorded to prove Freud was wrong.

SANTIAGO RAMÓN Y CAJAL, a Spanish histologist and anatomist known today as the father of modern neuroscience, was also a psychologist who believed psychoanalysis and Freudian dream theory were "collective lies." When Freud published *The Interpretation of Dreams* in 1900, the science world swooned over his theory of the unconscious. Puzzling dream images could unlock buried conflicts, the psychoanalyst said, given the correct interpretation. Cajal won the 1906 Nobel Prize for discovering neurons and intuiting the form and function of synapses. To disprove Freud's theory that every dream is the result of a repressed desire, Cajal kept a dream journal and collected the dreams of others, analyzing them with logic and rigor.

Cajal eventually deemed the project unpublishable. But before his death in 1934, he gave his research, scribbled on loose papers and in the margins of books, to his former student, the psychiatrist José Germain Cebrián. Germain typed the diary into a book, thought lost during the 1936 Spanish Civil War. In fact, he had kept the manuscript. Before his death, he gave it to José Rallo, a Spanish dream researcher. *Los Sueños de Santiago Ramón y Cajal* was published in Spanish in 2014, containing 103 of Cajal's dreams. Translated here into English for the first time, these dreams (illustrated by Federica Bordoni for *Nautilus*), and Cajal's notes on them, offer insight into the mind of a great scientist—insight that perhaps he himself did not always have.

A Common Dream

I attend a diplomatic soiree and as I am leaving my pants fall down (Is it desire?)
I take a walk by the bay (Santander?) and I fall into the water with one of my little daughters in my arms. I fight the waves, I am almost drowning, despite touching the seawall. The nightmare awakens me.

Morning Dream

12 December 1926
After lecturing from the podium on who knows what philosophical subjects. I find myself amongst friends. The question of what constitutes human nature is raised, I do not know how. Without allowing anyone else to speak in an authoritative tone and capturing the attention of my listeners—all friends and colleagues—(I hear myself proclaiming vehemently), I declare that the doctrines [—] of the unity of the human individual are an illusion, that in reality there are four men inside of us:

1. *The gangue man*, the cellular cadaver, the connective tissue, bone ***, intercellular materials X. It is the stuffing of life. Strength of stature is the façade and the plaster of the building.

2. *The glandular and sympathetic man*, that is to say, the set of internal and external secretory organs, coordinated by the *** sympathetic ganglia, governing vegetative life and controlling the higher individuals (emotional, synaesthetic) and the gangue man.

In the transcribed manuscript, [—] indicates where Cajal left a blank space in his original notes, while *** indicates where he crossed something out.

3. *The pneumonic and conscious man*, that is to say, the cerebral nervous system, the registry where sensory residues are stored. It is joined to the exterior world by the senses and to the higher self by certain cerebral pathways. This self can be conscious (sensation, perception) however it generally remains as a storage space for primary ideals (the "unconscious" of many authors). It produces the reflective and intuitive moment. The higher self is that active, imperious, conscious impulse, the selector that consults the files of the cerebral library, that [—] the pathways, decides on useful and deliberate reactions; attends, or not, to sensation; represses reflexes, moderates instincts and forges ideas

ILLUSTRATIONS BY FEDERICA BORDONI

and theories by changing the sensory material of the mind. This self is the critical self, that sees but is not seen, that in the dream state (hallucinatory orgy of the secondary self, fed up with contradictions says: Enough; all of this is an illusion, let us awaken. Believing that a representation is the self is like thinking that a photographic lens portrays itself. It would be possible if there were a mirror opposite. But in man there is no mirror of the self. The self is absolutely inaccessible. That which we take for a mirror, consciousness, only shows us the product of the [—] selection, thought to be the object, but what is thought to be the object is not what we think, but rather another part of the images about which one thinks …
The self is an energy, an invisible pull like a god …
Here I awaken.

Dream of the Printing Press

I find myself at a printer correcting copies of a book about regeneration. I discover that there are many letters missing, that prepositions are absent, and that syllables have run from one line to another. I am astonished and ashamed by all these errors.
Inconsistencies. I am not correcting book proofs during the course of the printing process, but rather a book that is printed and already for sale, and also translated into English. There is no point to my corrections, then. Moreover, the book, of which I do not desire to produce a new edition, was printed 12 years ago. I awaken.
Strong headache due to the stifling heat I feel while checking the errors, which are now unavoidable.
I am in Jaca.
This cannot be explained by Freud. There is nothing here but a reminiscence of a previous act with distortions.
I imagine that I am at Pueyo's press, where the book was not made. New inconsistencies.

—Ben Ehrlich

IDEAS

One Question, Two Scientists:

What scaling problem will your field need to solve in the future?

LUIS BETTENCOURT, ON CITIES:

The capital of the Galactic Republic in Star Wars, Coruscant, was once described as an "incandescent organ of life, visibly vibrating with the pulses of billions."

Cities have a special status in nature. They vastly surpass the imagination of any single individual. Despite attempts at control and regulation, they've always been subversive and creative places, capturing the successes and struggles of millions of human lives, past and present. In distilling these experiences in space and time, cities become near-magical places, mesmerizing and intense.

Present demographic trends suggest that by 2050, 2.5 billion more people may inhabit the planet. Megacities as big as 50 million will be a likely reality. These cities will be stranger and more intricate than anything that ever existed on Earth.

What will human imagination be capable of in this planet of megacities? The social psychologist Stanley Milgram thought surviving large cities meant adapting to information overload. Will the magnification of our imagination created by ever-larger cities result in collective schizophrenia? Or will it better human societies, garnering incredible new technologies, functioning politics, and a universal chance at the pursuit of happiness?

Cities may well be the greatest neuroscientific experiment ever performed.

—Luis Bettencourt is a professor of complex systems at the Santa Fe Institute.

JEREMY FREEMAN, ON NEUROSCIENCE:

The biggest problems in scaling neuroscience don't have to do with our experimental methods. They have to do instead with the institutions we use to evaluate and coordinate progress.

The independent path most young scientists are encouraged to pursue is both unrealistic, given the limits of funding, and unproductive, given the importance of collaboration. They end up vying for grants and promotions on which they are judged not by their creativity and abilities, but by their publications in high-profile journals.

So long as these largely for-profit entities are taken as the sole signifier of quality, scientists must waste precious time appeasing a slow, closed system, prone to personal bias, that ultimately places a tax upon the reproducibility of knowledge.

The Web can be a democratizing force for change. Research results are no longer just papers, but a rapidly evolving ecosystem of hardware, datasets, code, visualizations, techniques, and knowledge. With the Web, we can disseminate the entire output of the scientific process, as it develops, to the community and the wider public—where it ultimately belongs.

Only with open source and open science can we scale teams, projects, and even institutions, to build the neuroscience of the future.

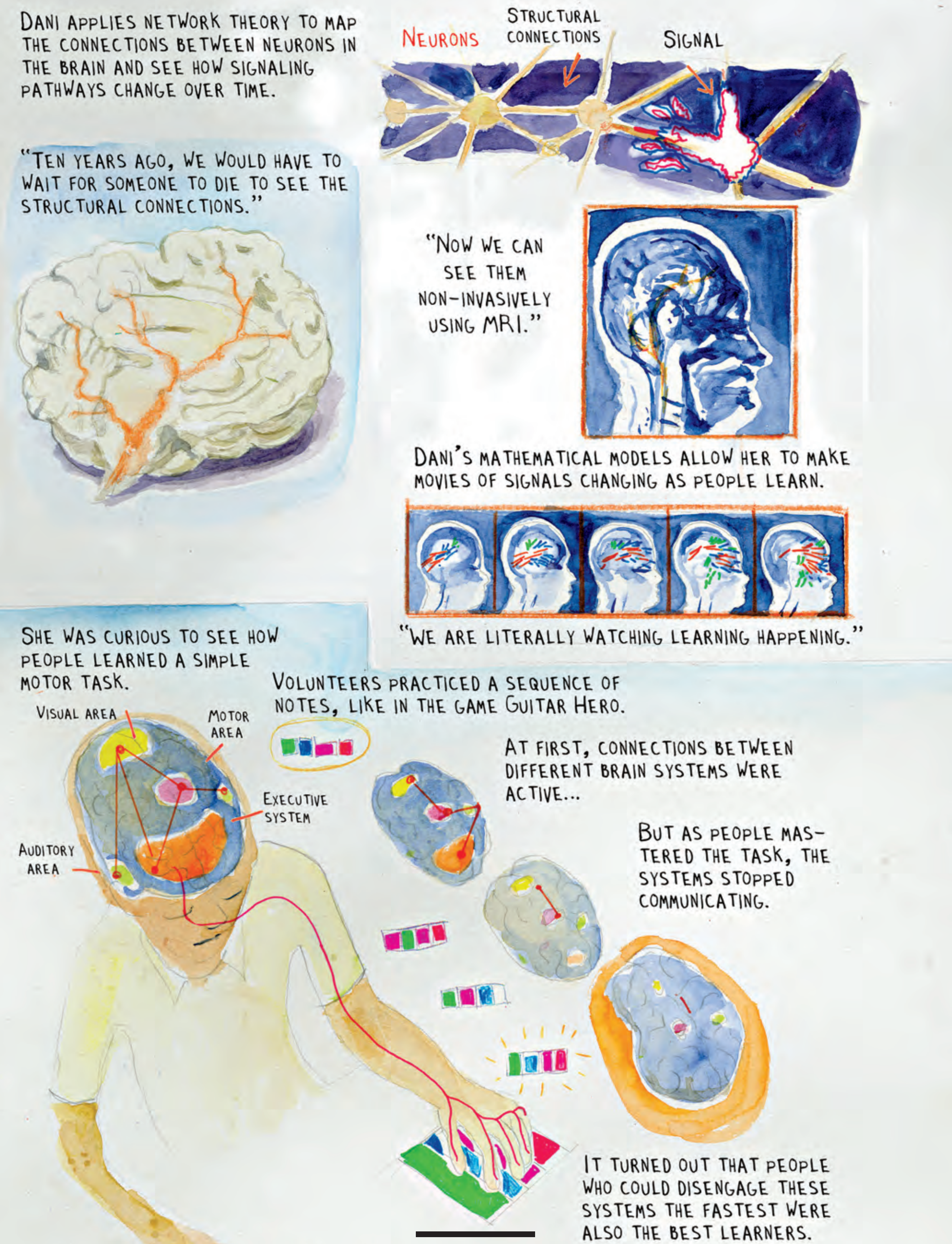
—Jeremy Freeman is a group leader and neuroscientist at the Janelia Research Campus.

ILLUSTRATION BY LEN SMALL

THE GENIUS OF LEARNING

BY LAUREN R. WEINSTEIN

A VISIT WITH PHYSICIST DANIELLE (DANI) BASSETT, MACARTHUR "GENIUS"


DANI APPLIES NETWORK THEORY TO MAP THE CONNECTIONS BETWEEN NEURONS IN THE BRAIN AND SEE HOW SIGNALING PATHWAYS CHANGE OVER TIME.
NEURONS
STRUCTURAL CONNECTIONS
SIGNAL
"TEN YEARS AGO, WE WOULD HAVE TO WAIT FOR SOMEONE TO DIE TO SEE THE STRUCTURAL CONNECTIONS."
"NOW WE CAN SEE THEM NON-INVASIVELY USING MRI."
DANI'S MATHEMATICAL MODELS ALLOW HER TO MAKE MOVIES OF SIGNALS CHANGING AS PEOPLE LEARN.
"WE ARE LITERALLY WATCHING LEARNING HAPPENING."
SHE WAS CURIOUS TO SEE HOW PEOPLE LEARNED A SIMPLE MOTOR TASK.
VISUAL AREA
MOTOR AREA
EXECUTIVE SYSTEM
AUDITORY AREA
VOLUNTEERS PRACTICED A SEQUENCE OF NOTES, LIKE IN THE GAME GUITAR HERO.
AT FIRST, CONNECTIONS BETWEEN DIFFERENT BRAIN SYSTEMS WERE ACTIVE...
BUT AS PEOPLE MASTERED THE TASK, THE SYSTEMS STOPPED COMMUNICATING.
IT TURNED OUT THAT PEOPLE WHO COULD DISENGAGE THESE SYSTEMS THE FASTEST WERE ALSO THE BEST LEARNERS.

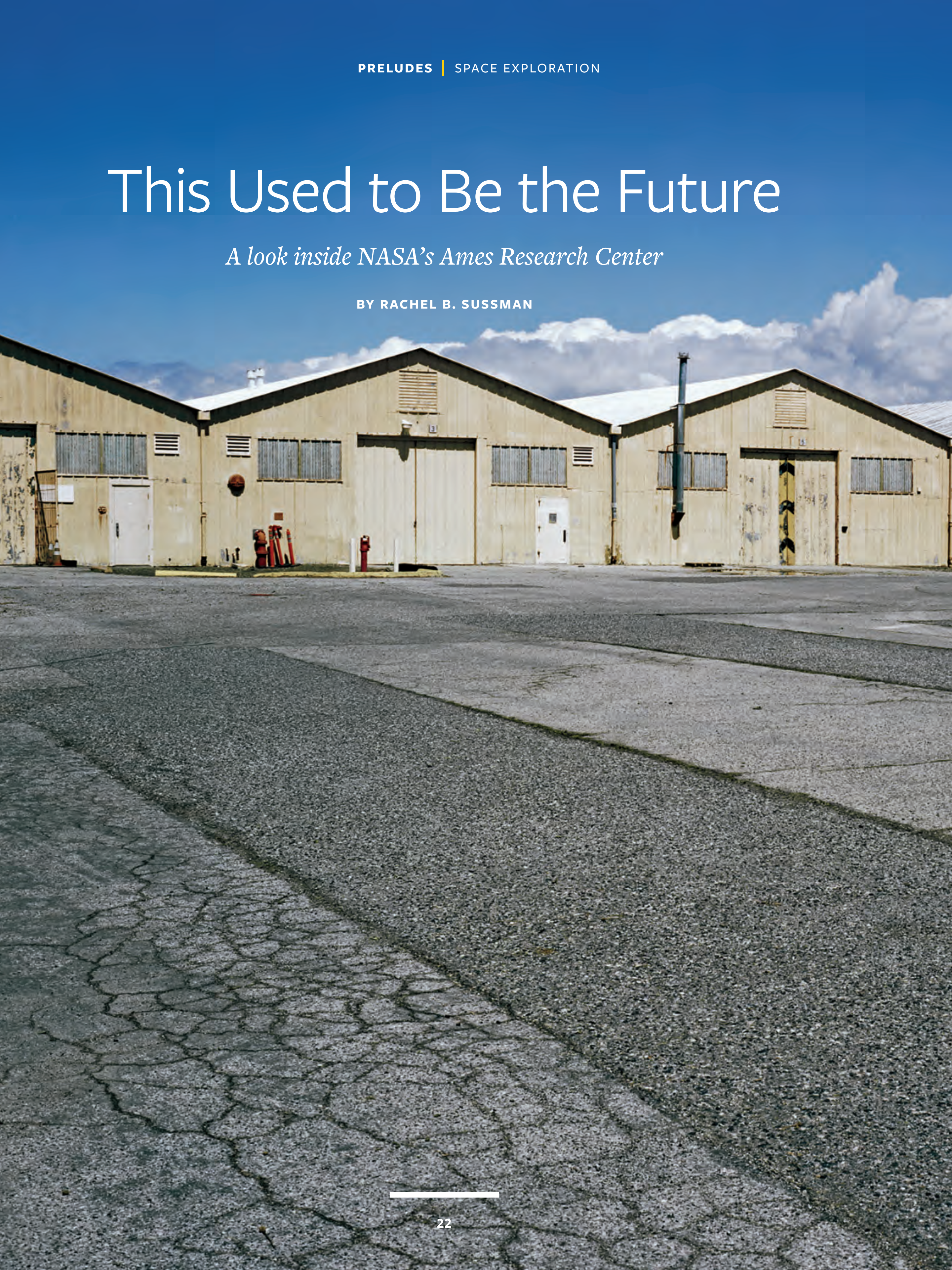

DANI SAYS THAT THE BIGGEST IMPEDIMENT TO LEARNING IS THE EXECUTIVE SYSTEM, THE PART OF THE BRAIN THAT MAKES CONSCIOUS DECISIONS.
EXECUTIVE SYSTEM
IT IS THE LAST BRAIN REGION TO DEVELOP. THIS KEEPS US FROM DELIBERATING TOO MUCH WHEN WE'RE YOUNG, MAKING LEARNING EASIER.
BUT WHEN WE GET OLDER, OUR INNER MANAGER CAN CAUSE US TO OVERTHINK THINGS.
SHE WANTS TO CREATE BETTER LEARNING ENVIRONMENTS FOR DIFFERENT KINDS OF MINDS.
DANI SAYS, "I KEEP THINKING OF WHAT MY DAD SAID TO ME WHEN WE PLAYED SOFTBALL."
You're trying too hard!
LOOKING AHEAD, HOW COULD WE DESIGN A CLASS THAT ENGENDERS FLEXIBILITY IN PEOPLE'S BRAINS? WHAT KIND OF THERAPIES OR INTERVENTIONS MIGHT BE HELPFUL?


SHE THEN INTRODUCES ME TO LAB MEMBER JOHN MEDAGLIA, A NEUROPSYCHOLOGIST. HE IS LOOKING FOR THE HUBS OF CONNECTIVITY THAT CONTRIBUTE TO COGNITIVE PROBLEMS.
HE PULLS FROM HIS BACKPACK A TRANSCRANIAL MAGNETIC STIMULATION (TMS) WAND.
IT'S A MAGNETIC COIL THAT GENERATES SMALL ELECTRIC CURRENTS IN THE PART OF THE BRAIN UNDER THE WAND.
TMS IS USED TO ALLEVIATE DEPRESSION AND MIGRAINES.
IF SCIENTISTS CAN BETTER UNDERSTAND THE NETWORKS BEHIND OTHER DISORDERS SUCH AS EPILEPSY AND PARKINSON'S, TMS MIGHT ONE DAY TREAT THOSE PROBLEMS TOO.
MAYBE IT COULD EVEN ENHANCE COGNITIVE ABILITIES, LIKE LEARNING.
DANI SHOWS ME OUT, MY BRAIN LOADED DOWN. SHE'S TELLING ME ABOUT A PROGRAM SHE FOUNDED TO TEACH KIDS ABOUT THE NETWORKED BRAIN. SOME OF THE KIDS DREW WHAT THEY IMAGINE THE CONNECTIONS INSIDE THEIR HEADS LOOK LIKE.
SO HOW DO *YOU* LEARN SOMETHING NEW?
I ASK MYSELF, AM I BEING FLEXIBLE?

This Used to Be the Future

A look inside NASA's Ames Research Center

BY RACHEL B. SUSSMAN



NASA AMES IS FILLED with the exotic technologies of a future that didn't quite come to pass. Ancient computers still operate equipment in the machine shop. A decommissioned nuclear missile sits in a parking lot, and the twin of the International Space Station sits out in the open air, under a tarp.

Originally dedicated as the Sunnyvale Naval Air Station in 1933, the site was to serve as a home base for the Navy dirigible, the U.S.S. Macon, which crashed in 1935. The Aeronautical Laboratory was founded in 1939, and in 1958 became a part of the newly formed National Aeronautics and Space Administration, or NASA. In its earliest days, Ames broke new ground in aerodynamics and high-speed flight. Today it is still an active participant in various NASA missions, including leading the Kepler space telescope mission, and partnering on the Mars Curiosity Rover.

I came to Ames as part of a creatively motivated examination of the felt experience of deep time and deep space, in conjunction with the LACMA Art + Tech Lab. How does one make art—let alone make sense—out of our human experience of the cosmos?

As I visited Ames, along with SpaceX, JPL, and CERN, I began to reconsider our contemporary relationship to space. Without fail, someone would always lament that we have never regained the promise and excitement of the early space era, epitomized by the moon landing. The Ames campus itself embodies that sentiment in its architecture; some structures are perfectly preserved and others are in varying degrees of disrepair.

As I took in the campus, I couldn't help but think: This used to be the future.

NASA AMES WAREHOUSE N-127
#0415-1301

Pre-fabricated surplus storage sheds, of a type that are common to Naval installations. The sheds contain the detritus from decades of research and experimentation, including machines, electronics and even old vehicles. As one employee put it, "If it's in the surplus sheds, it's junk."

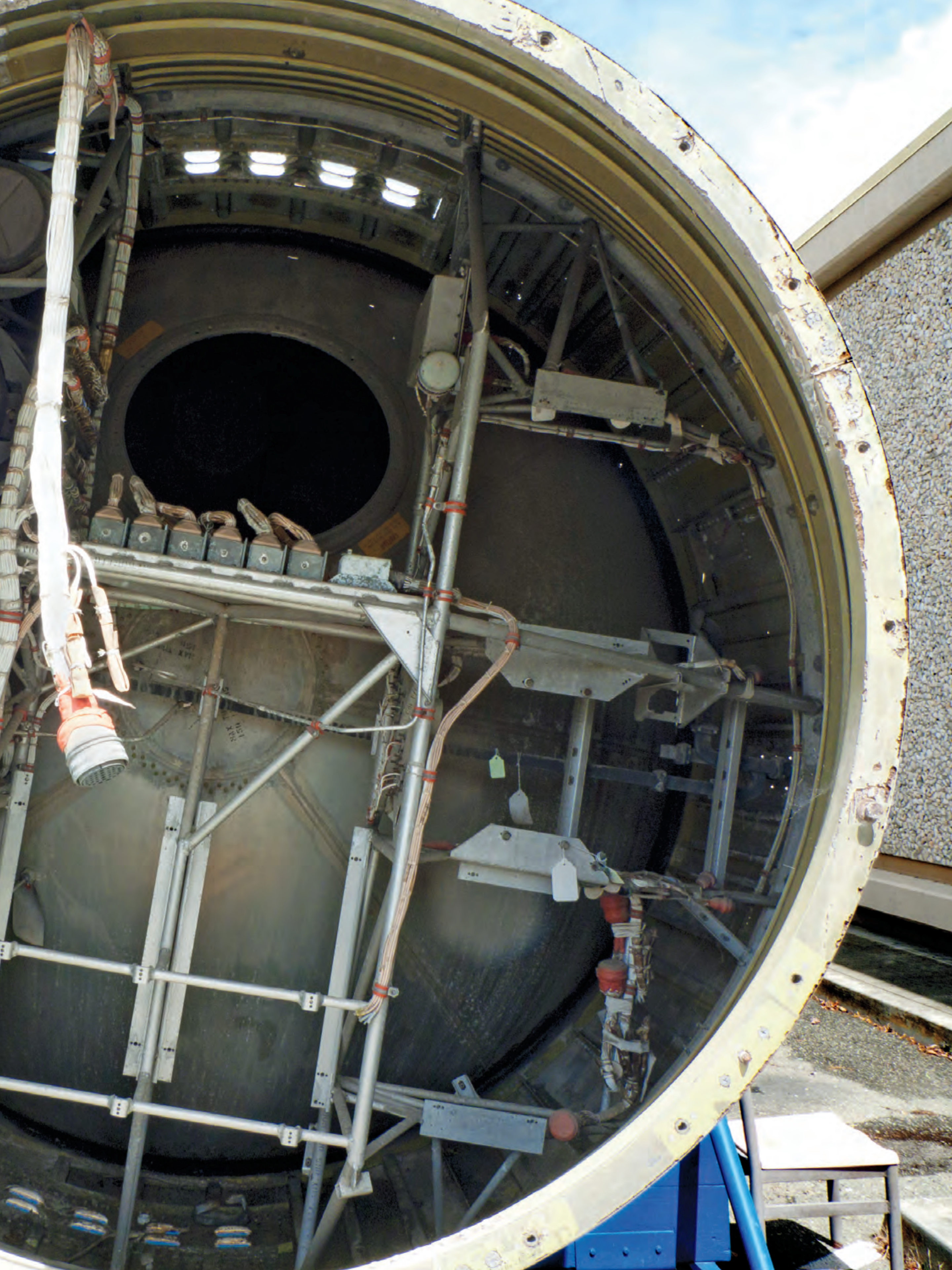
It was unclear what these particular sheds held, or the last time their bay doors had been opened.

TITAN I MISSILE (MCMOON PARKING LOT, NASA AMES) #0415-0415

On my first visit to NASA Ames, my contact took me to see the Titan, sitting in a parking lot next to an old McDonald's that had been converted into a moon research office. When we reached the nosecone he pointed out an unplugged cable, and asked me to guess what it might have connected to. I was stymied.

The Titan is an intercontinental ballistic missile. The cable was for a nuclear warhead.

I was struck how, up until this moment, I had not consciously contemplated the military aspects of space exploration. Later, when giving a lecture about my process at LACMA, someone asked me if my work is moral. My encounter with the Titan made clear to me that the answer is yes.



HANGAR ONE; MOFFETT FEDERAL AIRFIELD, NASA AMES #0415-3650

Hangar One was built in the 1930s to house "rigid airships," à la Hindenburg. It stands 200 feet tall, and covers a footprint of eight acres.

In the best thinking of the times, it was constructed with lead, PCBs, and asbestos, contaminating both the surrounding ground as well as San Francisco Bay. The toxins have all since been removed from the structure, leaving only its steel skeleton.

Hangar One will soon get a second life: It has recently been leased by Planetary Ventures, a Google subsidiary.

MICROBIAL MATS, NASA AMES RESEARCH GREENHOUSE #0415-1408

A row of research greenhouses, established in 1999, sits atop the roof of the astrobiology building. This one is filled with trays of cultivated microbial mats of cyanobacteria collected from a field site in Mexico, and maintained in corrosive brines.

One of the most ancient organisms on Earth, cyanobacteria could be similar to simple life on other planets. They could also indicate which organic compounds are associated with the presence of life.

Are You Smarter Than a Dolphin?

A lesson in animal intelligence

BY SHANNON HALL

WITHIN A FEW HOURS of Albert Einstein's death, his brain was removed from his skull, photographed from different angles and sliced into 240 chunks. It was then placed onto histological slides for research. Could Einstein's genius be identified in his brain tissue? At the root of this question was a hunger to pinpoint the exact relationship between the brain and intelligence.

Scientists have long been tempted to define an animal's intelligence based on brain size alone. A human's brain, after all, is larger than an ape's. But this was quickly threatened with the discovery of brains larger than ours, like elephants and whales. Although both animals have their brilliant moments—elephants grieve for their loved ones and whales send echoing calls to one another—neither can arguably compare to a human who explained gravity as a curvature in spacetime.

ILLUSTRATION BY JACKIE FERRENTINO

So maybe it isn't the brain's sheer size, but the brain's size relative to the body's size. Here, human beings come out close to the top. But so do mice. The ratio is biased toward small animals that have relatively large brains for their tiny bodies.

With one hypothesis thrown out, scientists turned to yet another ratio: Actual brain size relative to the predicted brain size for specific animals. Similarly sized bodies will require similarly sized brains to perform the same basic mechanical skills. Any extra brain mass can then go toward complex cognitive abilities. Or so the theory goes.

Here, human beings finally come out on top, with a so-called encephalization quotient (EQ) of 7.4, surpassing the dolphin's 4.1, the elephant's 2.0, and definitely the mouse's 0.5. In general, carnivores, cetaceans, and primates tend to come out above one (they need the extra brain mass for killing their prey, which in turn supplies their brain with the extra energy necessary to sustain it) and herbivores and insects below one.

But despite the fact that we're on top, is the EQ a fair measurement of intelligence across species? Many scientists argue no. Each animal serves a specific purpose in the circle of life. It's "like asking whether a hammer is a better tool than a screwdriver," says Brian Hare, an evolutionary anthropologist at Duke University. "Intelligence is anything but linear in light of evolution. A dolphin has sonar but would die if it tried to swing across trees, while bonobos can't even swim."

So the story is far from simple. Scientists are now looking at the number of neurons that fire within the brain or even the relative sizes of different structures within the brain. It may take another Einstein to discover the secret to a true genius.

Let's Play War

Could war games replace the real thing?

BY JONATHON KEATS

IN THE SPRING OF 1964, as fighting escalated in Vietnam, several dozen Americans gathered to play a game. They were some of the most powerful men in Washington: the director of Central Intelligence, the Army chief of staff, the national security advisor, and the head of the Strategic Air Command. Senior officials from the State Department and the Navy were also on hand.

Players were divided into two teams, red and blue, representing the Cold War superpowers. The teams operated out of separate rooms in the Pentagon, role-playing confrontation in Southeast Asia, simulated in a neutral command center. Receiving each team's orders, the command center's experts modeled the blue and red moves, and issued mock intelligence reports in response. Reports reflected the evolving conflict, but the intelligence was intentionally distorted to replicate the fog of war. After days of playing out different scenarios, the war gamers reached the conclusion that civilians in the United States and the rest of the world would vocally protest an American bombing offensive.

The need to anticipate the dynamics of conflict increased as the U.S. Congress passed the Gulf of Tonkin Resolution in August of 1964, effectively declaring war on North Vietnam. So another war game was played.[1] The objective was to play out the situation in Southeast Asia six months

ILLUSTRATION BY BRIAN STAUFFER

in the future. After ruling out an American nuclear attack, the teams role-played their way to a quagmire, in which the North Vietnamese countered every U.S. move in spite of lives lost and ruined infrastructure. The games forecast political crisis in the U.S., with no plausible path to American military victory. For the second time in a year, war games proved prescient, and also futile, as the government insisted on letting tragedy play out for real.

Buckminster Fuller foresaw the consequences of American intervention in Vietnam without the help of a military simulation. A professional visionary, Fuller was a self-made engineer-architect-inventor whose interests spanned from mathematics to philosophy. Born in Massachusetts in 1895, Fuller devoted his life to making "the world work for 100 percent of humanity, in the shortest possible time, through spontaneous cooperation, without ecological offense or the disadvantage of anyone."

As the Vietnam conflict spiraled out of control, Fuller had a solution. His idea was simple: Instead of playing secret war games deep inside the Pentagon, the United States should host a world peace game out in the open. The concept was an elaboration on his proposal to build a geoscope inside the U.S. Pavilion of the 1964 World's Fair. An animated Dymaxion world map would show all the resources on the planet, as well as all human and natural activity, from troop deployment to ocean currents.[2] On this map, the world's leaders and citizens of all nations would be invited to publicly wage peace. He cast the world game as a political system, a completely democratic alternative to voting in which people collectively played out potential solutions to shared problems.

GAMING PEACE Buckminister Fuller, at the head of the table, leads a seminar on his World Game in New York City in 1969. His Dymaxion map on the wall behind him envisions all the continents on Earth as a single island in a sea, underscoring the world population's interdependence.

"The objective of the game would be to explore for ways to make it possible for anybody and everybody in the human family to enjoy the total earth without any human interfering with any other human and without any human gaining advantage at the expense of another," Fuller wrote. "To win the World Game everybody must be made physically successful. Everybody must win."

Fuller's world game was a means of achieving "desovereignization," the importance of which he illustrated with a vivid military metaphor. "We have today, in fact, 150 supreme admirals and only one ship—Spaceship Earth," he wrote. "We have the 150 admirals in their 150 staterooms each trying to run their respective stateroom as if it were a separate ship." Those supreme admirals embodied geopolitics for Fuller. His world game was presented as an alternative to their warring.

World games, Fuller insisted, were a remedy for war because they were the antithesis of war games, and an antidote to "zero-sum" game theory, a system in which conflicts were modeled mathematically to rationally determine the optimal strategy for winning. Fuller got his idea all the way to Capitol Hill. "Game theory," he informed the Senate Subcommittee on Intergovernmental Relations in 1969, "is employed by all the powerful nations today in their computerized reconnoitering in scientific anticipation of hypothetical World Wars III, IV, and V." The theory of war gaming, he said, "which holds that ultimately one side or the other must die, either by war or starvation, is invalid." The U.S. government rejected Fuller's plan. The Pentagon-funded RAND Corporation called his writings and Senate testimony "a potpourri of pitchmanship for an ill-conceived computer-based game" that would "retard real progress in the field."

Peace will require something that the Vietnam war games so obviously lacked: the willpower to act on what gaming can teach.

Yet for all the good reasons that Fuller and RAND had to be wary of each other, their differences were never as zero-sum as they professed. In the years since the Cold War, the relationship between games of war and peace has grown more nuanced, and intertwined in today's computer game industry. As the maverick inventor envisioned, multi-user war games, networked across the globe, could allow the world to play for peace.

At the same time, the world has arguably grown more unstable. A nuclear-fueled standoff between two superpowers has been replaced by the unpredictable violence of myriad terrorist factions from the Taliban to ISIS. The impotence of the U.S. military as a counterforce—despite trillions of dollars in spending—shows the limits of conventional strategic and tactical thinking. In 2014 and 2015, the Atlantic Council, a think tank devoted to international affairs, conducted ISIS war games that concluded the terrorist organization is essentially impervious to U.S. forces. World peace is more elusive than ever.

Gaming new ways to reduce conflict has never been more urgent. Success will require all of the wisdom that can be drawn from war games over time. It will also take something that the 1964 war games so obviously lacked: the willpower to act on what gaming can teach.

1. Participants in the Sigma I and II war games are a who's who of the Vietnam era, including Robert McNamara, McGeorge Bundy, and Earl Wheeler. Military historian Martin van Creveld observes that "except perhaps for a few medieval tournaments, probably in the whole of history no higher-ranking group of men had ever played a war game of any kind."

2. *Dymaxion*—a composite of *dynamic*, *maximum*, and *tension*—was a sort of brand name Fuller applied to most everything he came up with.

WAR GAMES ARE AS ANCIENT AS GAMING, and as primordial as war. Some of the most archaic games from China and Greece, such as *weiqi* and *petteia*, modeled the tactical movement of soldiers. And chess, the ultimate game of strategy, is a direct forerunner to the Pentagon's Cold War simulations.

In its ancient Indian form, chess was called *chaturanga*. The game was played with markers signifying infantry, chariots, horses, and elephants, all overseen by pieces representing a vizier and monarch. Winning required the destruction of the opposing army or the capture of the king, much the same as in real battle at the time. While the game became less martial in outward appearance as it spread to Persia, China, and Europe, military men seem not to have been distracted by queens and bishops. The game provided mental training for commanders ranging from William the Conqueror to Tamerlane.

However, traditional chess, even when played with chariots and elephants, had obvious differences from battle. The opposing armies of chessmen were completely identical and the terrain was perfectly uniform, making the conflict artificially symmetrical. Both sides also had total knowledge of the entire battlefield, including all enemy positions. Orders were implausibly orderly, carried out instantaneously as each player politely took his turn. And there were no external factors akin to disease or storms. Chess was a closed system. Chaos and chance were eliminated.

This level of abstraction had obvious advantages. The purity of chess allowed players to focus on the grand challenge of anticipating an opponent's behavior while upsetting the opponent's expectations. But since strategic choices were never so stark in war, the most a commander could expect from chess was sharpened intellect, and there was always the threat that a young warrior would misunderstand what was being simulated and expect troops to obey as placidly as chess pieces.

Germany used war games to invent the blitzkrieg, Japan to occupy Pacific island outposts, and the U.S. to distinguish the Marine Corps.

Beginning in the 17th century, European military strategists considered ways in which to make chess conform more closely to real fighting so that chess could provide more well-rounded training. At first it was just a matter of enlarging the battlefield and making armies more varied with markers representing cavalry, artillery, and infantry. By the 18th century, the squares of the game board came to represent different kinds of terrain, either by varying their color or by transferring the grid onto a regional map. Rules were written to vary the speed at which troops advanced, based on whether they were on horse or foot, and whether they were crossing meadows or scaling mountains. Players were responsible for rudimentary logistics, ensuring there were supply lines to keep soldiers fed.

But that was just the beginning. The full transformation from chess to war games occurred in the 19th century, when a Prussian lieutenant named Georg von Reisswitz layered in aspects of a sandbox game invented by his father. The elder Reisswitz's game was played with ranks of toy soldiers engaged in mock combat, where the outcomes of ambushes and battles were decided by dice. (The results of each dice throw were tallied according to real battlefield statistics, specifying the range of casualties to be expected in any given scenario.) The young lieutenant replaced his father's sandbox battlefield with a flat topographic map, across which markers representing companies and units could be advanced at the rate permitted by the terrain. As in real warfare, neither side had total knowledge of the conflict. Each played on a separate board, with an umpire making his way back and forth. Rules derived from battlefield experience determined how much the umpire allowed each side to see of the opposition. Those rules also guided the dice-thrown results of combat. The game was known as *kriegsspiel*.

WORLD OF WARCRAFT, OLD SCHOOL Games got serious with *kriegsspiel* (German for war game), designed by a Prussian lieutenant. Each side advanced troops at a rate permitted by a certain terrain. Rules were derived from real battlefield experiences; the game became central to real military training.

CURTESY OF LOOK AND LEARN

The verisimilitude of *kriegsspiel* impressed Karl von Muffling, the Prussian chief of staff, when Reisswitz demonstrated his game in 1824. Muffling placed an article in the Prussian military weekly asserting that *kriegsspiel* balanced the "frivolous demands of a game" with the "serious business of war," and had game boards dispatched to every regiment. Thirteen years later, Muffling's successor, Helmuth von Moltke, promoted *kriegsspiel* even more, making the game central to officer training by periodically bringing the whole War College out to the Prussian border in order to game hypothetical enemy invasions. The game would be played on a map corresponding to the surrounding landscape. Precise data for each maneuver would be collected by marching the local garrison through the formations on the game board. On this basis, Moltke not only provided training but also supplied tactical plans for the garrison in case of actual invasion.

Yet as the realism of *kriegsspiel* increased, the rules governing it—and the effort of playing it—threatened to overwhelm war gaming. Partly this was a practical issue: The more time required to set up and play out a scenario, the smaller the number of scenarios that could be explored. But there was also the deeper risk that greater verisimilitude would paradoxically make gameplay less relevant. It was the opposite of the issue with chess, where the lessons learned were universal yet abstract. In *kriegsspiel*, the lessons were often so concrete as to be *sui generis*. And even if the perfect occasion arose for applying a war-gamed tactic, the complexity of *kriegsspiel* made it difficult to determine whether the results were biased by how the rules interacted.

In 1876, one of Moltke's officers, Colonel Julius von Verdy du Vernois, proposed an alternative: Replace the rules with the judgment of experienced umpires. "Free war games," as they were known, could be played in two adjoining rooms with nothing more than a pair of topographical maps and two sets of markers. The umpire passed back and forth between teams, collecting orders and providing intelligence. Instead of using charts, players used their instinct to estimate how fast troops could advance, and the outcomes of battles were decided—without dice or casualty tables—at the umpire's own discretion. This arrangement made the games fast like actual warfare, and the umpire knew the reason for his decisions, which meant he could help players to understand the outcome at any level of abstraction. The game was a prelude to discussion. Though Reisswitz-style games continued to be played, Verdy's influence was profound. His free *kriegsspiel* established a continuum from rigidity to openness, just as Reisswitz's rigid *kriegsspiel* established a continuum from abstraction to realism.

Robert F. Kennedy saw games as an alternative to political debate in which all interests could role-play their way to civil rights.

Games could be configured at any point along these two axes, optimized according to what the commander wished to achieve. And as wargaming developed, expectations increased. Games could be used for training officers, building camaraderie, identifying leaders, understanding enemies, anticipating conflicts, inventing tactics, testing strategies, predicting outcomes. In the United States, where *kriegsspiel* was imported in 1887, one of the first questions was logistical. The Naval War College gamed different scenarios to determine whether fuel supplies for battleships should be shifted from coal to oil. The games indicated that a switchover would be advantageous. The Navy did it, fortuitously modernizing their fleet in time for World War I.

In Europe, *kriegsspiel* was widely used to develop strategies for ground war. Given Prussian tradition—and German delusions of grandeur—Germany was especially active, developing whole file cabinets of battle plans. One of the most promising played out the invasions of Holland and Belgium in order to quash the French army before the British could assist. The game determined that Germany would triumph against France as long as ammunition could be rapidly replenished. For this purpose, Germany built the world's first motorized supply battalions, deployed in 1914. And the plan might have worked brilliantly, if the only players had been the German and French armies. But the German *kriegsspiel* failed to factor in the pride of Belgian civilians, who proved ready and able saboteurs—even of their own railroads—upsetting German momentum. Even more catastrophic, the game left out diplomacy which, by way of alliances, brought

America into the war—and not on the side of the Reich.

The defeat of Germany in World War I suggested the need for another dimension in war games: a sociopolitical axis. Depending on the circumstances, war games needed to model the non-military implications of military actions, and to do so from the local to the global scale. Only when all three axes were properly accounted for could a game function meaningfully. And the appropriate level of abstraction, openness, and inclusiveness were different for every situation and every purpose.

ALL THE MAJOR MILITARIES gamed at multiple levels in the interwar period, with varied results. Germany successfully used war games to invent the blitzkrieg, Japan gamed the maneuvers their navy would later use to occupy Pacific island outposts, and the U.S. gamed the amphibious tactics that distinguished the Marine Corps.

But games delving into politics were more treacherous. Free games played by Germany in the early '30s—in which participants included diplomats, industrialists, and journalists—failed even to protect the Weimar Republic from internal collapse. In Japan, the Total War Research Institute held political-military games in 1941 that simulated the political interests and military power of countries including the Soviet Union, Great Britain, and America. The games correctly predicted a Japanese defeat of England in the Far East, incorrectly anticipated a German victory over the U.S.S.R., and utterly discounted the resolve of the United States. Certainly there was no premonition of how political conditions in Nazi Germany would give America the scientific brainpower behind the Manhattan Project, ultimately leading to the atomic bombs dropped over Hiroshima and Nagasaki. The predictive aims of the 1941 games ended in colossal failure. However, the real problem had less to do with game mechanics or faulty data than the belief that *any* global interplay of cause and effect could be decisively modeled.

Arguably the United States used war games most effectively in World War II because the U.S. military was most attentive to their limitations. A post-war assessment by Admiral Chester Nimitz provides some insight into the American approach. "The war with Japan had been [enacted] in the game room here by so many people in so many different ways that nothing that happened during the war was a surprise—absolutely nothing except the Kamikaze," he said. In other words, the U.S. wasn't presuming to predict the future—to simulate geopolitics fraught with unknown unknowns—but rather was creating a vast database of short-term hypotheticals, an industrial-strength version of what Helmuth von Moltke once attempted in Prussia. American gaming explored the problem space of war in the '40s, and the games produced heuristics, or rules of thumb. The only limitation was the American military imagination, which was simply too American to conceive of Japanese suicide missions.

This exploratory approach was carried forward into the Cold War, reinforced by the circumstances of nuclear armament. The fundamental problem faced by both the U.S. and Soviet militaries in the 1950s and '60s was aptly summed up by the RAND physicist Herman Kahn.[3] When his expertise was questioned by military officials, he'd retort, "How many thermonuclear wars have you fought recently?"

The nuclear era was entirely unprecedented, and one wrong decision could cause the end of civilization. There was an urgent need to explore absolutely every eventuality while acknowledging that many eventualities couldn't possibly be foreseen. The Pentagon gamely simulated Joseph Stalin's sudden death and a Soviet first strike on Inauguration Day, role-played by mid-level military and government officials. The purpose of this free gaming was to develop intuitions: Since a good model would need to account for everything in the world—given that nuclear war was inherently global—good models were all but unbuildable. Instead the Pentagon opted for many inadequate simulations and gave low credence to any of them. In the words of one Navy analyst, gaming was a "training device for aiding intuitional development." RAND referred to it as "anticipatory experience."

WAR FOR THE WHOLE FAMILY
Tactics, created by a soldier named Charles Roberts in 1953, is likely the first mass-market war game. It contained tables for casualties and counters to represent battalions. Roberts started a company, Avalon Hill, that launched the commercial war-game industry.

Yet inevitably American government and military leaders wanted to master the Cold War. They sought victory over communism. Advances in computing stoked that ambition, as did progress in game theory as a model for non-zero sum games.

Around 1954, RAND analysts began to consider how the book, *Theory of Games and Economic Behavior*, by mathematician John von Neumann and economist Oskar Morgenstern, could be applied to warfare. (The book attempted to establish economics as an exact science by modeling economic scenarios as multi-player games.) RAND started by mathematically modeling campaigns from World War II, working out how opposing armies should have acted. If fighting tactics from the past could be optimized, then why not future planning for nuclear engagement?

In 1960, Harvard economist Thomas Schelling explored the possibility in a book called *The Strategy of Conflict*. His book took up von Neumann and Morgenstern's non-zero-sum games, showing that in an age of mutually assured destruction, the U.S. and U.S.S.R. could both win, with no risk of loss, if only they exercised mutual restraint.[4] This was an excellent solution, except there was no obvious way to apply it: neither a framework for trust nor the political will to see the adversary benefit. The level of abstraction at which game theory was viable made the most compelling conclusions practically irrelevant. In that sense, it was like chess.

At about the same time that Schelling published his book, the U.S. military acquired a computer devoted to war gaming. Installed at the Naval War College at a cost of $10 million, the Naval Electronic War Simulator had no game theory in it. Rather the machine was a sort of electromechanical umpire, managing data and calculating dice-throws for role-playing games. Later versions had a similar function, though one side or both might be played by the computer itself, allowing the gaming process to be greatly accelerated. Countless games could be played, countless options considered, countless outcomes recorded. If game theory was the *non plus ultra* of chess-like abstraction, these computerized simulations were the ultimate extreme of *kriegsspiel*: resolutely concrete and vulnerable to programming biases.

For strategic purposes, game theory was too vague and computer simulations were too specific. The most versatile and insightful technique remained the oldest still in use: the 19th-century free war games of Julius von Verdy du Vernois.[5]

If only they could provide more than heuristics. (Legitimate skepticism about their predictive value may partly explain why gaming had so little sway over American policy in Vietnam.) An early intimation of what free war games could become was suggested by Attorney General Robert F. Kennedy in 1963. After playing a politico-military game organized by Schelling, Kennedy inquired about gaming a resolution to racial inequality in the South: an alternative to political debate in which all interests could role-play their way to civil rights. The idea was abandoned following President John F. Kennedy's assassination, but a permutation arose in 1970, when Lincoln Bloomfield, a political scientist at the Massachusetts Institute of Technology, traveled to Moscow. As a guest of the Soviet government, Bloomfield orchestrated a simulation where Soviet, American, and Israeli officials unofficially war-gamed a hypothetical Middle East conflict akin to the Six-Day War. Bloomfield intentionally scrambled their positions. The pro-Arab Soviets played Israel, and the anti-Soviet Israelis and Americans played the Soviet Union. In these topsy-turvy circumstances, the Soviet "Israelis" surprised everyone by developing a policy of moderation.

Buckminister Fuller wasn't ambitious enough. The act of gaming must make peace in its own right.

I**N 1953, A FORMER** soldier named Charles Roberts designed a simple war game for civilians. Tactics was played on the map of a fictitious landscape. Akin to Reisswitz's *kriegsspiel*, there were tables to calculate casualties and counters to represent battalions. The self-published game sold well enough for Roberts to found a company, Avalon Hill, which launched the recreational war-gaming industry.[6]

Will Wright started playing Avalon Hill war games as a teenager in the 1970s. A decade later, as personal computers became commonplace, he decided to program a game of his own. Raid on Bungling Bay didn't appear as cerebral as the Avalon board games he'd played. On the surface, it was a first-person shooter embedded in a flight simulator. But Wright had incorporated a sort of military-industrial realism, where the targets chosen by a player impacted enemy capabilities. The way to win was not to develop better reflexes, but to intuit the dynamics of weapons manufacturing and supply chains.

Wright's next game dispensed with reflexes entirely. In SimCity, the player was mayor of a make-believe municipality, responsible for managing the urban dynamics of sustenance and growth. Crucially, there was no preordained goal. The player set personal standards of what the city

3. Kahn was one of the chief inspirations for the character Dr. Strangelove. (John von Neumann was another.)

4. Which isn't to say that Schelling was a peacenik. He argued that the appearance of recklessness could be advantageous. He compared it to teenagers playing chicken.

5. In 20th-century military jargon, free games were referred to by the formidable acronym *BOGSAT*. It stood for *Bunch Of Guys Sitting Around a Table*.

should become and strove to make the sim conform to that vision. As in any real city, it wasn't easy. (Attract companies by lowering taxes and the decline in social services may raise crime rates, driving away business.) The deep causal loops that made *kriegsspiel* so compelling were brought into the civilian realm, introduced to a single-player context where the conflict was internal. SimCity's urban scaffolding could support endless variations: Like *kriegsspiel*, it was not a specific game but a logical framework for gaming. Wright has described it as a "possibility space," in which a player becomes the game's designer, and the design of a game is a design for society.

SimCity and Wright's later creations—so-called "God games," including SimEarth and Spore—provide a link between the tensions of war games and the intentions of Fuller's world game. They were ludic platforms for utopian experimentation, and they foreshadowed one dimension of how Fuller's vision could be brought into the present.

Another dimension was emerging around the same time that Wright was transitioning from Avalon Hill to Bungling Bay. At the University of Essex in 1978, two students, Roy Trubshaw and Richard Bartle, programmed a multiplayer adventure game for the campus computer network. The text-based role-playing game was the first of its kind, a sort of Dungeons & Dragons quest open to anybody who logged onto the mainframe. Trubshaw and Bartle called their creation Multi-User Dungeon, or MUD, a name that became the moniker for a whole genre of network-based adventure games, especially once the Internet networked everyone.

As advances in computing passed from the military to the commercial sector, the MUDs that followed Multi-User Dungeon evolved from text-based interaction to graphic exploration. These online environments invited discovery and conquest. Players could collaborate or compete. They could build together or kill each other. Eventually these modes of online engagement drifted apart. The collaborative impulse led to virtual worlds, including Second Life, populated by player-controlled avatars that keep house, socialize, and dabble in virtual sex. The competitive drive resulted in massively multiplayer online games (MMOs) such as EverQuest and World of Warcraft, in which avatars go to battle and collect loot.

The number of people who participate in virtual worlds and MMOs is staggering. At its peak, Second Life hosted 800,000 inhabitants—nearly the number of people living in San Francisco—and World of Warcraft reached a peak population of 12 million. Another massively popular genre—one more pertinent to promoting peace—is the God game genre. (Wright's titles alone have sold 180 million copies.)[7]

But God games have never fit the massive multiplayer format, since the premise of a God game is omnipotence, which logically cannot be shared. Electronic Arts, the publisher of SimCity, tried to split the difference with an online multiplayer re-release in 2013. (Cities remained autonomous, but could trade and collaborate on "great works.") The awkward combination of antithetical genres quite naturally provoked a backlash. SimCity

6. There were predecessors, notably *Little Wars*, a rule book for a game with toy soldiers, written by H.G. Wells in 1913. Wells proposed opposing generals play his game instead of warring, leaving everyone else to live in peace.

cannot become what it was never meant to be. What's needed instead are games designed from the start to allow a massive multiplicity of players to interact in open-ended possibility spaces.

Crucially, these virtual worlds would not be neutral backdrops in the vein of Second Life. Like SimCity and war games, they'd be logically rigorous and internally consistent. There'd be causality and consequences, and there'd be tension, drawn out by constraints such as limited resources and time pressure. Also like SimCity and war games, these virtual worlds would be simplified, model worlds with deliberate and explicit compromises tailored to the topics being gamed. There could be many permutations, so that none inadvertently becomes authoritative. The only real guideline for setting variables would be to adjust them to breed what Wright has described as "life at the edge of chaos."

Within these worlds, scenarios could be played out by the massive multiplicity of globally networked gamers. Players wouldn't need to be designated red or blue, but could simply be themselves, self-organizing into larger factions as happens in many MMOs. Scenarios could be crises and opportunities. Imagine a global financial meltdown that destroys the value of all government-issued currencies, provoking the United Nations to issue a "globo" as an emergency unit of exchange. Would the globo be adopted, or would private currencies quash it? And what would be the consequences as the economy got rebuilt? A single universal currency

MAKE CITIES, NOT WAR SimCity creator Will Wright played Avalon Hill war games as a kid. He has described his popular game, in which players act as mayors of cities, as a "possibility space." In essence, players are designing their own game, and that game is a design for society.

SIMCITY 2013 BY ELECTRONIC ARTS/VIDEOGAMER.COM might be a stabilizing force, binding the economic interests of people and nations, or it could be destabilizing on account of its scale and complexity. It could promote peace or provoke war. Games allowing players to collaborate and compete their way out of crisis would serve as crowdsourced simulations, each different, none decisive, all informative.

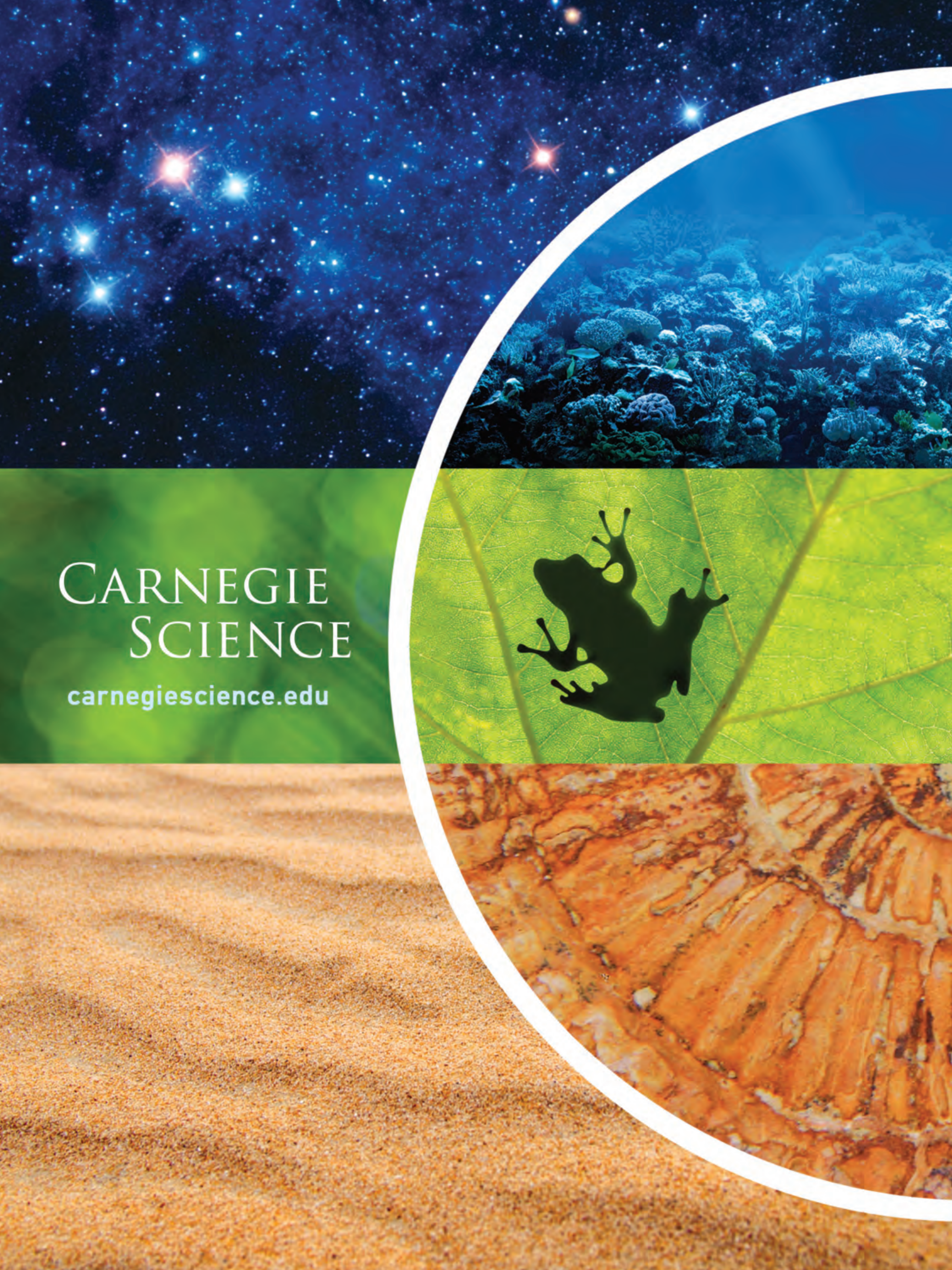
As the number of players increased through the evolution of world gaming, the outcomes of these games would inform an increasingly large proportion of the planet. At a certain stage, if the numbers became great enough, gameplay would verge on reality—and even merge into reality—because players would collectively accumulate sufficient anticipatory experience to play their part in the real world more wisely. Whole aspects of game-generated infrastructure—such as in-game non-governmental organizations and businesses—could be readily exported since the essential relationships would have already been built. Games would also serve as richly informative polls, revealing public opinion to politicians.

7. Such numbers have inspired Jane McGonigal, a social game designer, to argue that gamers are "our most readily engagable citizens." However, contrary to Fuller, she says, "there's a better chance of world peace coming out of games involving world-changing science than diplomacy and geopolitical gain."

Or they could play a more direct goal in governance. One of Fuller's ideas—that gaming could serve as an alternative to voting—could potentially be realized with a plurality of people gaming national and global eventualities. For any given issue, different proposals could be gamed in parallel. As some games collapsed, gamers would be able to join more viable games until the most gameable proposal was played through by all. That game would be a surrogate ballot, the majority position within the game serving as a legislatively or diplomatically binding decision. Provided that citizens consented from the start, it would be fully compatible with democratic principles—and could break the gridlock undermining modern democracies.

When Fuller presented the world game as a method of reckoning how to achieve world peace, he wasn't ambitious enough. The act of gaming must make peace in its own right. Operating at the scale of reality, the game that everybody wins must build our future world.

JONATHON KEATS is a writer, artist, and experimental philosopher based in San Francisco and Northern Italy. He is the author of six books, including *The Book of the Unknown*, awarded the American Library Association's Sophie Brody Medal in 2010. His art has been exhibited at institutions ranging from the Berkeley Art Museum to the Wellcome Collection. This essay is adapted from *You Belong to the Universe: Buckminster Fuller and the Future*, which will be published by Oxford University Press in April, 2016.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WHILE THE NEAR FUTURE is a choice, the distant future is an institution. Governments and nonprofits produce long-term forecasts by the thousands. Fortunes change hands based on corporate earnings expectations. Courts debate wills written decades ago. People have constructed over 10,000 active time capsules.

Despite all of this frenetic activity, the future is more often than not a surprise. As Tom Vanderbilt points out in this issue, the contents of time capsules are frequently boring. Flying cars never showed up, but women in the workforce did.

Robert Sapolsky identifies a wrinkle in today's increasingly fluid attitude toward gender: our own brain. And Julian Savalescu points out that we effectively answered certain ethical concerns about future technology long ago.

The basic truth about prognostication, then, turns out to be that oldest of maxims: Know thyself.

Welcome to "2050."

—MS

"Between these visions of heaven and hell lies the likely truth: When something like the Record comes along, it won't reshape the basic ways we live and love."

JAMES SOMERS
"What Searchable Speech Will Do to You" p.48

2050

TIME FLIES

What Searchable Speech Will Do to You

Will recording every spoken word help or hurt us?

BY JAMES SOMERS

ILLUSTRATION BY CHRISTIAN NORTHEAST

WE ARE GOING TO START recording and automatically transcribing most of what we say. Instead of evaporating into memory, words spoken aloud will calcify as text, into a Record that will be referenced, searched, and mined. It will happen by our standard combination of willing and allowing. It will happen because it can. It will happen sooner than we think.

It will make incredible things possible. Think of all the reasons that you search through your email. Suddenly your own speech will be available in just the same way. "Show me all conversations with Michael before January of last year ... What was the address of that restaurant Mum recommended? ... When was the first time I mentioned Rob's now-wife? ... Who was at that meeting again?" Robin Hanson, an economist at George Mason University and a co-author of a forthcoming book on evolutionary psychology, has speculated that we might all get in the habit of peppering our speech with keywords, to help us look it up later. Or, while you're talking, a software agent could search your old conversations for relevant material. Details would come to your attention at just the moment that you needed them.

Much of what is said aloud would be published and made part of the Web. An unfathomable mass of expertise, opinion, wit, and culture—now lost—would be as accessible as any article or comment thread is today. You could, at any time, listen in on airline pilots, on barbershops, on grad-school bull sessions. You could search every mention of your company's name. You could read stories told by father to son, or explanations from colleague to colleague. People would become Internet-famous for being good conversationalists. The Record would be mined by advertisers, lawyers, academics. The sheer number of words available for sifting and savoring would explode—simply because people talk a lot more than they write.

With help from computers, you could trace quotes across speakers, or highlight your most common phrases, or find *un*common phrases that you say more often than average to see who else out there shares your way of talking. You could detect when other people were recording the same thing as you—say, at a concert or during a television show—and automatically collate your commentary.

Bill Schilit, a Googler who did early work mining the Google Books corpus, suggested that you could even use quotations to find connections between scientific subjects. "In science you have this problem that the same thing is called different names by different people; but quotations tend to bridge the nomenclature between disciplines," he said. He described a project where Google looked at quotations used by researchers in different fields. In each document, they'd extract the sentence just before the quotation—the one that introduced it—and then compare those two descriptions; that way they could find out what the quotation *stood for*: what it meant to different authors, what writers in different disciplines called the same thing.

But would all of this help or hurt us? In his book *The Shallows*, Nicholas Carr argues that new technology that augments our minds might actually leave them worse off. The more we come to rely on a tool, the less we rely on our own brains. That is, parts of the brain seem to behave like muscle: You either use it (and it grows), or you lose it. Carr cites a famous study of London taxi drivers studying for "The Knowledge," a grueling test of street maps and points of interest that drivers must pass if they are to get their official taxi license. As the taxi drivers ingested more information about London's streets, the parts of their brain responsible for spatial information literally grew. And what's more, those growing parts took over the space formally occupied by other gray matter.

You'd think we were a strange species, if you listened to the whole of humanity's recorded corpus today.

Paradoxically, long-term memory doesn't seem to work the same way; it doesn't "fill up." By offloading more of memory's demands onto the Record, therefore, it might not be that we're making space for other, more important thinking. We might just be depriving our brains of useful material. "When a person fails to consolidate a fact, an idea, or an experience in long-term memory," Carr writes, "he's not 'freeing up' space in his brain for other functions ... When we start using the Web as a substitute for personal memory, bypassing the inner processes of consolidation, we risk emptying our minds of their riches."

The worry, then, is twofold: If you stopped working out the part of your brain that recalls speech, or names, or that-book-that-Brian-recommended-when-you-spoke-to-him-in-the-diner-that-day-after-the-football-game, maybe those parts of your brain would atrophy. Even more pernicious, as you came to rely more on the Record as a store of events and ideas, you would decide less often to commit them to your own long-term memory. And so your mind would become a less interesting place.

If that's frightening, consider also what it might be like to live in a society where everything is recorded. There is an episode of the British sci-fi series *Black Mirror* set in a world where Google Glass–style voice and video recording is ubiquitous. It is a kind of hell. At airport security, the agents ask you to replay your last 24 hours at high speed, so they can clear all the faces you interacted with. At parties, instead of making new conversation, people pore over their "redos" and ask to see their friends.' In lonely moments, instead of rehearsing memories in the usual way—using the faulty, foggy, nonlinear recall apparatus of their own minds—people replay videos, zooming in on parts they missed the first time around. They seem to live so much in the past as to be trapped by it. The past seems distorted and refracted by the too-perfect, too-public record. In the episode's most vividly dark moment, we see a couple passionately making love, only to realize that the great sex is happening in "redos" that they're both watching on their implanted eye-screens; in the real present, they're humping lovelessly on a cold bed, two drugged-out zombies.

Between these visions of heaven and hell lies the likely truth: When something like the Record comes along, it won't reshape the basic ways we live and love. It won't turn our brains to mush, or make us supermen. We will continue to be our usual old boring selves, on occasion deceitful, on occasion ingenuous. Yes, we will have new abilities—but what we *want* will change more slowly than what we can do.

SPEECH RECOGNITION HAS LONG BEEN a holy grail of artificial intelligence research. "The attraction is perhaps similar to the attraction of schemes for turning water into gasoline, extracting gold from the sea, curing cancer, or going to the moon," the Bell Labs engineer J.R. Pierce wrote in 1969. He argued that we attacked and funded the problem not because it was tractable or even useful, but simply because there would be something magnificent in talking to a computer. It would be like science fiction. The machine would seem alive.

The fact that the problem of recognizing speech seemed to contain within it the whole problem of human understanding—after all, in order to parse an ambiguous sound, we bring to bear not just knowledge of language but knowledge of the world—only made it more enticing. Progress in speech recognition would stand for progress in AI more generally. And so it became a benchmark and a prize.

The earliest working systems restricted themselves to a simple vocabulary—say, the digits "zero" through "nine" spoken one at a time—and distinguished words by looking for specific features in their sound waves.

People will continue to be less concerned with how they sound than how they look. They will be far more likely to pause for a selfie than for a soliloquy.

RATHER BE ELSEWHERE
This scene from the sci-fi series *Black Mirror* depicts a couple in bed, each using implanted technology to relive an episode from their past.

As you might expect, when the vocabulary grew, the distinctions between different words' sound waves became more subtle. The approach fell apart. Researchers realized they needed something more robust.

Their insight, arrived at in the 1970s, was to model speech as a sequence at multiple levels simultaneously. That is, at each moment, they imagined their recognition system as being in some state at the sound level, the syllable level, the word level, the phrase level, and so on. Its job was to predict, at each level, what the next state would be. To do so it used large tables of probabilities that said, in essence, "If you see state A, then state B happens 0.1 percent of the time, state C happens 30 percent of the time, state D happens 11 percent of the time," and so on. These tables were made by training the system on labeled data (recordings that had been transcribed by hand, and were known to be correct). The trick was that if the word-level prediction was ambiguous—maybe because the environment was noisy, or the speaker's voice was distorted—predictions from the other levels could be used to rule out possibilities and home in on the correct choice. It was a massive advance. It was like going from trying to solve the crossword one clue at a time to playing on the grid: Each clue offered hints about the others, simplifying and reducing the puzzle.

This insight, combined with the exponential growth of training data and computational power, underwrote most of the progress in speech recognition in the last four decades. It's what got us workable but error-prone dictation software, like Dragon Naturally Speaking, the first versions of Siri, and those automated phone trees that let you speak your selection ("billing inquiry" or "schedule maintenance"). But around 2010 it seemed as though progress might *always* be incremental—like there were no big ideas left in speech recognition. The field seemed to have plateaued. Then deep learning came along.

Geoffrey Hinton and his collaborators, then at the University of Toronto and now at Google, were experimenting with deep neural nets. Neural nets are computer programs that work a little like the brain: They are made of layers of neuron-like cells that receive input from other neurons, compute some simple function (like a sum or average) over those inputs, and either fire or not based on the value of that function, spreading activation to other neurons deeper in the net. The nets are trained by entering inputs into the bottommost layer, and seeing what comes out of the topmost layer; if the output isn't what you were expecting, you use a simple learning algorithm to adjust the strength of the connections (the "synapses") between neurons until you get what you want. Rinse and repeat over many billions of examples, and your net might come to encode important features of the problem at hand, and work well as a recognizer.

Most neural nets are stateless, in the sense that the output for a given sense of inputs depends on that input alone. This limits their effectiveness for modeling speech. But Alex Graves, working in Hinton's lab, wondered what would happen if you tackled the speech recognition problem using neural nets whose output could depend on sequences of inputs, known as "recurrent neural nets." They were remarkably effective. Graves' RNNs—which are given far less information about language than those multi-level prediction systems that had long been a mainstay of the field—were soon matching and then surpassing the performance of the old approach.

When I spoke to Hinton, and asked him how such simple programs could recognize speech so effectively, he said he was reminded of some sketches that he likes, by Leonardo da Vinci, of turbulent water going past a lock. The water is rushing and frothing and swirling in eddies, a complex mess. But its behavior, Hinton said, "It's all described by the extremely simple Navier-Stokes equations." A few simple rules generate all the complexity. The same thing, he argues, happens when a neural network learns to recognize speech. "You don't need to hand-engineer lots of complicated speech phenomena into the system," Hinton says.

At Google, Hinton and his colleagues are doing basic research in computer science, examining, as he put it, "the space of learning algorithms that work well." Their findings will have a huge number of applications. But speech continues to be a top priority, and not just because it's a good proving ground for their algorithms. "The thing about speech," Hinton told me, "is that it's the most natural way to interact with things."

Google, Apple, Amazon, and Microsoft are not interested, today, in recording and transcribing everything we say. They are interested in voice as an interface. The Amazon Echo, for instance, sits and waits for you to issue it commands; for playing music or looking up a bit of trivia, talking is easier than typing, especially when you can do it from anywhere in the room. And as computers get smaller, and move onto our wrist or the bridge of our nose, perhaps someday into our ear, keyboards stop being practical—and yet we still need a way to tell the computer what to do. Why not just tell it? Why not just say, "Ok Google, direct me home?"

This is how it's going to happen. Speech recognition technology is being driven both by basic research into AI—because it's a model problem—and by the perceived need of Google and its ilk to create better voice interfaces for their new devices. Intentionally or not, the tech will soon get so good as to reach a tipping point—what the journalist Matt Thompson called the Speakularity—where "the default expectation for recorded speech will be that it's searchable and readable, nearly in the instant." The only question, then, will be what we decide to record.

YOU'D THINK WE WERE a strange species, if you listened to the whole of humanity's recorded corpus today. You'd find all the blathering radio hosts there ever were, and the many takes of voiceover actors, and you'd find journalists talking to their subjects, and pilots to their controllers—and that would all be but the tiniest speck in a vast sea of calls to customer service, "recorded for quality purposes." You wouldn't get a sense of what human life actually sounded like, of what we actually talked about.

Megan Robbins, an assistant professor of psychology at the University of California, Riverside, has listened to more regular talk than almost anyone in the world. Her research relies on a device, called the EAR (for Electronically Activated Recorder), designed for "sampling behavior in naturalistic settings." Research subjects agree to wear it all day. It turns on at periodic intervals about five times an hour, and records everything the wearer says and hears for about 30 seconds. The subject can review and delete any clips they like before handing them over to Robbins for analysis.

With the EAR, Robbins can be a scientist of everyday life. For instance, she can listen to how couples refer to themselves: Do they say "she and I" or "we?" She can listen to people laugh, and try to figure out why. One study found that "Overwhelmingly, most laughs didn't occur in the presence of humorous stimulus." By and large, laughs are social, and used to signal things, like "I think you're higher status than me," or "I want to affiliate with you."

Robbins is currently using the EAR to study couples coping with a cancer diagnosis. What do they talk about? Do they talk about the cancer? Do they laugh less? "You'd never think to run a focused study about how often do breast cancer patients laugh," she says. But with hours and hours of transcripts and tape, a world of questions about our basic behavior opens up. As it turns out, the cancer patients are laughing in about 7 percent of their clips, comparable to college students. They talk about cancer about the same percent of the time. Robbins explains that there seems to be a robustness to the everyday, even when you're diagnosed with cancer. "It's really difficult for people to *not* carry on with their normal daily activities."

She explains that people talk a lot—on average, about 40 percent of their waking lives. Her undergraduate research assistants, who come to her lab excited to eavesdrop on people, "are sometimes heartbroken to find that daily life, it's sometimes mundane. It's comprised of things like TV watching, and conversations about what you're going to have for dinner. And conversations about TV." Robbins says she was surprised at just how much television regular people watch. "It's a topic that's almost completely ignored in psych, but shows up in the EAR research ... it's second only to talking in the cancer coping couples."

One thing people don't talk about, in general, is the EAR itself. "Self-reports indicate no impact on their life. They generally forgot they were wearing it." Indeed, one can track mentions of the EAR in the transcripts. They drop off significantly after only two and a half hours. "Normal life goes on," Robbins says.

When presented with the idea of the Record, we might imagine that people won't be able to carry on a normal conversation because they'll be too busy performing. But anyone who's ever recorded someone knows that self-conscious monitoring of your own speech is just too mentally expensive to carry on for very long. Robbins' data supports the intuition that, after a short while, you go back to normal.

Hanson also thinks "normal" would be the operative word once ubiquitous speech transcription arrives. He's not convinced that it would change the world as much as some seem to think it would. "As soon as you see just how different our world is from 1,000 years ago, it's really hard to get very worked up about this," he says.

There was almost no privacy 1,000 years ago, he explains. Living quarters were dense. Rooms were tiny and didn't lock. There were no hallways. Other people could overhear your lovemaking. When you traveled, you hardly ever went by yourself; you roamed around in little groups. Most people lived in small towns, where most everybody knew everybody else and gossiped about them. The differences in how we lived between then and now were huge. And yet we adapted. "I gotta figure the changes we're looking at are small by comparison," he says. People have always been able to distinguish between their close friends and their less-close friends. They've always been able to decide who to trust, and they've always found ways to communicate intimacy. They've always been able to lie.

"Even our forager ancestors were quite capable of not telling each other something," he says. "Foragers are supposed to share food. But they hide a lot of food. They eat a lot on the way back to camp, they hide some at camp, they're selective about which food they give to who." Even in a band of 30 people, where the average person would meet a half-dozen other bands at most in their lifetime, and everybody stayed in the same camp at night—even in that environment, our ancestors were capable of being evasive, and tuning their speech and gestures to their advantage.

Having a Record will just give us a new dimension on which to map a capacity we've always had. People who are constantly being recorded will adapt to that fact by becoming expert at knowing what's in the transcript and what's not. They'll be like parents talking around children. They'll become masters of plausible deniability. They'll use sarcasm, or they'll grimace or grin or lean their head back or smirk, or they'll direct their gaze, so as to say a thing without saying it.

It sounds exhausting, but of course we already fluidly adapt to the spectrum of private, small-group, and public conversations—just go to a workplace. Or go to a party. We are constantly asking and answering subtle questions about our audience, and tuning our speech based on the answers. (Is Jack in earshot? Is Jack's wife in earshot?)

"There's no way this means that everything we say is now in the open," Hanson argues. "There's a *layer* of what we say that's in the open ... but we're always talking at several levels at once."

WHENEVER WE CONTEMPLATE a new technology, we tend to obsess and fixate, as though every aspect of the world must now be understood in terms of it. We are a hypochondriacal society. But the fact is that the hardware running inside our heads hardly changes at all, and the software only slowly, over the course of generations.

The Record will not turn our brains to mush. Yes, we will likely spend less energy committing great talk to our long-term memories. And transcripts will relieve us from having to track certain details that come up in conversation. But we won't thereby lose the *ability* to track details—just as we didn't lose our ability to plan when we invented the calendar, or our ability to memorize when we invented the pen. We will enrich our long-term memories in some other way (say, by poring over the vast stores of material newly made available by transcription). Our brains adapted to writing, to libraries, and to the Web. They will adapt to the Record. And people will, anyway, continue to be less concerned with how they sound than with how they look. They will be far more likely to pause for a selfie than for a soliloquy.

Nor is life like a *Black Mirror* episode, where every scene and line revolves, because it must, around the newest tech. Sure, the Record may enhance our narcissism, our nostalgia, our impatience and paranoia. It might even corrupt or stupefy us en masse. But even that has happened before, whether with smartphones or television or mirrors or alcohol, and somehow we have managed to end up, above all, ourselves.

JAMES SOMERS is a programmer and writer based in New York. He works at *Genius*.

Caitlyn Jenner and Our Cognitive Dissonance

While biology shows us gender can be fluid, our brains struggle to see it that way

BY ROBERT SAPOLSKY

SOMEWHERE IN THE MIDDLE OF THE NIGHT in a Central African rainforest, a chimpanzee gives birth. Soon after, as the sun rises, mother and newborn sit there, dazed, amid a coffee klatch of friends and relatives. Inevitably, at some point, virtually every member of the group will come over, pull the kid's legs apart and sniff: Boy or girl?

It's the most binary question in biology, producing an answer that is set in stone. But in reality the binary nature of gender isn't all that binary after all. Biologists have long known about exceptions to the boring, staid notion that organisms are, and remain, either female or male. Now our culture is inching toward recognizing that the permanent, cleanly binary nature of gender is incorrect.

In fact, it's headline news. Bruce Jenner, a male gold medalist in the 1976 Olympics, and a cover boy on a Wheaties box, is now Caitlyn Jenner, a 2015 cover girl on *Vanity Fair*. Laverne Cox, a transgender actor, is nominated for an Emmy for outstanding actress. America has seen openly transgender individuals serve as a mayor, state legislator, judge, police officer, a model for a global cosmetics brand, and a high school homecoming queen. Even amid the appallingly high rates of discrimination and violence against transgender people, there is a growing recognition that gender designation need not be permanent.

Many people are questioning whether there is even such a thing as "gender." These are individuals whose psychosexual self-image may be of both genders, a third gender, no gender, or whose visceral perception of the social world does not include implicitly seeing people as gendered.

This new continent was formalized by as august and ancient an institution as Facebook, which offers 58 gender specification options on one's profile page. These include Agender, Bigender, Intersex, Gender Fluid, Gender Questioning, Non-binary, Pangender, and my two favorites—Two-spirit, with a vaguely Native American grooviness to it, and Other, which basically implies that, Whoa, Nellie, we've barely scratched the surface!

In many ways the most radical departures from a binary gender system comes with gamers who spend

ILLUSTRATION BY ANGIE WANG

virtually their entire lives role-playing as their avatars in a virtual world. Be whoever you want—male, female, neither, a hybrid. Be whatever you want—bonobo, parakeet, centaur, Lord Vishnu. Heck, pick the right site and you can spend years online as some paramecium trying to evolve multi-cellularity. And have relationships with other people's avatars in the process. All easily done, since the physical, phenotypic reality of what kind of body you have is irrelevant online.

Given all this—permanent, binary gender designation becoming increasingly fuzzy—one might expect it won't be long before it will be non-existent. Unfortunately, society is only going to get so far down that road before it's stymied by a cognitive feature of our brains. Before we hit that roadblock, though, let's review just how far our knowledge of gender has come.

FOR STARTERS THERE'S PLANTS, a number of which are "monoecious," which is to say that any given plant has both female and male organs (those stamens and pistils). Things are stranger with animals. There are parthenogenic species, where females reproduce without males—numerous reptiles fall in this category, including the incomparably cool Komodo dragon. There are synchronous hermaphrodites where, like monoecious plants, an individual has both sexes' organs simultaneously. This includes worms, sea cucumbers, snails, and sea bass.

Then there's spotted hyenas, gender-bending pseudo-hermaphrodites. It's nearly impossible to determine the sex of a hyena by just looking, as females are big and muscular (due to higher levels than males of some androgenic hormones), have fake scrotal sacs, and enlarged clitorises that can become as erect as the male's penis. None of which was covered in *The Lion King*.

And then there's sequential hermaphrodites like the sea wrasse and clownfish, where an individual changes sex opportunistically. There'll be a single, dominant individual in a group (male among sea wrasse, female among clownfish), while the remaining subordinate members are of the opposite sex. If that dominant individual dies, the highest-ranking of the opposite sex changes sex and assumes the role. There's even bidirectional hermaphroditic fish, switching back and forth depending on the lay of the land's reproductive potential.

OK, aren't nature's oddities so charming? But consider this about something as commonplace as lab mice—every mouse's brain, regardless of its sex, has the circuitry for both male- and female-typical behavior (mounting and pelvic thrusting in the former, arching of the back to expose the rump in the latter). Manipulate things just right experimentally and you can bring either to the behavioral forefront.

Let's turn now to another humdrum mammal, the solidly dichotomized human. Which turns out not to be so solid.

Biologists have long known about exceptions to the boring, staid notion that organisms are, and remain, either female or male.

The *sine qua non* of human sex designation in humans is chromosomal—all your cells either have two X chromosomes, making you female, or one X and one Y, making you male. End of story. But no: Instead, there's various chromosomal disorders where individuals can be XYY, XXY, XXX, X, or XXYY. Most result in infertility; some, like Turner syndrome (in which there is solely an X) produce neurological, metabolic, endocrine, and cardiovascular abnormalities.

Much more interesting than these rare disorders is the recent finding that adult men typically have some XX (that is, female) stem cells scattered throughout the body, which have differentiated into mature cells, including neurons. Meanwhile, women who have given birth to a son have a similar scattering of XY stem cells. Remarkably, during pregnancy, some maternal stem cells become incorporated into the fetus, some fetal stem cells into the mother. Thus, many of us are sex-chromosome mosaics (with, at present, unknown consequences).

Once sex chromosomes are determined, everything else about gender designation follows suit: XX versus XY determines whether you wind up with ovaries or testes. That determines whether it's predominantly estrogen and progesterone, or testosterone in your bloodstream. The hormones you're marinated in then determines which type of genitals you form as a fetus, as well as secondary sexual characteristics ranging from the chemical composition of your sweat to the workings of your brain. Chromosomal, gonadal, endocrine, genital, and phenotypic sex go hand in hand.

Except they don't, as it turns out—there are numerous disorders where someone might be male in some of those ways, but female in others.

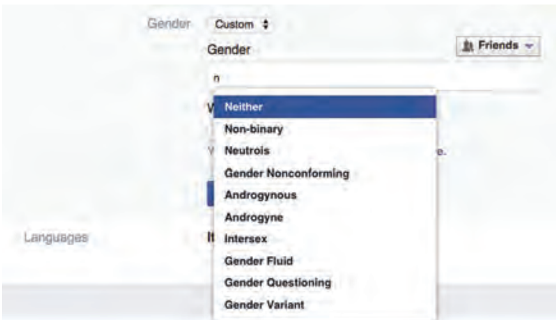
To begin with, chromosomal sex and gonadal/anatomical sex can disagree. In a syndrome called 46,XY DSD, people have normal male sex chromosomes, testes—genitals that are usually classified as male—plus a womb and Fallopian tubes. In ovotesticular disorder, the person has the sex chromosomes of one sex, but both ovarian and testicular tissue, producing ambiguous genitals.

Then there's cases where a disconnect occurs at the level of hormones. One well-studied example concerns the fact that testosterone exerts some of its effects in target cells by being converted to a related hormone, DHT (dihydrotestosterone)—unless you have a mutation that inactivates the enzyme that does that conversion. This occurs in "5-alpha-reductase deficiency"; the individual is XY, has testes and normal levels of testosterone, but the person's phenotype—their external appearance—can range from male to ambiguous to female. For those with a predominantly female phenotype at birth, there's typically masculinization at puberty (the long-hidden testes descend, the clitoris enlarges, voice deepens). Clusters of cases of this disorder have been identified in some inbred, isolated populations (for example, in the mountains of the Dominican Republic) where, remarkably, there's been a fair degree of cultural accommodation—"Honey, this is called puberty. Sometimes you get acne. Sometimes your clitoris becomes a penis. Whatever."

Hormones affect target cells by interacting with specific receptors (estrogen receptors bind estrogen, insulin receptors bind insulin). Another type of dissociation at the hormone level is seen with "testicular

COVER GIRL Caitlyn Jenner, who has put a spotlight on transgender persons like nobody before her, is seen here at the ESPYS, where she received the Arthur Ashe Courage Award.

KEVIN WINTERS/GETTY IMAGES



THE FACEBOOK 58 Our culture's growing recognition that gender can be fluid was institutionalized by Facebook in 2014, when it allowed users to select from 58 gender choices on their profile page.

feminization syndrome," where there is a mutation that inactivates the androgen receptor, which normally binds testosterone and DHT. Normal XY, normal testes, normal levels of the two hormones, but the hormones have no effects, producing a phenotype that ranges from ambiguous to female. In the latter case, the disorder is usually discovered around puberty, when the girl fails to start menstruating. She fails to start because, as it turns out, there's no ovaries or uterus, the vagina dead ends, and way up in the stomach are testes pouring out androgens.

Thus there's numerous ways where chromosomal sex and phenotypic sex differ, accounting for 1 percent of births. This is not rare—pick a human at random and the odds are greater that they were born with ambiguous intersex genitals than they have an IQ greater than 140.

Perhaps the most interesting dissociation occurs one step further down the line. This is where the person has the chromosomes, gonads, hormones, genitals, and secondary sexual characteristics—hair, voice, musculature, facial structure, the works—of one sex. But has always felt like the other.

This is the transgender world, and some intriguing science hints at its neurobiological bases. There are a number of places in the human brain that are "sexually dimorphic" (where the size, structure, function, and/or chemical makeup of the area differ by sex). The differences aren't big enough so that you could identify someone's sex just by knowing the size of one of those regions. However, there are statistical differences between populations of men and women, differences with likely functional consequences.

So you have someone who by every measure discussed, from sex chromosomes to phenotype, is Sex A, but who insists that they have always felt like they are Sex B. What's up in the sexually dimorphic brain regions? A number of studies report the brain bears a close resemblance to Sex B. And this shouldn't seem surprising—we are determined by our brains, we *are* our brains, regardless of our pattern of facial hair, the thickness of our larynx, or what the landscape is like between our legs.

In other words, it's not that transgender individuals think they are a different gender than they actually are. It's that they've had the profoundly crappy luck to be

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stuck with bodies that are a different gender from who they actually are.

Slowly, a word becomes pertinent—"continuum." Gender in humans is on a continuum, coming in scads of variants, where genes, organs, hormones, external appearance, and psychosexual identification can vary independently, and where many people have categories of gender identification going on in their heads (and brains) that bear no resemblance to yours. All with a frequency that, while rare, are no rarer than various human traits we label as "normal."

> "Honey, this is called puberty. Sometimes you get acne. Sometimes your clitoris becomes a penis. Whatever."

GIVEN CURRENT KNOWLEDGE into the gender continuum, with new scientific insights (and celebrity disclosures) sure to come, we might expect that in the near future people will effortlessly think about gender as fluid and not strictly male or female. To be blunt: No way. That's because our minds are very resistant to continua. Instead, we tend to break continua into discrete chunks, into categories.

This is the case, for example, in sensory perception. Anthropological linguists have explored this with respect to color perception. The visual spectrum produces a continuum of color; despite this, we perceive color as if it comes in categories, invent words in every language that arbitrarily break the continuum. Such color terms reinforce our categorical perception of color. In English, for example, a language in which there are distinct terms for "blue" and "green," two shades of blue are viewed as more similar than a shade of blue and one of green, even if all are equidistant on the visual spectrum.

Our propensity to break continua into categories on a neurobiological level was shown in a beautiful study in which monkeys looked at pictures of a dog or a cat, while the electrical activity of neurons in their frontal cortexes were recorded. There would be neurons that solely responded to dog, others to cat. Then, the scientists morphed the dog and cat together, producing pictures of an 80 percent dog/20 percent cat, a 60 percent dog/40 percent cat, 40/60 and 20/80. Remarkably, neurons responded categorically. For example, a "dog" neuron would respond equally robustly to 100 percent dog and 60 percent dog, and hardly at all to 40 percent dog. In other words, the drive toward categorizing is so strong that in this circumstance, these neurons consider 60 to be closer to 100 than to 40.

For a hunter-gatherer, a beneficial automatic categorization would probably have been "animals that I do/don't have to run away from ASAP."

So we think categorically. And dichotomized gender is one of the strongest natural categories the brain has. The categorization is crazy fast—neuroimaging studies show the brain processes faces according to gender, within 150 milliseconds—that's 150 thousandths of a second—before there's conscious awareness of gender.

Automatic categorization by gender is deeply ingrained. This was shown subtly in a study. In the first part of the study, subjects are shown a series of photos of guys in basketball jerseys, each paired with a sentence, such as "You were the ones that started the fight." Half of the players are white and half are black; all are dressed the same. Afterward, subjects are asked to match the player with his particular remark. When subjects pick the wrong player, there's a greater than 50 percent chance the misidentified player will be of the same race as the person who uttered the sentence. That tells us our minds make automatic categorizations by race. As subjects search to remember who made a particular remark, they're not thinking, "Hmm, I'm not sure, it was definitely one of the guys with square shoulders, but which one?" They're thinking, "Not sure, but it was definitely one of the [whichever race] guys."

In the second part, photos show half the players of each race wearing yellow jerseys and half gray ones. Once again, subjects are asked to match the player with his sentence. Now misattribution is more likely to be by jersey color than by race, revealing race may not be as deeply engrained as expected, given it can be trumped by something as seemingly trivial as a jersey's color. Finally, the study repeats the same experiment, but this time the players, rather than differing by race, differ by gender. When all the players are wearing the same colored jerseys, subjects misidentify by gender. And when players are wearing different colored jerseys, subjects *still* misidentify by gender. What does that tell us? That gender is a stronger, deeper automatic category in our minds than race and visual cues.

There are many advantages to thinking categorically. It's easier to remember things that have been categorically labeled, and easier to manipulate, organize, and make executive decisions about information that is categorically digital rather than on an analog continuum. For a traditional hunter-gatherer, a beneficial automatic categorization would probably have been "animals that I do/don't have to run away from ASAP." An example from our Westernized lives is so ingrained it's hard to appreciate: "Red means stop and green means go." If we were in a foreign country whose red lights were a different shade than our own, that sure wouldn't make us hesitate about stopping at a busy intersection.

There are disadvantages, of course: We underestimate the differences between points arbitrarily chunked in the same category, overestimate the difference when they are in separate ones. This is the heart of parochialism and xenophobia, of stereotyping and prejudice. But nonetheless the advantages of categorical thinking have seemingly been sufficient to make it the strong cognitive tendency that it is.

Why have our brains evolved to think in such a powerfully categorical way when it comes to gender, despite the biological reality of it not being all that categorical? The simple answer is we are not monoecious plants, sea bass, or hyenas. The human exceptions to cleanly dichotomized gender are still uncommon, and many are not easily detected, phenotypically. After all, before some scientific advances in the mid 20th century—that is to say, 99.9 percent of hominid history—a male with testicular feminization syndrome was just a female who couldn't get pregnant.

Culture and its artifacts can affect the distribution of biological traits, as well as our attitudes about those traits. It is commonplace now to have a trait that everyone back in our hunter-gatherer past would have correctly viewed as eventually fatal—being near-sighted and therefore not-so-hot at spotting predators. Thanks to eyeglasses, there has been relaxed selective pressure against myopia. Unlike the distant past, people with lousy eyesight pass on as many copies of their genes as do the sharp-eyed, and the genes related to myopia are no longer being winnowed away by natural selection.

It's difficult to imagine, though, any strong selective pressure against our brain's automatic binary categorization by gender—it can be handy when it comes to that evolutionarily relevant goal of finding a mate. Accepting the fragility of that categorization requires some heavy lifting by the neocortex, the recently evolved, egg-heady part of the brain that is tasked with assimilating the information in an article like this. In 35 years, most of us will still be sniffing at crotches, asking, Boy or girl? Maybe things will be different in 350 years, or 3,500 years. It's possible. Of course, by then, maybe all anyone will be asking is which operating system you had your consciousness uploaded to.

Robert Sapolsky is a professor of biology, neurology, and neurosurgery at Stanford University.

Why Futurism Has a Cultural Blindspot

We predicted cell phones, but not women in the workplace

BY TOM VANDERBILT

IN EARLY 1999, during the halftime of a University of Washington basketball game, a time capsule from 1927 was opened. Among the contents of this portal to the past were some yellowing newspapers, a Mercury dime, a student handbook, and a building permit. The crowd promptly erupted into boos. One student declared the items "dumb."

Such disappointment in time capsules seems to run endemic, suggests William E. Jarvis in his book *Time Capsules: A Cultural History*. A headline from *The Onion*, he notes, sums it up: "Newly unearthed time capsule just full of useless old crap." Time capsules, after all, exude a kind of pathos: They show us that the future was not quite as advanced as we thought it would be, nor did it come as quickly. The past, meanwhile, turns out to not be as radically distinct as we thought.

In his book *Predicting the Future*, Nicholas Rescher writes that "we incline to view the future through a telescope, as it were, thereby magnifying and bringing nearer what we can manage to see." So too do we view the past through the other end of the telescope, making things look farther away than they actually were, or losing sight of some things altogether.

These observations apply neatly to technology. We don't have the personal flying cars we predicted we would. Coal, notes the historian David Edgerton in his book *The Shock of the Old*, was a bigger source of power at the dawn of the 21st century than in sooty 1900; steam was more significant in 1900 than 1800.

But when it comes to culture we tend to believe not that the future will be very different than the present day, but that it will be roughly the same. Try to imagine yourself at some future date. Where do you imagine you will be living? What will you be wearing? What music will you love?

Chances are, that person resembles you now. As the psychologist George Lowenstein and colleagues have argued, in a phenomenon they termed "projection bias,"[1] people "tend to exaggerate the degree to which their future tastes will resemble their current tastes."

ILLUSTRATION BY ROBIN DAVEY

In one experimental example, people were asked how much they would pay to see their favorite band now perform in 10 years; others were asked how much they would pay now to see their favorite band from 10 years ago. "Participants," the authors reported, "substantially overpaid for a future opportunity to indulge a current preference." They called it the "end of history illusion"; people believed they had reached some "watershed moment" in which they had become their authentic self.[2] Francis Fukuyama's 1989 essay, "The End of History?" made a similar argument for Western liberal democracy as a kind of endpoint of societal evolution.

This over- and under-predicting is embedded into how we conceive of the future. "Futurology is almost always wrong," the historian Judith Flanders suggested to me, "because it rarely takes into account behavioral changes." And, she says, we look at the wrong things: "Transport to work, rather than the shape of work; technology itself, rather than how our behavior is changed by the very changes that technology brings." It turns out that predicting who we will be is harder than predicting what we will be able to do.

LIKE THE HUNGRY PERSON who orders more food at dinner than they will ultimately want—to use an example from Lowenstein and colleagues—forecasters have a tendency to take something that is (in the language of behavioral economics) salient today, and assume that it will play an outsized role in the future. And what is most salient today? It is that which is novel, "disruptive," and easily fathomed: new technology.

As the theorist Nassim Nicholas Taleb writes in *Antifragile*, "we notice what varies and changes more than what plays a larger role but doesn't change. We rely more on water than on cell phones, but because water does not change and cell phones do, we are prone to thinking that cell phones play a larger role than they do."

The result is that we begin to wonder how life was possible before some technology came along. But as the economist Robert Fogel famously noted, if the railroad had not been invented, we would have done almost as well, in terms of economic output, with ships and canals.[3] Or we assume that modern technology was wonderfully preordained instead of, as it often is, an accident. Instagram began life as a Yelp-style app called Burbn, with photos an afterthought (photos on your phone, is that a thing?). Texting, meanwhile, started out as a diagnostic channel for short test messages—because who would prefer fumbling through tiny alphanumeric buttons to simply talking?*

Transportation seems to be a particular poster child of fevered futurist speculation, bearing a disproportionate load of this deferred wish fulfillment (perhaps because we simply find daily travel painful, reminding us of its shared root with the word "travail"). The lament for the perpetually forestalled flying car focuses around childlike wishes (*why can't I have this now?*), and ignores massive externalities like aerial traffic jams, and fatality rates likely to be higher than terrestrial driving.

The "self-driving car," it is promised, will radically reshape the way we live, forgetting that, throughout history, humans have largely endeavored to keep their daily travel time within a stable bound.[4] "Travelators," or moving walkways, were supposed to transform urban mobility; nowadays, when they actually work, they move (standing) people in airports at a slower-than-walking speed. In considering the future of transportation, it is worth keeping in mind that, today, we mostly move around thanks to old technology. As Amazon experiments with aerial drone delivery, its "same day" products are being moved through New York City thanks to that 19th-century killer app: the bicycle.

Edgerton notes that the "innovation-centric" worldview—those sexy devices that "changed the world"—runs not merely to the future, but also the past. "The horse," he writes, "made a greater contribution to Nazi conquest than the V2." We noticed what was invented more than what was actually used.

In the same way that our focus on recent innovations causes people to overemphasize their importance, to see them as hastening a radically transformed future—like Google Glass was supposed to—the backward look is distorted so that technologies are rendered prematurely obsolete. The prescience of near-future speculations, like *Bladerunner*, comes less from

* These cases were suggested to me by the writer Clive Thompson.

As Amazon experiments with aerial drone delivery, its "same day" products are being moved through New York City thanks to that 19th-century killer app: the bicycle.

uncannily predicting future technologies (it shows computer identification of voices, but Bell Labs was working on spectrographic analysis of human voices in the 1940s[5]) than in anticipating that new and old will be jarringly intermingled. Films that depict uniformly futuristic worlds are subtly unconvincing—much like historical period films in which cars on the street are all perfect specimens (because those are the only ones that have survived). Dirt and ruin are as much a part of the future as they are the past.

People in the innovation-obsessed present tend to overstate the impact of technology not only in the future, but also the present. We tend to imagine we are living in a world that could scarcely have been imagined a few decades ago. It is not uncommon to read assertions like: "Someone would have been unable at the beginning of the 20th century to even dream of what transportation would look like a half a century later."[6] And yet zeppelins were flying in 1900; a year before, in New York City, the first pedestrian had already been killed by an automobile. Was the notion of air travel, or the thought that the car was going to change life on the street, really so beyond envisioning—or is it merely the chauvinism of the present, peering with faint condescension at our hopelessly primitive predecessors?

"When we think of information technology we forget about postal systems, the telegraph, the telephone, radio, and television," writes Edgerton. "When we celebrate on-line shopping, the mail order catalogue goes missing." To read, for instance, that the film *The Net* boldly anticipated online pizza delivery decades ahead of its arrival[7] ignores the question of how much of an advance it is: Using an electronic communication medium to order a real-time, customizable pizza has been going on since the 1960s. And when I took a subway to a café to write this article and electronically transmit it to a distant editor, I was doing something I could have done in New York City in the 1920s, using that same subway, the Roosevelt Brothers coffee shop, and the telegram, albeit less efficiently. (Whether all that efficiency has helped me personally, or just made me work more for declining wages, is an open question). We expect more change than actually happens in the future because we imagine our lives have changed more than they actually have.

GIBSONPICTURES

One futurist noted that a 1960s film of the "office of the future" made on-par technological predictions (fax machines and the like), but had a glaring omission: The office had no women.

IN HER BOOK *The Making of Home*, Judith Flanders describes an offhand reference by the diarist Samuel Pepys, in 1662, to something called a "spitting sheet." She speculates this was a sheet affixed to a wall near a spittoon to protect wall coverings from an errant spitter. It is an example of what she calls "invisible furniture." We all know what a spittoon is. And yet, as they scarcely register in literature and are rarely depicted in art, it is easy to overlook just how commonplace the act of spitting was, even in polite society.

Flanders notes that the United States actually used to regulate where spitting was allowed on trains, stations, and on platforms. A 1917 conference of boards of health, held in Washington, D.C., mandates that "an adequate supply of cuspidors shall be provided" in train cars. Today, both the word "cuspidor" (meaning spittoon) and the object have virtually vanished (though Supreme Court Justices still get one). Its disappearance is not because some technology went obsolete. It is because our behavior has changed.

While the technological past and future appear to be more different than they actually are, these cultural differences in time seem surprising. Working as historical consultant on the video game Assassin's Creed, Flanders had to constantly remind writers to cut the word "cheers" from the script, because, she told me, "people didn't use that word until the 20th century." The writers wanted to know what they did say. "They had huge trouble wrapping their heads around the idea that mostly people didn't say anything. Giving some form of salutation before you drink is so normal to them, it's actually hard to accept that for centuries people didn't feel the need."

The historian Lawrence Samuel has called social progress the "Achilles heel" of futurism.[8] He argues that people forget the injunction of the historian and philosopher Arnold Toynbee: Ideas, not technology, have driven the biggest historical changes. When technology changes people, it is often not in the ways one might expect: Mobile technology, for example, did not augur the "death of distance," but actually strengthened the power of urbanism. The washing machine freed women from labor, and, as the social psychologists Nina Hansen and Tom Postmes note, could have sparked a revolution in gender roles and relations. But, "instead of fueling feminism," they write, "technology adoption (at least in the first instance) enabled the emergence of the new role of housewife: middle-class women did not take advantage of the freed-up time … to rebel against structures or even to capitalize on their independence." Instead, the authors argue, the women simply assumed the jobs once held by their servants.

Take away the object from the historical view, and you lose sight of the historical behavior. Projecting the future often presents a similar problem: The object is foregrounded, while the behavioral impact is occluded. The "*Jetsons* idea" of jetpacking and meals in a pill missed what actually has changed: The notion of a stable career, or the social ritual of lunch.

One futurist noted that a 1960s film of the "office of the future" made on-par technological predictions (fax machines and the like), but had a glaring omission: The office had no women.[9] Self-driving car images of the 1950s showed families playing board games as their tail-finned cars whisked down the highways. Now, 70 years later, we suspect the automated car will simply allow for the expansion of productive time, and hence working hours. The self-driving car has, in a sense, always been a given. But modern culture hasn't.

WHY IS CULTURAL CHANGE so hard to predict? For one, we have long tended to forget that it *does* change. Status quo bias reigns. "Until recently, culture explained why things stayed the same, not why they changed," notes the sociologist Kieran Healy. "Understood as a monolithic block of passively internalized norms transmitted by socialization and canonized by tradition, culture was normally seen as inhibiting individuals."[10]

And when culture does change, the precipitating events can be surprisingly random and small. As the writer Charles Duhigg describes in *The Power of Habit*, one of the landmark events in the evolution of gay rights in the U.S. was a change, by the Library of Congress, from classifying books about the gay movement as "Abnormal Sexual Relations, Including Sexual Crimes," to "Homosexuality, Lesbianism—Gay Liberation, Homophile Movement." This seemingly minor change, much touted by activists, helped pave the way for other, larger changes (a year later, the American Psychiatric Association stopped defining homosexuality as a mental illness). He quotes an organizational psychologist: "Small wins do not combine in a neat, serial form, with each step being a demonstrable step closer to some predetermined goal."

We might say the same about the future.

TOM VANDERBILT writes on design, technology, science, and culture, among other subjects.

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The Philosopher Who Says We Should Play God

Why ethical objections to interfering with nature are too late

BY STEVE PAULSON

AUSTRALIAN BIOETHICIST JULIAN SAVULESCU has a knack for provocation. Take human cloning. He says most of us would readily accept it if it benefited us. As for eugenics—creating smarter, stronger, more beautiful babies—he believes we have an ethical obligation to use advanced technology to select the best possible children.

A protégé of the philosopher Peter Singer, Savulescu is a prominent moral philosopher at the University of Oxford, where he directs the Uehiro Centre for Practical Ethics. He also edits the *Journal of Medical Ethics*. Savulescu isn't shy about stepping onto ethical minefields. He sees nothing wrong with doping to help cyclists climb those steep mountains in the Tour de France. Some elite athletes will always cheat to boost their performance, so instead of trying to enforce rules that will be broken, he claims we'd be better off with a system that allows low-dose doping.

So does Savulescu just get off being outrageous? "I actually think of myself as the voice of common sense," he says, though he admits to receiving his share of hate mail. He's frustrated by how hard it is to have reasoned arguments about loaded issues without getting flamed on the Internet. Savulescu thinks we need to become far more adept at sorting out difficult moral issues. Otherwise, he says, the human species will face dire consequences in the coming decades.

I caught up with Savulescu in Australia, where he was on sabbatical. We talked about a wide range of looming ethical issues, from new technology that will change how we're born and how we die, to transhumanism, to how the world might end.

What ethical challenges are raised by new technologies like genetic engineering and human cloning?

People will vote with their feet once those technologies offer significant benefits. At the moment they have concerns about nature or God, but that will change if you can double somebody's lifespan with genetic engineering, which we've done in animals. People will use genetic engineering if you can ensure that your child won't get Alzheimer's disease or Parkinson's disease or diabetes. When it offers spare organs and the cure of aging, then of course it will be used.

ILLUSTRATION BY JACKIE FERRENTINO

Human cloning is now off the table. Will that change?

Cloning of farm animals is routine, and cloning in humans is used to produce stem cells for the treatment of disease. It's now possible to clone a human being. You can split an early human embryo into identical twins. That's safe and it's reasonably efficient. You could freeze one of those identical twins and then implant it some years after the first, so you could have identical twins 10 years apart in age. So that technology is already there. It's not done because there's no clear point to it, apart from curiosity or the hubris of a scientist. But once there is a real need, people will see the benefits.

Why would we ever need to do this?

Imagine women having children later and later, even after not being able to have children with in vitro fertilization. Let's say you've got one embryo left and that last embryo was implanted. Then you're in a car accident and about to lose the pregnancy from bleeding. You could take a cell from that embryo and clone another embryo if that pregnancy was lost. It would give you the chance to have your own child. So one of the lessons of ethics is you can't make general pronouncements—for instance, that cloning is always unethical and must be banned under all circumstances.

THE CANDID PHILOSOPHER "I actually think of myself as the voice of common sense," says Julian Savulescu. "If you looked at things without any kind of baggage, you'd view them like me."

So you don't see any fundamental ethical objection to human cloning?

In reality, hardly anybody does. Remember that 1 in 300 pregnancies involves clones. Identical twins are clones. They are much more genetically related than a clone using the nuclear transfer technique, where you take a skin cell from one individual and create a clone from it.

But twins are not something we engineer. That just happened.

One of the big mistakes in ethics is to think that means make all the difference. The fact that we've done it or nature has done it is irrelevant to individuals and is largely irrelevant to society. What difference would it make if a couple of identical twins come not through a natural splitting of an embryo, but because some IVF doctor had divided the embryo at the third day after conception? Should we suddenly treat them differently? The fact that they arose through choice and not chance is morally irrelevant.

So the idea that we could play god and tamper with the laws of nature, creating things that wouldn't otherwise exist, is a red herring?

We're playing god every day. As the English philosopher Thomas Hobbes said, the natural state for human beings is a life that's nasty, brutish, and short. We play god when we vaccinate. We play god when we give women pain relief during labor. The challenge is to decide *how* to change the course of nature, not whether to change it. Our whole life is entirely unnatural. The correction of infertility is interfering in nature. Contraception is interfering in the most fundamental aspect of nature.

But using condoms has nowhere near the ethical complications of altering the genetic makeup of your future baby.

You alter the genetic makeup of your future baby when you smoke or drink alcohol. Viruses alter the human genome. So why would you single out one intentional act aimed at producing a beneficial outcome from all these other events that have far less beneficial outcomes? In my view, we should not only use tests to look for genes so a child is not disposed to a major genetic disorder, like Thalassemia or Cystic Fibrosis or Down syndrome, but also to look at genes correlated with greater advantages in life. My argument is we ought to select children who have opportunities for better lives. Most people say that's fine when it comes to diseases, but we shouldn't interfere in nature once you get into the healthy range.

This raises the specter of tinkering with our genes. You could create smarter, stronger, more beautiful children.

Indeed, you could. In my view, we should choose genes if those characteristics affect a person's happiness. A rising percentage of kids today are on Ritalin for Attention Deficit Hyperactive Disorder. But that's not because there's suddenly been some epidemic of ADHD. It's because you're crippled as a human being if you have poor impulse control and can't concentrate long enough, if you can't defer small rewards now for larger rewards in the future. Having self-control is extremely important to strategic planning, and Ritalin enhances that characteristic in children at the low end of impulse control. Now, if you were able to test for poor impulse control in embryos, I believe we should select ones with a better chance of having more choices in life, whether you want to be a plumber, a taxi driver, a lawyer, or the president.

It's one thing to talk about impulse control and quite another to enhance the intelligence of a baby. Doesn't this raise a whole new level of ethical concerns?

It does raise another level of ethical concerns, but we already aim to enhance intelligence through education. Computers and the Internet are also cognitive enhancers. We give children food supplements and better diets to enhance cognitive ability. So why should we treat a genetic mechanism differently than a dietary supplement or some external technology like the Internet? The only difference is gene therapy is really risky, and that's why we don't do it. But if it becomes safe, there's no difference in ethical terms between gene therapy and any other sort of biological or social intervention. If science gives us the opportunity of improving people's lives, we should use it.

Why should we treat a genetic mechanism differently than a dietary supplement or some external technology like the Internet?

Won't the rich have much more access to creating smarter and more beautiful children than the poor?

It could massively increase inequality. We need to create some kind of safety net for people, rather than just ramping up the current trend of ever-increasing inequality. Although the standard of living for many people has increased, in the 1800s the difference between the richest and poorest country was 3 to 1. It's more than 100 to 1 today, and the richest three individuals in the world own as much as the poorest 600 million people. So some kinds of ethical constraints are going to have to be placed on unconstrained capitalism. We're in a period where capitalism has served us very well. My father escaped from Romania after World War II to escape communism. I wouldn't change that history. But we can't think capitalism is the end of history. We will need rules to constrain the dark sides of our nature. The market is not going to solve our biggest problems.

Do you worry about eugenics—creating superior groups of people?

People concerned about eugenics remember the Nazi program of sterilization and the extermination of people deemed to be unfit. Now it's important to recognize this wasn't unique to Nazi Germany. The extermination part was, but sterilization was common through Europe and the United States. Many states in the U.S. had eugenics laws so people who were intellectually disabled or mentally ill were sterilized against their will. This kind of eugenics was one of the darker sides of the 20th century.

But eugenics just means having a child who is better in some way. Eugenics is alive and well today. When people screen their pregnancies for Down syndrome or intellectual disability, that's eugenics. What was wrong with Nazi eugenics was that it was involuntary. People had no choice. People today can choose to utilize the fruits of science to make these selection decisions. Today, eugenics is about giving couples the choice of a better or worse life for themselves.

We've talked about new reproductive technology. Do we also need to rethink the ethics of how people die?

There are two aspects that we'll have to confront. One we're already confronting—how we die—which I think is ethically uninteresting. Of course people should be allowed to decide when and how they exit this world. The reason we have laws against it are either religious or based on arcane, outdated laws, like your body belonged to the King and you couldn't render it unfit for fighting! Now, these are quite inappropriate in a secular society. If I want to end my life and someone else wants to help me, what business is it of the state or other people to interfere?

So what's the interesting question about death?

The interesting question is how long we should live. At the moment we've pretty much maxed out what we can do with treating cardiovascular disease or cancer. But if we could attack aging, which is the real disease that causes adult onset cancer and cardiovascular disease, stroke and diabetes, people could live healthily for 200 years or longer. Then we'll face the deep question, how long should we live? How many people should there be? How we will pay for people living to 150? How will younger people carve out a place in society? Will life become boring? These are really deep and difficult questions. Is this something that people should be able to choose, or should we place termination criteria on how long people can live? It may be that our death starts to become not just our choice, but society's choice. Is it better to have a society with 500 million people living to 80, or 250 million people living to 160? Those are difficult questions that we may well have to decide. This idea that we'll just leave it to the market to resolve is not going to wash.

We're not the kind of animal that's designed to live in the world that our enormous cognitive capacity has created.

Would you like to live 200 or 500 years?

I want to live as long as possible. I don't see anything being there afterward! I want to live in as bad a condition for as long as possible.

So you're not one of these people who thinks the prospect of death somehow gives life meaning?

No, not at all. The prospect of failure gives life meaning. The reality is people are often prepared to embrace death when it's not staring them in the face. Some people choose euthanasia not because they want death, but because they don't want any longer the poor quality of life they have. But if you're in full health, there are very few people who actually want to die just because they've lived too long. I think the challenge is to continue to reinvent yourself and your life. You're already seeing people today having two or three careers, two or three families during their lives, and they don't say they've had enough. I want to go on as long as possible.

What do you make of Ray Kurzweil and the transhumanists who think there will be some sort of singularity—a merging of human and machine that leads to an entirely new species in a post-human future?

I have some sympathy for them and I think it's great that they're out there pushing that line of argument. I'm not a transhumanist or a post-humanist. I think it starts to take on characteristics of a religion and is a kind of belief in itself. But the ideas are interesting and need to be taken seriously. I wouldn't put all my eggs in their basket, but I'd put some eggs in their basket. The capacity for technology to increase in power is exponential; the capacity of humans to control it doesn't increase exponentially. We have to realize that the technology we've created has reached a point of being runaway.

If we speculate about how the ethical landscape might change by the year 2050, what do you see as the biggest challenges ahead?

We're in a very critical period. We'll either learn to live with people across the world or we'll face extinction. We've evolved in groups of 150, and to some degree we've managed to extend that to nation states. But what you see now is the ability of individuals or small groups to challenge those larger groups. They haven't yet used weapons of mass destruction such as biological weapons, but within a decade or two those weapons will be in the hands of hundreds of thousands of people. The idea that we can continue to maintain order at a national level but not at an international level is untenable.

So our biggest threat is renegade terrorists with weapons of mass destruction?

I think there are two threats: single individuals or groups using weapons of mass destruction, and the limitations of our moral dispositions as we face problems of collective action. Climate change is not a problem caused by a single individual, but by whole groups. It requires coordination to solve. Historically we could solve those problems when we were in small groups. If we saw other farmers overgrazing and depleting a communal resource, we could punish them. But when it comes to issues like climate change, depletion of resources, global inequality, or the threat of pandemics, we can't see our own contribution in the same way. Our psychology is a barrier to dealing with collective problems.

Because we evolved in small groups and people outside our tribes were potential enemies. You're saying we need to get past that psychology?

Yes. Racism is implicit. It's built in. If you study people's dispositions, they identify out-group members at a subconscious level and behave differently toward them. That's not to say we can't overcome those biases and prejudices through laws or moral education. But we do face a significant challenge. We're not the kind of animal that's designed to live in the world that our enormous cognitive capacity has created—global interconnectivity and massively advanced technology. We're entering a new phase where the rules and codes governing our behavior are no longer suitable. The deeply difficult question comes when we face the moral challenges of becoming less prejudiced and less racist.

There are different kinds of threats. Cosmologists worry about an asteroid hitting us. Nick Bostrom says artificial intelligence could become so sophisticated that it wipes us out. Are you talking about something else?

I think we are the biggest threat to ourselves. The elephant in the room is the human being. For the first time in human history we really are the masters of our destiny. We've got enormous potential to have unprecedentedly good lives. We'll be able to live twice as long. With our computers and the Internet, we already are smarter than any of our predecessors. But we also have the possibility to completely shackle ourselves, if not destroy ourselves. The Internet is a good example. In George Orwell's *1984*, Big Brother was placing us under surveillance, controlling and censoring everything that happened. In some ways we already are under surveillance. But my worry is not the government—at least not in the U.K. or the U.S.; it's each other. As soon as we publish something, it's immediately pumped around the Internet to every fanatical group, which then mobilizes within minutes and creates such momentum that it doesn't matter what you said or what the truth is; what matters is the perception. So we now live under a kind of censorship of each other and that's just going to increase.

STEVE PAULSON is the executive producer of Wisconsin Public Radio's nationally syndicated show To the Best of Our Knowledge. He's the author of *Atoms and Eden: Conversations on Religion and Science*.

Don't Worry, Smart Machines Will Take Us with Them

Why human intelligence and AI will co-evolve

BY STEPHEN HSU

WHEN IT COMES TO artificial intelligence, we may all be suffering from the fallacy of availability: thinking that creating intelligence is much easier than it is, because we see examples all around us. In a recent poll, machine intelligence experts predicted that computers would gain human-level ability around the year 2050, and superhuman ability less than 30 years after.[1] But, like a tribe on a tropical island littered with World War II debris imagining that the manufacture of aluminum propellers or steel casings would be within their power, our confidence is probably inflated.

AI can be thought of as a search problem over an effectively infinite, high-dimensional landscape of possible programs. Nature solved this search problem by brute force, effectively performing a huge computation involving trillions of evolving agents of varying information processing capability in a complex environment (the Earth). It took billions of years to go from the first tiny DNA replicators to *Homo Sapiens*. What evolution accomplished required tremendous resources. While silicon-based technologies are increasingly capable of *simulating* a mammalian or even human brain, we have little idea of how to find the tiny subset of all possible programs running on this hardware that would exhibit intelligent behavior.

But there is hope. By 2050, there will be another rapidly evolving and advancing intelligence besides that of machines: our own. The cost to sequence a human genome has fallen below $1,000, and powerful methods have been developed to unravel the genetic architecture of complex traits such as human cognitive ability. Technologies already exist which allow genomic selection of embryos during in vitro fertilization—an embryo's DNA can be sequenced from a single extracted cell. Recent advances such as CRISPR allow highly targeted editing of genomes, and will eventually find their uses in human reproduction.

The potential for improved human intelligence is enormous. Cognitive ability is influenced by thousands

ILLUSTRATION BY SACHIN TENG

of genetic loci, each of small effect. If all were simultaneously improved, it would be possible to achieve, very roughly, about 100 standard deviations of improvement, corresponding to an IQ of over 1,000.[2] We can't imagine what capabilities this level of intelligence represents, but we can be sure it is far beyond our own. Cognitive engineering, via direct edits to embryonic human DNA, will eventually produce individuals who are well beyond all historical figures in cognitive ability. By 2050, this process will likely have begun.

These two threads—smarter people and smarter machines—will inevitably intersect. Just as machines will be much smarter in 2050, we can expect that the humans who design, build, and program them will also be smarter. Naively, one would expect the rate of advance of machine intelligence to outstrip that of biological intelligence. Tinkering with a machine seems easier than modifying a living species, one generation at a time. But advances in genomics—both in our ability to relate complex traits to the underlying genetic codes, and the ability to make direct edits to genomes—will allow rapid advances in biologically-based cognition. Also, once machines reach human levels of intelligence, our ability to tinker starts to be limited by ethical considerations. Rebooting an operating system is one thing, but what about a sentient being with memories and a sense of free will?

Therefore, the answer to the question "Will AI or genetic modification have the greater impact in the year 2050?" is yes. Considering one without the other neglects an important interaction.

IT HAS HAPPENED BEFORE. It is easy to forget that the computer revolution was led by a handful of geniuses: individuals with truly unusual cognitive ability. Alan Turing and John von Neumann both contributed to the realization of computers whose program is stored in memory and can be modified during execution. This idea appeared originally in the form of the Turing Machine, and was given practical realization in the so-called von Neumann architecture of the first electronic computers, such as the EDVAC. While this computing design seems natural, even obvious, to us now, it was at the time a significant conceptual leap.

Turing and von Neumann were special, and far beyond peers of their era. Both played an essential role in the Allied victory in WWII. Turing famously broke the German Enigma codes, but not before conceptualizing the notion of "mechanized thought" in his Turing Machine, which was to become the main theoretical construct in modern computer science. Before the war, von Neumann placed the new quantum theory on a rigorous mathematical foundation. As a frequent visitor to Los Alamos he made contributions to hydrodynamics and computation that were essential to the United States' nuclear weapons program. His close colleague, the Nobel Laureate Hans A. Bethe, established the singular

MINDS BUILDING MINDS
Alan Turing (right) at work on an early computer c. 1951.

ALFRED EISENSTAEDT/GETTY IMAGES

nature of his abilities, and the range of possibilities for human cognition, when he said "I always thought von Neumann's brain indicated that he was from another species, an evolution beyond man."

Today, we need geniuses like von Neumann and Turing more than ever before. That's because we may already be running into the genetic limits of intelligence. In a 1983 interview, Noam Chomsky was asked whether genetic barriers to further progress have become obvious in some areas of art and science.[3] He answered:

> You could give an argument that something like this has happened in quite a few fields ... I think it has happened in physics and mathematics, for example ... In talking to students at MIT, I notice that many of the very brightest ones, who would have gone into physics twenty years ago, are now going into biology. I think part of the reason for this shift is that there are discoveries to be made in biology that are within the range of an intelligent human being. This may not be true in other areas.

AI research also pushes even very bright humans to their limits. The frontier machine intelligence architecture of the moment uses deep neural nets: multilayered networks of simulated neurons inspired by their biological counterparts. Silicon brains of this kind, running on huge clusters of GPUs (graphical processor units made cheap by research and development and economies of scale in the video game industry), have recently surpassed human performance on a number of narrowly defined tasks, such as image or character recognition. We are learning how to tune deep neural nets using large samples of training data, but the resulting structures are mysterious to us. The theoretical basis for this work is still primitive, and it remains largely an empirical black art. The neural networks researcher and physicist Michael Nielsen puts it this way:

> ... in neural networks there are large numbers of parameters and hyper-parameters, and extremely complex interactions between them. In such extraordinarily complex systems it's exceedingly difficult to establish reliable general statements. Understanding neural networks in their full generality is a problem that, like quantum foundations, tests the limits of the human mind.[4]

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A TITAN AT TEATIME John von Neumann talking to graduate students during afternoon tea.

The detailed inner workings of a complex machine intelligence (or of a biological brain) may turn out to be incomprehensible to our human minds—or at least the human minds of today. While one can imagine a researcher "getting lucky" by stumbling on an architecture or design whose performance surpasses her own capability to understand it, it is hard to imagine systematic improvements without deeper comprehension.

BUT PERHAPS WE WILL experience a positive feedback loop: Better human minds invent better machine learning methods, which in turn accelerate our ability to improve human DNA and create even better minds. In my own work, I use methods from machine learning (so-called compressed sensing, or convex optimization in high dimensional geometry) to extract predictive models from genomic data. Thanks to recent advances, we can predict a phase transition in the behavior of these learning algorithms, representing a sudden increase in their effectiveness. We expect this transition to happen within about a decade, when we reach a critical threshold of about 1 million human genomes worth of data. Several entities, including the U.S. government's Precision Medicine Initiative and the private company Human Longevity Inc. (founded by Craig Venter), are pursuing plans to genotype 1 million individuals or more.

The feedback loop between algorithms and genomes will result in a rich and complex world, with myriad types of intelligences at play: the ordinary human (rapidly losing the ability to comprehend what is going on around them); the enhanced human (the driver of change over the next 100 years, but perhaps eventually surpassed); and all around them vast machine intellects, some alien (evolved completely in silico) and some strangely familiar (hybrids). Rather than the standard science-fiction scenario of relatively unchanged, familiar humans interacting with ever-improving computer minds, we will experience a future with a diversity of both human and machine intelligences. For the first time, sentient beings of many different types will interact collaboratively to create ever greater advances, both through standard forms of communication and through new technologies allowing brain interfaces. We may even see human minds uploaded into cyberspace, with further hybridization to follow in the purely virtual realm. These uploaded minds could combine with artificial algorithms and structures to produce an unknowable but humanlike consciousness. Researchers have recently linked mouse and monkey brains together, allowing the animals to collaborate—via an electronic connection—to solve problems. This is just the beginning of "shared thought."

It may seem incredible, or even disturbing, to predict that ordinary humans will lose touch with the most consequential developments on planet Earth, developments that determine the ultimate fate of our civilization and species. Yet consider the early 20th-century development of quantum mechanics. The first physicists studying quantum mechanics in Berlin—men like Albert Einstein and Max Planck—worried that human minds might not be capable of understanding the physics of the atomic realm. Today, no more than a fraction of a percent of the population has a good understanding of quantum physics, although it underlies many of our most important technologies: Some have estimated that 10-30 percent of modern gross domestic product is based on quantum mechanics. In the same way, ordinary humans of the future will come to accept machine intelligence as everyday technological magic, like the flat screen TV or smartphone, but with no deeper understanding of how it is possible.

New gods will arise, as mysterious and familiar as the old.

STEPHEN HSU is Vice-President for Research and Professor of Theoretical Physics at Michigan State University. He is also a scientific advisor to BGI (formerly, Beijing Genomics Institute) and a founder of its Cognitive Genomics Lab.

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"MULTIPLICITY"
ILLUSTRATION BY **ANGIE WANG**

29

THERE IS A CLASSIC SET of Soviet jokes all about how different cultures scale. One Englishmen, it goes, makes a gentleman. Two make a bet, and three a parliament. A single Frenchman, by comparison, makes a lady's man, two make a duel, and three a Paris commune.

These jokes have a kernel of truth (regardless of what you think of the English and French): How things become bigger or smaller reveals a lot about them. How big can a city get and still be a city? What about a classroom? Is there some cosmic censorship preventing a car-sized object from being in two places at once, just like electrons and photons can be? Can a "theory of everything" describe our universe at all possible scales?

"How much," we learn, is often just as important as "why" or "how."

Welcome to "Scaling."

—MS

"There would always be new physics to discover, and there would never be a final, universal theory that applies for all scales of space and time."

LAWRENCE M. KRAUSS
"The Trouble with Theories of Everything" p.90

Scaling

WHATEVER FITS

Is Life Special Just Because It's Rare?

Vitalism in the age of modern science

BY ALAN LIGHTMAN

A **ROCKET POWERED BY KEROSENE** and liquid oxygen and carrying a scientific observatory blasted off into space at 10:49 p.m., March 6, 2009 (by local calendars and clocks). The launch came from the third planet out from a G-type star, 25,000 light-years from the center of a galaxy called the Milky Way, itself located on the outskirts of the Virgo Cluster of galaxies. On the night of the launch, the sky was clear, with no precipitation or wind, and the temperature was 292 degrees by the absolute temperature scale. Local intelligent life forms cheered the launch. Shortly before the blastoff, the government agency responsible for spacecraft, named the National Aeronautics and Space Administration, wrote in the global network of computers: "We are looking at a gorgeous night to launch the Kepler observatory on the first-ever mission dedicated to finding planets like ours outside the solar system."

The above account might have been written by an intelligent life form located on exactly the kind of distant planet that Kepler would soon begin to search for. Named after the Renaissance astronomer Johannes Kepler, the observatory was specifically designed to find planets outside our solar system that would be "habitable"—that is, neither so near their central star that water would be boiled off, nor so far away that water would freeze. Most biologists consider liquid water to be a precondition for life, even life very different from that on Earth. Kepler has surveyed about 150,000 sun-like stellar systems in our galaxy and discovered ovr 1,000 alien planets. Although the satellite stopped functioning in 2013, its enormous stockpile of data is still being analyzed.

For centuries, we human beings have speculated on the possible existence and prevalence of life elsewhere in the universe. For the first time in history, we can begin to answer that profound question. At this point, the results of the Kepler mission can be extrapolated to suggest that something like 10 percent of all stars have a habitable planet in orbit. That fraction is large. With

ILLUSTRATION BY GIZEM VURAL

100 billion stars just in our galaxy alone, and so many other galaxies out there, it is highly probable that there are many, many other solar systems with life. From this perspective, life in the cosmos is common.

However, there's another, grander perspective from which life in the cosmos is rare. That perspective considers *all* forms of matter, both animate and inanimate. Even if all "habitable" planets (as determined by Kepler) do indeed harbor life, the fraction of all material in the universe in living form is fantastically small. Assuming that the fraction of planet Earth in living form, called the biosphere, is typical of other life-sustaining planets, I have estimated that the fraction of all matter in the universe in living form is roughly one-billionth of one-billionth. Here's a way to visualize such a tiny fraction. If the Gobi Desert represents all of the matter flung across the cosmos, living matter is a single grain of sand on that desert. How should we think about this extreme rarity of life?

MOST OF US HUMAN BEINGS throughout history have considered ourselves and other life forms to contain some special, nonmaterial essence that is absent in nonliving matter and that obeys different principles than does nonliving matter. Such a belief is called "vitalism." Plato and Aristotle were vitalists. Descartes was a vitalist. Jöns Jakob Berzelius, the 19th-century father of modern chemistry, was a vitalist. The hypothesized nonmaterial vital essence, especially in human beings, has sometimes been called "spirit." Sometimes "soul." The eighth-century B.C. Egyptian royal official Kuttamuwa built an 800-pound monument to house his immortal soul and asked that his friends feast there after his physical demise to commemorate him in his afterlife. The 10th-century Persian polymath Avicenna argued that since we would be able to think and to be self-aware even if we were totally disconnected from all external sensory input, there must be some nonmaterial soul inside of us. These are all vitalist ideas.

Modern biology has challenged the theory of vitalism. In 1828, the German chemist Friedrich Wöhler synthesized the organic substance urea from nonorganic chemicals. Urea is a byproduct of metabolism in many living organisms and, previous to Wöhler's work,

was believed to be uniquely associated with living beings. Later in the century, the German physiologist Max Rubner showed that the energy used by human beings in movement, respiration, and other forms of activity is precisely equal to the energy content of food consumed. That is, there are no hidden and nonmaterial sources of energy that power human beings. In more recent years, the composition of proteins, hormones, brain cells, and genes has been reduced to individual atoms, without the need to invoke nonmaterial substances.

Yet, I would argue that most of us, either knowingly or unknowingly, remain closet vitalists. Although there are moments when the material nature of our bodies screams out at us, such as when we have muscle injuries or change our mood with psychoactive drugs, our mental life seems to be a unique phenomenon arising from a different kind of substance, a nonmaterial substance. The sensations of consciousness, of thought and self-awareness, are so gripping and immediate and magnificent that we find it preposterous that they could have their origins entirely within the humdrum electrical and chemical tinglings of cells in our brains. However, neuroscientists say that is so.

Polls of the American public show that three-quarters of people believe in some form of life after death. Surely, this belief too is a version of vitalism. If our bodies and brains are nothing more than material atoms, then, as Lucretius wrote two millennia ago, when those atoms disperse as they do after death, there can be no further existence of the living

If the Gobi Desert represents all of the matter flung across the cosmos, living matter is a single grain of sand on that desert.

ADRIENC/GETTY IMAGES

A universe without comment is a universe without meaning.

being that once was.

Paradoxically, if we can give up the belief that our bodies and brains contain some transcendent, nonmaterial essence, if we can embrace the idea that we are completely material, then we arrive at a new kind of specialness—an alternative to the specialness of "vitalism." We are special material. We humans living on our one planet wring our hands about the brevity of our lives and our mortal restraints, but we do not often think about how improbable it is to be alive at all. Of all the zillions of atoms and molecules in the universe, we have the privilege of being composed of those very, very few atoms that have joined together in the special arrangement to make living matter. We exist in that one-billionth of one-billionth. We are that one grain of sand on the desert.

And what is that special arrangement deemed "life?" The ability to form an outer membrane around the organism that separates it from the external world. The ability to organize material and processes within the organism. The ability to extract energy from the external world. The ability to respond to stimuli from the external world. The ability to maintain stability within the organism. The ability to grow. The ability to reproduce. We human beings, of course, have all of these properties and more. For we have billions of neurons connected to each other in an exquisite tapestry of communication and feedback loops. We have consciousness and self-awareness.

THE TWO TRAMPS in Samuel Beckett's *Waiting for Godot*, placed on a minimalist stage without time and without space, waiting interminably for the mysterious Godot, capture our bafflement with the meaning of existence.

> Estragen: "What did we do yesterday?"
> Vladimir: "What did we do yesterday?"
> Estragen: "Yes."
> Vladimir: "Why … (Angrily) Nothing is certain when you're about."

Of course, there are questions that do not have answers.

But if we can manage to get outside of our usual thinking, if we can rise to a truly mind-bending view of the cosmos, there's another way to think of existence. In our extraordinarily entitled position of being not only living matter but conscious matter, we are the cosmic "observers." We are uniquely aware of ourselves and the cosmos around us. We can watch and record. We are the only mechanism by which the universe can comment on itself. All the rest, all those other grains of sand on the desert, are dumb, lifeless matter.

Of course, the universe does not need to comment on itself. A universe with no living matter at all could function without any trouble—mindlessly following the conservation of energy and the principle of cause and effect and the other laws of physics. A universe does not need minds, or any living matter at all. (Indeed, in the recent "multiverse" hypothesis endorsed by many physicists, the vast majority of universes are totally lifeless.) But in this writer's opinion, a universe without comment is a universe without meaning. What does it mean to say that a waterfall, or a mountain, is beautiful? The concept of beauty, and indeed all concepts of value and meaning, require observers. Without a mind to observe it, a waterfall is only a waterfall, a mountain is only a mountain. It is we conscious matter, the rarest of all forms of matter, that can take stock and record and announce this cosmic panorama of existence before us.

I realize that there is a certain amount of circularity in the above comments. For meaning is relevant, perhaps, only in the context of minds and intelligence. If the minds don't exist, then neither does meaning. However, the fact is that we do exist. And we have minds. We have thoughts. The physicists may contemplate billions of self-consistent universes that do not have planets or stars or living material, but we should not neglect our own modest universe and the fact of our own existence. And even though I have argued that our bodies and brains are nothing more than material atoms and molecules, we have created our own cosmos of meaning. We make societies. We create values. We make cities. We make science and art. And we have done so as far back as recorded history.

In his book *The Mysterious Flame* (1999), the British philosopher Colin McGinn argues that it is impossible to understand the phenomenon of consciousness because we cannot get outside of our minds to discuss it. We are inescapably trapped within the network of neurons whose mysterious experience we are attempting to analyze. Likewise, I would argue that we are imprisoned within our own cosmos of meaning. We cannot imagine a universe without meaning. We are not talking necessarily about some grand cosmic meaning, or a divine meaning bestowed by God, or even a lasting, eternal meaning. But just the simple, particular meaning of everyday events, fleeting events like the momentary play of light on a lake, or the birth of a child. For better or for worse, meaning is part of the way we exist in the world.

And given our existence, our universe must have meaning, big and small meanings. I have not met any of the life forms living out there in the vast cosmos beyond Earth. But I would be astonished if some of them were not intelligent. And I would be further astonished if those intelligences were not, like us, making science and art and attempting to take stock and record this cosmic panorama of existence. We share with those other beings not the mysterious, transcendent essence of vitalism, but the highly improbable fact of being alive.

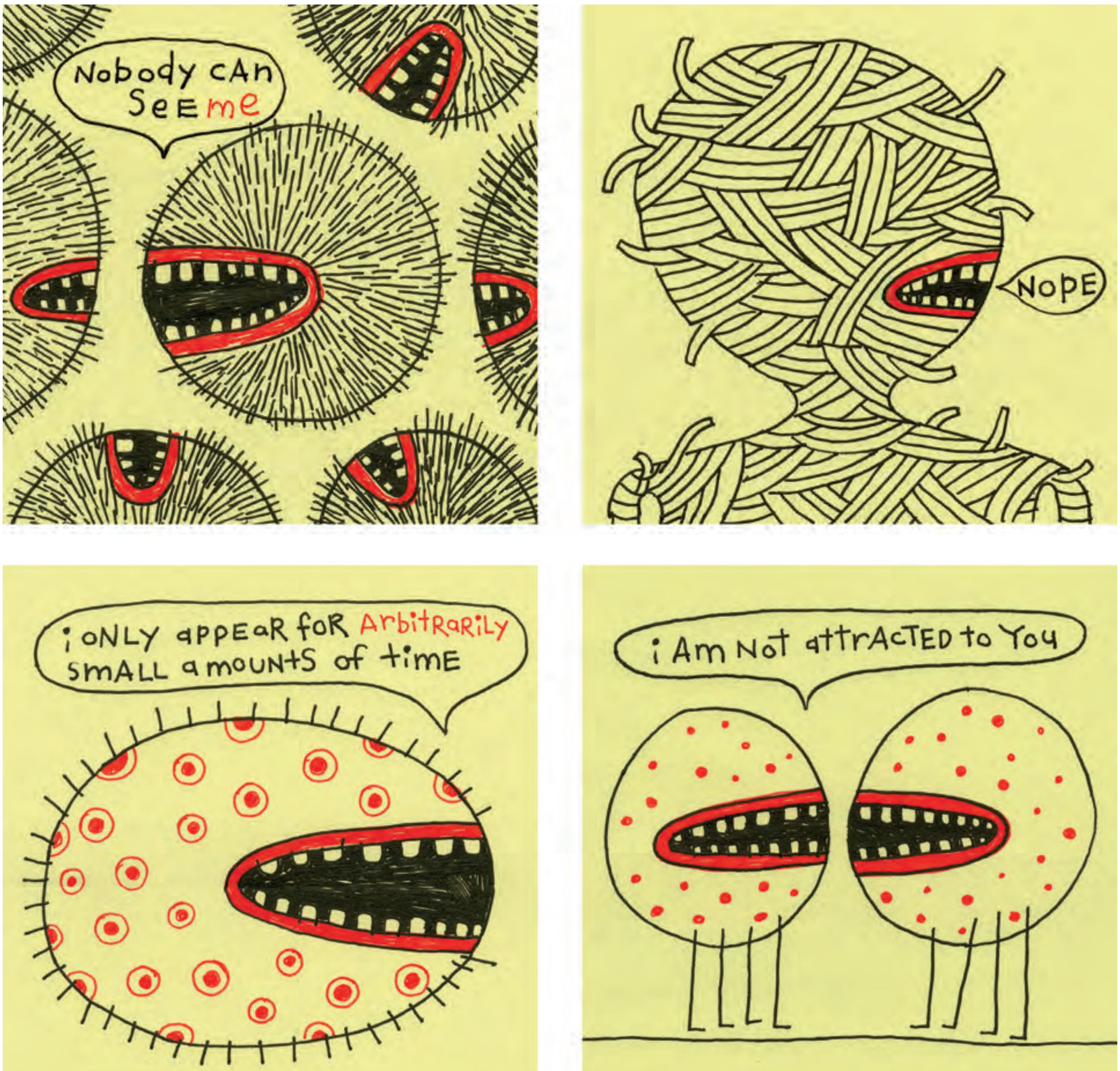
ALAN LIGHTMAN is a physicist, novelist, and professor of the practice of the humanities at the Massachusetts Institute of Technology. His latest book is *Screening Room*.

The Trouble with Theories of Everything

There is no known physics theory that is true at every scale, and there may never be one

BY LAWRENCE M. KRAUSS

ILLUSTRATIONS BY MELINDA BECK


Nobody cAn SeE me
NOPE
i ONLY appEaR foR ArbitRaRiLy SMALL amouNtS of timE
i Am Not attrACTED to You

W**HENEVER YOU SAY ANYTHING** about your daily life, a scale is implied. Try it out. "I'm too busy" only works for an assumed time scale: today, for example, or this week. Not this century or this nanosecond. "Taxes are onerous" only makes sense for a certain income range. And so on.

Surely the same restriction doesn't hold true in science, you might say. After all, for centuries after the introduction of the scientific method, conventional wisdom held that there were theories that were absolutely true for all scales, even if we could never be empirically certain of this in advance. Newton's universal law of gravity, for example, was, after all, universal! It applied to falling apples and falling planets alike, and accounted for every significant observation made under the sun, and over it as well.

With the advent of relativity, and general relativity in particular, it became clear that Newton's law of gravity was merely an approximation of a more fundamental theory. But the more fundamental theory, general relativity, was so mathematically beautiful that it seemed reasonable to assume that it codified perfectly and completely the behavior of space and time in the presence of mass and energy.

The advent of quantum mechanics changed everything. When quantum mechanics is combined with relativity, it turns out, rather unexpectedly in fact, that the detailed nature of the physical laws that govern matter and energy actually depend on the physical scale at which you measure them. This led to perhaps the biggest unsung scientific revolution in the 20th century: We know of no theory that both makes contact with the empirical world, and is absolutely and always true. (I don't envisage this changing anytime soon, string theorists' hopes notwithstanding.) Despite this, theoretical physicists have devoted considerable energy to chasing exactly this kind of theory. So, what is going on? Is a universal theory a legitimate goal, or will scientific truth always be scale-dependent?

THE COMBINATION OF QUANTUM MECHANICS and relativity implies an immediate scaling problem. Heisenberg's famous uncertainty principle, which lies at the heart of quantum mechanics, implies that on small scales, for short times, it is impossible to completely constrain the behavior of elementary particles. There is an inherent uncertainty in energy and momenta that can never be reduced. When this fact is combined with special relativity, the conclusion is that you cannot actually even constrain the number of particles present in a small volume for short times. So called "virtual particles" can pop in and out of the vacuum on timescales so short you cannot measure their presence directly.

One striking effect of this is that when we measure the force between electrons, say, the actual measured charge on the electron—the thing that determines how strong the electric force is—depends on what scale you measure it at. The closer you get to the electron, the more deeply you are penetrating inside of the "cloud" of virtual particles that are surrounding the electron. Since positive virtual particles are attracted to the electron, the deeper you penetrate into the cloud, the less of the positive cloud and more of the negative charge on the electron you see.

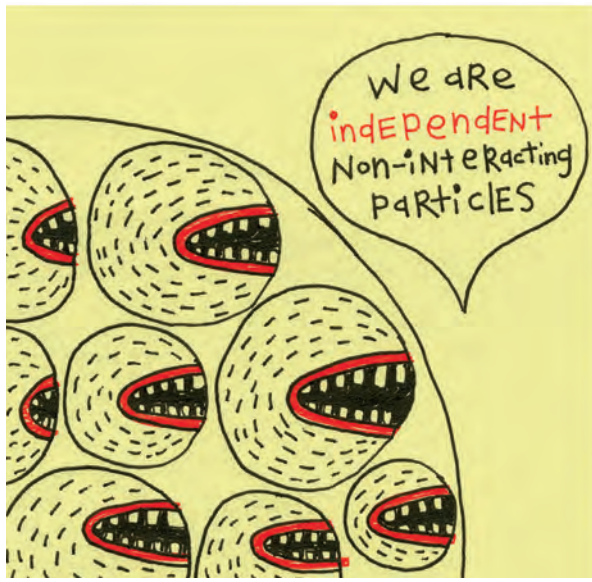
> Feynman's concerns were, in a sense, misplaced. The problem was not with the theory.

Then, when you set out to calculate the force between two particles, you need to include the effects of all possible virtual particles that could pop out of empty space during the period of measuring the force. This includes particles with arbitrarily large amounts of mass and energy, appearing for arbitrarily small amounts of time. When you include such effects, the calculated force is infinite.

Richard Feynman shared the Nobel Prize for arriving at a method to consistently calculate a finite residual force after extracting a variety of otherwise ambiguous infinities. As a result, we can now compute, from fundamental principles, quantities such as the magnetic moment of the electron to 10 significant figures, comparing it with experiments at a level unachievable in any other area of science.

But Feynman was ultimately disappointed with what he had accomplished—something that is clear from his 1965 Nobel lecture, where he said, "I think that the renormalization theory is simply a way to sweep the difficulties of the divergences of electrodynamics under the rug." He thought that no sensible complete theory should produce infinities in the first place, and that the mathematical tricks he and others had developed were ultimately a kind of kludge.

Now, though, we understand things differently. Feynman's concerns were, in a sense, misplaced. The problem was not with the theory, but with trying to push the theory beyond the scales where it provides the correct description of nature.



THERE IS A REASON that the infinities produced by virtual particles with arbitrarily large masses and energies are not physically relevant: They are based on the erroneous presumption that the theory is complete. Or, put another way, that the theory describes physics on all scales, even arbitrarily small scales of distance and time. But if we expect our theories to be complete, that means that before we can have a theory of *anything*, we would first have to have a theory of *everything*—a theory that included the effects of all elementary particles we already have discovered, plus all the particles we haven't yet discovered! That is impractical at best, and impossible at worst.

Thus, theories that make sense must be insensitive, at the scales we can measure in the laboratory, to the effects of possible new physics at much smaller distance scales (or less likely, on much bigger scales). This is not just a practical workaround of a temporary problem, which we expect will go away as we move toward ever-better descriptions of nature. Since our empirical knowledge is likely to always be partially incomplete, the theories that work to explain that part of the universe we can probe will, by practical necessity, be insensitive to possible new physics at scales beyond our current reach. It is a feature of our epistemology, and something we did not fully appreciate before we began to explore the extreme scales where quantum mechanics and relativity both become important.

This applies even to the best physical theory we have in nature: quantum electrodynamics, which describes the quantum interactions between electrons and light. The reason we can, following Feynman's lead, throw away with impunity the infinities that theory produces is that they are artificial. They correspond to extrapolating the theory to domains where it is probably no longer valid. Feynman was wrong to have been disappointed with his own success in maneuvering around these infinities—that is the best he could have done without understanding new physics at scales far smaller than could have been probed at the time. Even today, half a century later, the theory that takes over at the scales where quantum electrodynamics is no longer the correct description is itself expected to break down at still smaller scales.

THERE IS AN ALTERNATIVE narrative to the story of scale in physical theory. Rather than legitimately separating theories into their individual domains, outside of which they are ineffective, scaling arguments have revealed hidden connections between theories, and pointed the way to new unified theories that encompass the original theories and themselves apply at a broader range of scale.

For example, all of the hoopla over the past several years associated with the discovery of the Higgs particle was due to the fact that it was the last missing link in a theory that unifies quantum electrodynamics with another force, called the weak interaction. These are two of the four known forces in nature, and on the surface they appear very different. But we now understand that on very small scales, and very high energies, the two forces can be understood as different manifestations of the same underlying force, called the electroweak force.

Scale has also motivated physicists to try to unify another of nature's basic forces, the strong force, into a broader theory. The strong force, which acts on the quarks that make up protons and neutrons, resisted understanding until 1973. That year, three theorists, David Gross, Frank Wilczek, and David Politzer, demonstrated something absolutely unexpected and remarkable. They demonstrated that a candidate theory to describe this force, called quantum chromodynamics—in analogy with quantum electrodynamics—possessed a property they called "Asymptotic Freedom."

Asymptotic Freedom causes the strong force between quarks to get weaker as the quarks are brought closer together. This explained not only an experimental phenomenon that had become known as "scaling"—where quarks within protons appeared to behave as if they were independent non-interacting particles at high energies and small distances—but it also offered the possibility to explain why no free quarks are observed in nature. If the strong force becomes weaker at small distances, it presumably can be strong enough at large distances to ensure that no free quarks ever escape their partners.

The discovery that the strong force gets weaker at small distances, while electromagnetism, which gets united with the weak force, gets stronger at small distances, led theorists in the 1970s to propose that at sufficiently small scales, perhaps 15 orders of magnitude smaller than the size of a proton, all three forces (strong, weak, and electromagnetic) get unified together as a single force in what has become known as a Grand Unified Theory. Over the past 40 years we have been searching for direct evidence of this—in fact the Large Hadron Collider is just now searching for a whole set of new elementary particles that appear to be necessary for the scaling of the three forces to be just right. But while there is indirect evidence, no direct smoking gun has yet been found.

Naturally, efforts to unify three of the four known forces led to further efforts to incorporate the fourth force, gravity, into the mix. In order to do this, proposals have been made that gravity itself is merely an effective theory and at sufficiently small scales it gets merged with the other forces, but only if there are a host of extra spatial dimensions in nature that we do not observe. This theory, often called superstring theory, produced a great deal of excitement among theorists in the 1980s and 1990s, but to date there is not any evidence that it actually describes the universe we live in.

If it does then it will possess a unique and new feature. Superstring theory may ultimately produce no infinities at all. Therefore, it has the potential to apply at all distance scales, no matter how small. For this reason it has become known to some as a "theory of everything"—though, in fact, the scale where all the exotica of the theory would actually appear is so small as to be essentially physically irrelevant as far as foreseeable experimental measurements would be concerned.

THE RECOGNITION OF THE SCALE dependence of our understanding of physical reality has led us, over time, toward a proposed theory—string theory—for which this limitation vanishes. Is that effort the reflection of a misplaced audacity by theoretical physicists accustomed to success after success in understanding reality at ever-smaller scales?

While we don't know the answers to that question, we should, at the very least, be skeptical. There is no example so far where an extrapolation as grand as that associated with string theory, not grounded by direct experimental or observational results, has provided a successful model of nature. In addition, the more we learn about string theory, the more complicated it appears to be, and many early expectations about its universalism may have been optimistic.

At least as likely is the possibility that nature, as Feynman once speculated, could be like an onion, with a huge number of layers. As we peel back each layer we may find that our beautiful existing theories get subsumed in a new and larger framework. So there would always be new physics to discover, and there would never be a final, universal theory that applies for all scales of space and time, without modification.

Which road is the real road to reality is up for grabs. If we knew the correct path to discovery, it wouldn't be discovery. Perhaps my own predilection is just based on a misplaced hope of continued job security for physicists! But I also like the possibility that there will forever be mysteries to solve. Because life without mystery can get very boring, at any scale.

LAWRENCE M. KRAUSS is a theoretical physicist and cosmologist, Director of the Origins Project and Foundation Professor in the School of Earth and Space Exploration at Arizona State University. He is also the author of bestselling books including *A Universe from Nothing* and *The Physics of Star Trek*.

How Big Can Schrödinger's Kittens Get?

Scientists are slowly scaling up quantum effects from atomic to human size

BY PHILIP BALL

IT'S TIME WE THOUGHT again about quantum theory. There's nothing actually wrong with the theory itself—it works fantastically well for understanding how atoms and subatomic particles behave.

The problem is how we *talk* about quantum theory. We keep insisting that it's weird: waves becoming particles, things being in two places (or two states) at once, spooky action at a distance, that sort of thing. Isn't it perverse to clothe in mystery a theory that scientists use routinely to understand the world?

Part of the issue is that everyday objects are discrete, localized, and unambiguous, and so, very different to quantum objects. But why is that the case? Why is our everyday world always "this or that" and never "this *and* that"? Why, as things get bigger, does quantum physics turn into classical physics, governed by laws like those that Isaac Newton wrote down over three centuries ago?

This switch is called the quantum-classical transition, and it has puzzled scientists for many decades. We still don't completely understand it. But over the past two or so decades, new experimental techniques have pushed the transition to ever-larger sizes. Most scientists agree that technical difficulties will prevent us from ever putting a basketball, or even a human, in two places at once. But an emerging understanding of the quantum-classical transition also suggests that there is nothing in principle that prohibits it—no cosmic censorship separates out "normal" world from the "weird" world that lurks beneath it. In other words, the quantum world may not be so weird after all.

IMAGINE A BROKEN DRYING machine that spits out pairs of unmatched socks. They come in complementary contrasts: if one is red, the other is green. Or, if one is white, the other is black, and so on. We don't know which of these options we'll get until we look—but we *do* know that if we find one is red, we can be sure the

ILLUSTRATION BY ELLEN WEINSTEIN

other is green. Whatever the actual colors are, they are correlated with one another.

Now imagine the quantum mechanical version of this same machine. According to the Copenhagen interpretation of quantum mechanics developed in the mid-1920s by Niels Bohr, Werner Heisenberg, and collaborators, quantum socks in a correlated state (where the color of one is linked to the color of the other) don't actually have any fixed colors until we look. The very act of looking at one quantum sock *determines* the color of the other. If we look in one way, the first sock might be red (and the other therefore green). If we look in another, the first is white (and the other black).

Crudely, you could say that in these correlated pairs the colors of the socks are characteristics that extend well beyond the socks themselves. The color of a given sock is not local, that is, not contained in the properties of just that one sock. The two colors are said to be *entangled* with each other.

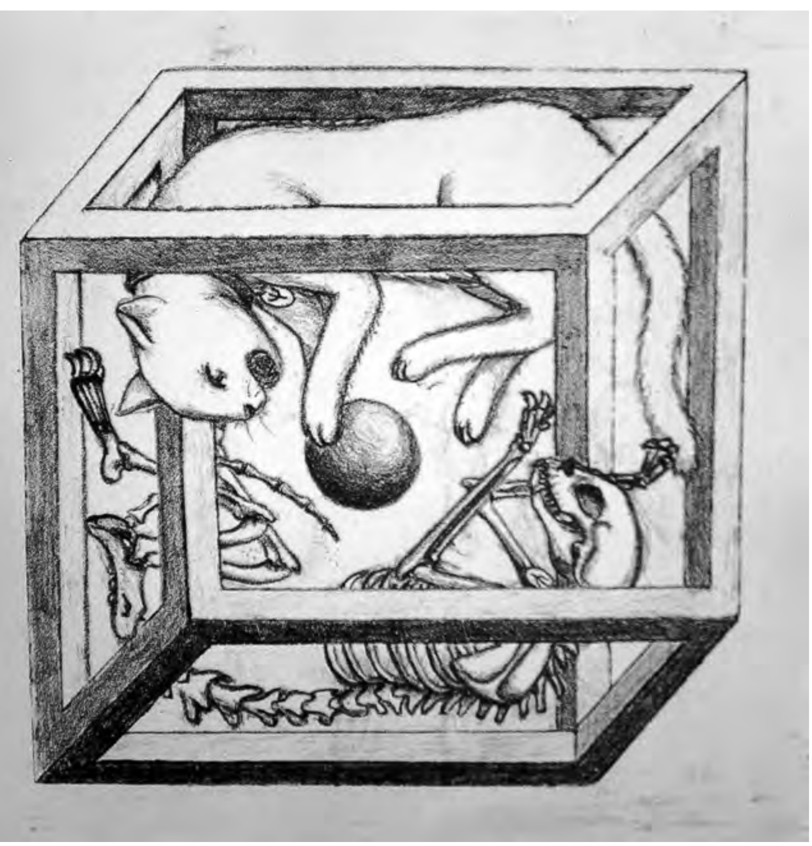
The physicist Erwin Schrödinger described entanglement as the key to quantum behavior, and used it to construct a famous paradox. It begins with an unfortunate cat that Schrödinger imagined trapped inside a box, into which a lethal poison was released by the outcome of some quantum event. Because the event was quantum, it could be in what physicists call a superposition state: both triggering the poison release, and not triggering it.

These superpositions are not unusual for tiny objects like atoms that are firmly in the quantum realm. But, because Schrödinger entangled the event with a large cat, the result is the paradoxical conclusion that the cat is both killed and not killed.

The conventional resolution to the paradox was to claim that making a measurement on a superposition state, like the live–dead cat, forces a choice, so that the superposition collapses the cat—indeed, in effect the whole universe—into one state or another: The cat is either dead or alive, but not both. In that view, we can never see the live–dead cat.

But what was the state of the cat before we looked? According to the Copenhagen interpretation, the question has no meaning. Reality, it maintains, is what we can observe and measure, and it makes no sense to wonder about what things are *really* like before we make those observations.

Others, most prominently Albert Einstein, couldn't accept this. They stuck with the classical "realist" view, which says that everything has particular, objective properties, whether we look or not. Einstein and two young colleagues, Boris Podolsky and Nathan



LIFE-AND-DEATH PHYSICS If a quantum event determined whether a cat in a box were killed, would it be both alive and dead?

PHOTO BY JIE QI ON FLICKR

Decoherence bleeds away discord. Quantum phenomena are converted to ones that obey classical rules.

Rosen, came up with a version of the "quantum drying machine" thought experiment to try to demonstrate how quantum theory led to a paradox, in which a measurement in one place instantly affected an object in another place. But in the 1980s, measurements of laser photons showed that entanglement really does work that way—not because of "faster-than-light" communication, but because quantum properties can be genuinely non-local, spread over more than one particle.

Since then, experimentalists have been working on building ever-larger quantum objects, which are big compared with atoms but small compared with real cats. They are often called "Schrödinger's kittens," and they are rapidly growing up.

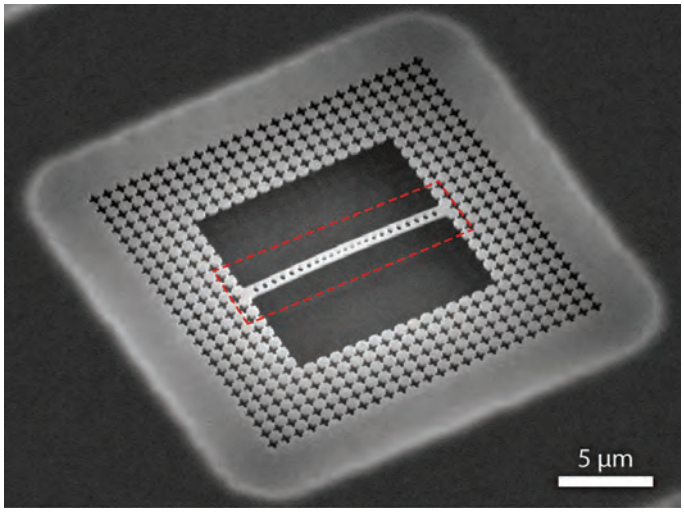
ONE KEY TO THESE KITTENS becoming cats has been learning how to maintain quantum coherence, or roughly, the ability for the peaks and troughs of wave-like quantum particles to stay synchronized. As a quantum state evolves, it gets entangled with its environment, and quantum coherence can leak away into the surroundings. One might very crudely imagine it to be a little like the way heat in a hot body gets dissipated into a cooler surrounding environment.

Another way to think of it is to say that information gets increasingly local. The point about quantum systems is that non-local correlations mean you can't know everything about some part of it by making measurements just on that part. There's always some residual ignorance. In contrast, once we have established that a sock is red or green, there's nothing left to be known about what color it is. Wojciech Zurek of Los Alamos National Laboratory in New Mexico has formulated an expression for the ignorance that remains once the state of the measuring apparatus has been determined, which he calls quantum discord. For a classical system, the discord is zero. If it is greater than zero, the system has some quantumness to it.

Decoherence bleeds away discord. Quantum phenomena are converted to ones that obey classical rules: no superpositions, no entanglement, no non-locality, and a time and a place for everything.

How big, then, can quantum systems get before decoherence starts to destroy their quantumness? We have known that very small particles like electrons can behave as coherent quantum waves ever since the ground-breaking observation of electron interference in the late 1920s. Soon after, the wavelike properties of entire atoms were demonstrated. But it wasn't until the 1990s, when it became possible to create coherent "matter waves," that quantum wave interference was observed for atoms and molecules.

How big can these chunks of matter get while still undergoing interference? In 1999 a team at the



A SCHRÖDINGER KITTEN The beam in the center of this shape (surrounded with a dotted red line) can be made to vibrate in two different ways at the same time, an example of quantum superposition.

University of Vienna led by Anton Zeilinger and Markus Arndt marshaled 60-atom carbon molecules called fullerenes (C_{60}) into a beam, passed it through a grating of slits spaced 100 nanometers apart and made from the ceramic silicon nitride, and detected an interference pattern on the far side. Arndt and his coworkers have now demonstrated that this quantum waviness persists for tailor-made organic molecules containing 430 atoms and up to 6 nanometers across: easily big enough to see in an electron microscope and comparable to the size of small proteins. The interference patterns can be washed out by decoherence: They vanish as the researchers admit gas into the apparatus, increasing the interactions of the molecules with their environment.

Because this interference depends on the molecules being in superposition states—in effect, each passes through more than one slit at a time—the molecules can be thought of as molecular Schrödinger's kittens. They're still very tiny, though, and obviously not alive. Might it be possible to push up the size scale to that at which life becomes possible—for example, to look for interference in "Schrödinger's viruses?"

That idea has been proposed by Ignacio Cirac and Oriol Romero-Isart at the Max Planck Institute for Quantum Optics in Garching, Germany. They have outlined an experimental method for preparing superposition states not only for viruses (with sizes of around 100 nanometers or more) but also for extremely hardy microscopic creatures called tardigrades or water bears (which are up to 1 millimeter or so in size). These objects would be levitated in an optical trap made of intense laser-light fields and then coaxed into a superposition of their vibrational states within the trapping force field (like balls rolling back and forth in the bottom of a bowl). Tardigrades have been shown to survive on the outside of spacecraft, and so might withstand the rigours of a high-vacuum experiment like this. So far, however, it's just a proposal.

We know already, however, that objects large

OSKAR PAINTER

enough to see with the naked eye can be placed in entangled stages. A team led by Ian Walmsley, a physicist at the University of Oxford, achieved this in 2011 using laser pulses to excite entangled quantum vibrations (phonons) in two diamond crystals 3 millimeters wide and 15 centimeters apart. Each phonon involves the coherent vibration of about 10^{16} atoms, corresponding to a region of the crystal measuring about 0.05 by 0.25 millimeters. To create the superposition, the researchers first placed a laser photon in an entangled state by using a beam splitter to send it toward either diamond with equal probability. So long as they don't detect this path, the photon creates an entangled vibration in both crystals. When a phonon is excited, it emits a secondary photon, which the researchers could detect without finding out which crystal it comes from. In that case the phonon must be considered non-local, in a sense embracing both diamonds.

Another way to look at quantum effects in relatively large systems is to study the vibrations of very small springy structures like nanometer-scale cantilevers and other "nanomechanical resonators." At the scale of molecules, vibrations are quantized: They can only occur at well-defined frequencies, or in mixed superpositions of these allowed quantum states. Nanomechanical resonators are also small and light enough to have, in theory, distinguishable quantized vibration states. An ideal way to read out the vibrational state of the resonating element is to couple its mechanical motion to light, an approach called optomechanics. In its simplest form, this might involve making a chamber in which light can bounce back and forth between mirrors, with one of the mirrors attached to a spring so that it can oscillate.

Several groups have now demonstrated quantum behavior in such nanoscale optomechanical systems. John Teufel and his coworkers at the National Institute of Standards and Technology in Boulder, Colorado, for example, used a drum-like aluminum membrane 100 nanometers thick and 15 micrometers (μm) wide as the resonator, coupled to a microwave-frequency cavity, while Oskar Painter and colleagues at the California Institute of Technology in Pasadena used a thin silicon beam 15 micrometers long, with a 600 by 100 nanometer cross-section, clamped at both ends. You need a microscope to see those objects, but they're immense compared with molecules. To ensure that their oscillators stayed in a single, lowest-energy vibrating state, both teams chilled their devices close to absolute zero using cryogenics, and then used laser beams or microwaves to reduce the temperature even further.

If you want to generate quantum effects such as superpositions and entanglement in these resonators, you need to be able to control their quantum behavior. One way to do this is to couple the resonators to a quantum object whose state can be switched at will, such as a two-state "quantum bit" of the kind being used to build quantum computers. Andrew Cleland of the University of California at Santa Barbara and his coworkers achieved this for a microscopic sheet of aluminum nitride. Others are hoping to prepare oscillators in superposition states and then watch how they decohere as they get entangled with their environment: middle-sized Schrödinger kittens bouncing in the void.

IF WE COULD TOTALLY suppress decoherence, would that get us all the way to a full-size Schrödinger cat? It might not be that simple. This is because, to know that you'd made one, you'd have to look at it. Sure, the act of entangling a system with a measuring apparatus could itself decohere it—but the problem might be even worse than that. Physicists Johannes Kofler, now at the Max Planck Institute for Quantum Optics in Garching, and Caslav Brukner of the University of Vienna proposed in 2007 that the very act of studying a large quantum system experimentally may induce the emergence of classical behavior even without any decoherence. Measurement itself can turn quantum multiplicity into classical uniqueness.

This, say Kofler and Brukner, is because measurements can't be infinitely precise. The argument is often made in textbooks that the limits of experimental resolution prevent us from being able to see quantum discreteness in a macroscopic system: Because the discrete energy states get ever closer as the size of the system increases, they seem to blur into the continuum of energies that we perceive in, say, a moving tennis ball. But that can't be the only reason why tennis balls are "classical", because it doesn't actually eliminate the quantumness of the object—forbidding, for example, a superposition of tennis-ball velocities.

Kofler and Brukner showed that, when a measurement is "coarse-grained," so that the resolution is insufficient to distinguish several closely spaced quantum states of a very large system, the quantum-mechanical equations describing how it evolves in time collapse into the classical equations of mechanics devised by Isaac Newton. "We can rigorously show that under the coarse-grained measurements, entanglement or nonlocal features of many-particle states are washed out," says Brukner. Classical physics emerges from quantum physics when measurement becomes fuzzy, as it always must for "big" systems: ones composed of many particles with many possible states.

The argument is not airtight: It's possible in principle (though extremely hard in practice) to create exotic situations in which the coarse-graining of measuring some property of the system doesn't ensure classicality. But Hyunseok Jeong of Seoul National University in South Korea and his collaborators have shown that even here there's an aspect of measurement that destroys quantum behavior. In addition to some inevitable fuzziness in *what* we measure, says Jeong, there is also a degree of ambiguity about exactly *when* and *where* we measure: what he calls the measurement references. This too has the effect of making a quantum system appear to behave like a classical one.

Kofler says that decoherence and coarse-graining of measurements offer two complementary routes to the classical world. "If you have sufficiently strong decoherence, you get classicality independent of your measurements," he says. "And if you have coarse-grained measurement, you get classicality independent of the interaction with the environment."

This picture offers a striking resolution of the Schrödinger's cat puzzle. We could never see it in a live–dead superposition, Brukner says, not because it can't exist as such, or because of decoherence, but because, well, we just couldn't actually *see* it. "Even if somebody would prepare a Schrödinger-cat state in front of us, we would not be able to reveal it as such without having an instrument of sufficient precision." That's to say, any measurement we could actually make on the cat wouldn't show anything that couldn't equally be explained by a classical picture. Even for the oscillators of optomechanical devices, detecting genuine superposition states will be challenging, involving positional differences of just fractions of an ångstrøm (10^{-10} meters). For such reasons, "it is quite challenging to test these ideas in a real experiment," Jeong admits. Even so, he optimistically adds, "I hope to see my idea be tested in a laboratory in the near future."

There are other arguments, too, for why decoherence isn't the whole explanation for the quantum-classical transition. In the 1980s and 1990s the eminent mathematical physicist Roger Penrose, and independently the Hungarian physicist Lajos Diósi, suggested that quantum behavior of mechanical systems might also be disrupted by gravity. If that's so, it means that classical behavior is bound to manifest itself at a certain mass limit even if you could entirely suppress decoherence—because there is never any hiding from gravity. When one object "feels" the position of the other via gravity, it amounts to a kind of measurement that can destroy the quantum coherence.

Some researchers, such as Markus Aspelmeyer at the University of Vienna and Dirk Bouwmeester at the University of California at Santa Barbara, are hoping to test this type of decoherence using optomechanics. Among the proposals, Aspelmeyer and colleagues want to conduct an experiment called MAQRO on a space satellite in zero gravity, where they could very sensitively probe matter-wave interference of particles about 100 nanometers across (huge in quantum terms) as they undergo free fall. Some theories, such as the gravitational-collapse idea of Penrose and Diósi, predict that for large enough particles the interference should vanish.

Very recently, physicist Roman Schnabel of the University of Hamburg outlined another experimental test of gravity-induced decoherence. It would involve two large mirrors, weighing 100 grams each and attached to springs that let them oscillate, that become entangled with light beams bouncing between them, so that entanglement in the light (which is relatively easy to arrange) can be converted into entanglement of the two mirrors. By switching off the light and watching how the mirrors' oscillations evolve over the ensuing microseconds, it would be possible to look for quantum correlations between them, and to search for deviations of the decoherence rate beyond that predicted by standard quantum theory owing to gravitational effects.

THERE'S NO DOUBT THAT strictly quantum-mechanical effects can be seen at the macroscale: Both superfluidity, when an ultracold fluid flows with no viscosity, and superconductivity, when a material carries an electrical current without resistance, are examples of that. And in a sense pretty much everything we experience, from vision to the solidity of objects, depends on effects that only quantum physics can explain.

But what seem to us to be the real peculiarities of quantum physics (entanglement and superpositions, or in other words retaining quantum discord) are another matter. There is a chance we may not need to scale these effects up to large sizes to see them: The human eye can register just three or so photons, and physicists at the University of Illinois, Urbana-Champaign, are hoping to find out how the brain responds to photons in a superposition or entangled state. Some researchers have argued that such a superposition could persist in the nerve signal sent from the retina to the brain, so that fleeting "perceptual superpositions" are possible.

Still, engineering entanglement and superposition into macroscopically large systems remains an important goal, even if it's a distant one. Putting large systems in Schrödinger's cat states isn't just a question of seeing whether curiosity really does kill/not kill the cat. There would be practical benefits too: Quantum computers, which use quantum effects to give a huge boost to processing power, will need to achieve the entanglement and superpositions of large numbers of quantum bits to be practical. So understanding how decoherence kicks in as the scale increases, and finding ways to suppress it, is one of the keys to a viable quantum information technology.

More and more, though, physicists seem to be concluding that the roadblocks to real-life Schrödinger cats are technical, not fundamental. For now, that distinction might not matter much, because of the limits on what an experiment can realistically attain. "I think, it is practically impossible to completely suppress decoherence of macroscopic superpositions or entanglement," says Jeong. "And even if you could, another enemy—coarsening of measurements—might be waiting to kill macroscopic quantum superpositions." But he thinks that, if we were ever to develop instruments fine enough, and systems isolated enough, there's no reason to suppose that quantum effects wouldn't survive to human-size scales. So far, nothing we have discovered about objects in the middle ground between micro and macro contradicts that view.

For 2,000 years we have assumed that Plato's common-sense view in the *Republic* applies to our tangible world: "The same thing cannot ever act or be acted upon in two opposite ways, or be two opposite things, at the same time." Now we're not so sure. With Schrödinger's kittens growing up, weird isn't what it used to be.

PHILIP BALL is the author of *Invisible: The Dangerous Allure of the Unseen* and many books on science and art.

Will the Earth Ever Fill Up?

We've predicted and broken human population limits for centuries

BY ADAM KUCHARSKI

TO SAY THAT THOMAS ROBERT MALTHUS was unpopular would be putting it mildly. His 19th-century contemporary Percy Shelley, the revered poet, called him a eunuch and a tyrant. The philosopher William Godwin dubbed him "a dark and terrible genius that is ever at hand to blast all the hopes of all mankind." As Malthus' biographer later put it, he was the most abused man of his age. And that was the age of Napoleon Bonaparte.

The catalyst for this vilification was the 1798 book *An Essay on the Principle of Population*. In it, Malthus—a curly haired, 32-year-old curate of a small English chapel—attacked the claims of utopian thinkers like Godwin, who believed that reason and scientific progress would ultimately create a perfect society, free of inequality and suffering. Malthus took a more pessimistic view. Using United States census data compiled by Benjamin Franklin, he predicted that the "passion of the sexes" would soon cause human populations to outstrip their resources, leading to poverty and hardship. If unchecked, people would continue to multiply exponentially, doubling every 25 years. Agricultural yields, however, would at best increase linearly, by a similar amount each year. In 100 years, Great Britain would have 16 times as many mouths to feed (112 million), but less than half enough food.

That didn't happen, of course. By 1900, the British population had swelled only fivefold, to 35 million citizens, most of them well fed. But Malthus foresaw the possibility of this slowdown in growth, too. To prevent populations from booming and busting—the infamous "Malthusian catastrophe"—he said that Nature imposed two types of checks. "Preventive" checks reduced the birth rate: When times were hard, and food scarce, men—particularly poor men—would foresee the troubles ahead and delay getting married and starting families. "Positive" checks—famine, disease, murder, war—increased the death rate. Once food production caught up with demand, however, strife would lessen and families would grow. Thus the "grinding

ILLUSTRATION BY SÉBASTIEN THIBAULT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law of necessity, misery, and the fear of misery" kept the size of a population oscillating in sync with supply. To his critics' disgust, Malthus used this theory to argue against England's Poor Laws, which provided welfare to needy families according to the number of children they had. Why encourage the poor to procreate, he argued, when Nature will turn around and trample them?

Malthus, though, had overlooked an important caveat. If Nature forces us to live within our means, Malthus drastically underestimated our ability to expand those means. By his death, in 1834, an agricultural revolution was underway in Europe. Farmers learned to breed plumper, faster-growing livestock and plant nitrogen-fixing crops to restore depleted soils. With the industrial revolution came coal-powered plows and threshers. And in the mid-1900s, the green revolution brought high-yielding seeds and synthetic fertilizers to growers worldwide. Between 1900 and 2000, in defiance of Malthus' gloomy forecast, the global population quadrupled, from 1.6 to 6.1 billion. Meanwhile, grain production quintupled, from 400 million to 1.9 billion tons.

Regional famines aside, the human species has so far managed to avoid a Malthusian fate. Earth currently supports 7.3 billion people, and, according to the United Nations, that number will rise to 9.7 billion in 2050 and to 11.2 billion by the end of the century. If the planet has a maximum occupancy, it remains elusive. What Malthus failed to see was that the limit may depend as much on our own resourcefulness as on the laws of Nature.

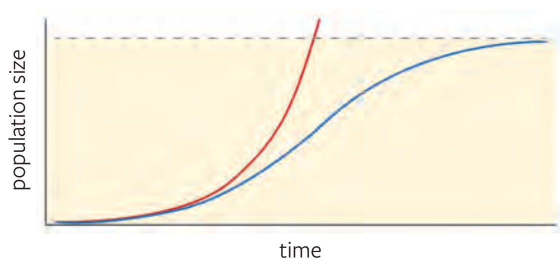
WHILE CRITICS DISMISSED MALTHUS' stark pessimism and cruel social politics, his ideas endured. Classical economists applied them in the defense of free-market capitalism. Both Charles Darwin and Alfred Russell Wallace cited Malthus' book, with its emphasis on an inevitable struggle for existence, as inspiration for the theory of evolution by natural selection. But Malthus' biggest influence was in the study of populations. His theory of natural checks launched the field of modern demography, and with it the quest to find humanity's maximum growth, known as its carrying capacity.

In 1838, the Belgian mathematician Pierre Verhulst expanded on Malthus' work by putting the theory in mathematical terms. Malthus had calculated unchecked growth by a simple formula: the size of a population, N, multiplied by the per capita increase, r (births minus deaths per person). Following this model, a population would keep growing and growing, faster and faster, forever. But Malthus had said that dwindling resources would eventually curb its growth. To account for this behaviour, Verhulst added another factor to act as a brake, making the growth rate equal to

$$rN\left(\frac{K-N}{K}\right).$$

In this model, which Verhulst called the logistic function, K is the carrying capacity. At first, growth accelerates, as Malthus had assumed. But as N (population size) approaches K, growth slows to a crawl before stopping at its limit.

Fitting his new function to demographic trends in



MAXED OUT In Malthus' exponential function, a population keeps growing indefinitely (red line). In Verhulst's logistic function (blue), it will eventually reach a limit (dotted line).

Belgium, Verhulst determined that the country's population was growing at 2.6 percent per year, and would eventually max out at 6.6 million people. But he was wary of this prediction. Even though the curve nicely followed historical data, it relied on assumptions about the long-term nature of populations that might not be true. So two years later, he pushed the original function aside and had another go, producing the following revised description of the population growth rate:

$$r\left(\frac{K-N}{K}\right).$$

JOHN LINNELL/WELLCOME IMAGES

Like the logistic function, the adjusted model also matched past trends, but it resulted in a more gradual slowdown in growth as the population neared its limit. This bumped Belgium's carrying capacity to 9.4 million. Neither estimate, however, turned out to be true. (The current tally is 11 million.) And Verhulst never came up with a solid mathematical theory he felt confident in. Even his former teacher and academic rival, Adolphe Quetelet, criticized his work for failing to provide a precise law for human behavior. After Verhulst died, in 1849, the logistic function faded into obscurity for more than 70 years.

Worries about population expansion resurfaced with World War I. "Population pressure is always a major cause of war," remarked biologist Raymond Pearl in his 1925 book *The Biology of Population Growth*. As head statistician for the U.S. Food Administration during the conflict, Pearl had to keep an adequate supply of food flowing to troops, witnessing first-hand the economic struggles that Malthus had predicted. After the war, with statistician Lowell Reed, he developed a "logarithmic curve" to investigate how populations change.

DEMOGRAPHY'S DEBBIE DOWNER The English cleric Thomas Robert Malthus challenged the 18th-century view that society was headed toward perfection. Instead, he argued that runaway population growth and limited resources will ultimately lead to famine and misery.

Humans don't just extract from a fixed set of resources, but can create new resources through invention.

Although the researchers didn't know it at the time, they had stumbled upon Verhulst's long-forgotten logistic function. When they fitted the curve to U.S. population data from 1790 to 1910, they found it was a remarkably good match. Their estimates of carrying capacity, however, weren't any better than Verhulst's. The U.S. limit, they said, would be about 200 million, which the population climbed past in 1968. (It is now at 319 million.) Pearl later estimated a world limit of 2 billion, which was surpassed by 1930.

The following decades saw the appearance of one carrying capacity estimate after another. In 1995, mathematician Joel Cohen, at Rockefeller University in New York, tallied up dozens of global forecasts published to date, and found that they varied widely, from less than 1 billion to more than 1 trillion. Most early estimates were, like Pearl's, far below 6 billion, the world's population at the time.

According to Cohen, their flaw lay in the assumption that resource constraints, and hence carrying capacity, were fixed. In mathematical lingo, K was a constant: It never changed. This presumption, Cohen said, ignored human innovation. "Let us recognize, in the phrase of U.S. president [George H.W. Bush], that 'every human being represents hands to work, and not just another mouth to feed'," he wrote in the journal *Science*. "Additional people clear rocks from fields, build irrigation canals, discover ore deposits and antibiotics, and invent steam engines; they also clear-cut primary forests, contribute to the erosion of topsoil, and manufacture chlorofluorocarbons and plutonium. Additional people may increase savings or dilute and deplete capital; they may increase or decrease the human carrying capacity."

This had been the missing ingredient in early population models: Humans don't just extract from a fixed set of resources, but can create new resources through invention.

IN 1960, HEINZ VON FOERSTER and his colleagues at the University of Illinois were some of the first demographers to account for human ingenuity. They tweaked the logistic function to allow carrying capacity to vary with population size, resulting in the following formula for the growth rate:

$$rN\,(N^d).$$

The constant d represents humanity's impact on its resource pool. Based on historical patterns, the researchers concluded that d was equal to 1.01, meaning the pool was expanding. As the population grew, so did its ability to sustain itself, avoiding a Malthusian decline. Here was a way to quantify the power of innovation that previous models had missed.

Still, the future wasn't exactly utopian. Solving their growth rate equation for population size N, the researchers concluded that in year t, N would be proportional to

$$\frac{1}{(2026.87-t)^{\frac{1}{d}}}.$$

As time ticked forward, and t got closer and closer to 2026.87, the population would grow larger and larger. At this exact point, the bottom of the fraction would shrink to zero, causing population size to become infinite, or as mathematicians say, to "blow up." Based on this analysis, the team predicted that Doomsday would come in 2026 A.D.

TO THE GILLS One of the world's most crowded cities, Mumbai, India has more than 50,000 people per square mile.

Foerster’s observation that resources are a function of population size showed that innovation can change patterns of growth in ways that are hard to predict.

The precise date, which happened to fall in November, on Friday the 13th, was tongue-in-cheek. But Foerster’s observation that resources are a function of population size showed that innovation can change patterns of growth in ways that are hard to predict.

And technology doesn’t just affect the amount of resources that humans are able to extract; it also makes sharing those resources critically important. Take, for example, the question of space. Pearl’s calculations in the 1920s had suggested that about 4,000 people would eventually have to squeeze into every square mile of the U.S.—a density he said was “manifestly ridiculous.” Yet many cities already exceed this number, thanks to innovations such as high-rise architecture and indoor plumbing. The world’s most crowded places, including Mumbai and Seoul, now hold more than 40,000 people per square mile. But they still depend on provincial land to draw water, grow food, and generate power. A steady flow of goods between cities and the countryside can increase the carrying capacity of both. On the other hand, if one or the other is prevented from obtaining the resources it needs, both may suffer.

Countries, too, are interdependent: They trade with other nations and share global resources such as oceans, biodiversity, and climate. Understanding how a given nation will grow requires examining what happens outside its borders. In 2013, for instance, researchers led by Samir Suweis, at the University of Padua, in Italy, modelled the carrying capacities of 52 countries by analyzing their water trade network. Some of these countries, including Australia, Brazil, and the U.S., are “water-rich,” meaning they can produce their own water and the food that depends on it. Other countries, including Mexico and most of Europe, are “water poor”: They rely on imports.

The researchers considered two possible scenarios. First, they assumed that as water-rich populations neared their limit, they would stop exporting and instead hoard their water resources. In this situation, according to the team’s calculations, water-dependent populations would peak around 2030. However, if countries worked together, continuing to trade as supplies decreased, the entire network could sustain itself until as late as 2060.

Maybe Malthus’ bleak prophecy, more than a century overdue, will finally come to pass. But maybe not. Maybe we’ll find an economical way to desalinate seawater. Maybe we’ll figure out how to grow all of our food in vertical farms. Maybe we’ll start to colonize other planets. For the next generation of demographers to come up with a new, higher limit, though, we’ll need to do more than create: We’ll need to cooperate.

ADAM KUCHARSKI is a lecturer in mathematical modeling at the London School of Hygiene & Tropical Medicine. His first book *The Perfect Bet: How Science and Math Are Taking the Luck Out of Gambling* will be published in the spring of 2016.

EDUCATION IMAGES / CONTRIBUTOR


BUZELLI

Why the Russians Decapitated Major Tom

The story of the genetically engineered mouse cosmonaut

BY ROBERTO KAZ

IT WAS A LITTLE before 7 in the morning in western Russia when Major Tom reentered the atmosphere. Though he had no window to see the approaching Earth, the return had been announced earlier that day, when the braking engines were activated for six minutes, and his recovery capsule separated from the rest of the spacecraft. After having endured 30 days in space, in which he completed 477 orbits around the Earth, it was about time to come back. It was time to face, once again, the effects of gravity.

As soon as the capsule reached the atmosphere, the heating and the G forces began. Major Tom was thrown against the roof of his compartment while the air slowed the capsule and the outside temperature rose to about 3,600 degrees Fahrenheit (2,000 degrees Celsius). When he reached an altitude of nine kilometers, a parachute opened, throwing him back to the floor (which was about 10 centimeters from the roof). At 7:11 a.m. on Sunday, May 19, 2013, the Bion-M1 spacecraft finally landed in the green field of a Russian farm.

Alexander Andreev-Andrievskiy would arrive 10 minutes later, in one of seven military helicopters that headed to the landing site. The 30-year-old biologist had been awake all night in the nearby city of Orenburg, discussing the latest information that arrived, by telemetry, from the spacecraft. "I was very anxious," he told me. "Once I got there I still had to wait another 40 minutes for the capsule to be dismantled. And I did not know if the mice were doing well."

Major Tom was just one of 45 mice that had been lofted into low-Earth orbit that spring. Unfortunately, information sent back to Earth over the course of the previous month had suggested that at least half of them had died. But there was always a chance that the computer was sending incorrect data, or that the remaining crew had died during reentry. This is why, along with everything else that happened on that morning, Andreev-Andrievskiy remembers best the moment he first saw a mouse moving in the cage. "I was happy, but

ILLUSTRATION BY CHRIS BUZELLI

there was no time for emotion," he recalled. "It was too much work."

Once removed from the capsule, the cages were taken to an orange tent, improvised in the field as a laboratory. There, with the help of tweezers, Andreev-Andrievskiy took the mice by the tails, one by one, and placed them in a clean compartment to do the final count. Out of the 45 rodent cosmonauts, 16 had survived. One was Major Tom.

EVERY HUMAN EXPANSION—be it to Europe, Asia, and much later, by boat, to the Americas—has been done in the unwanted company of mice. The abilities to run fast, to squeeze into small spaces, and to eat almost anything have made them the second most successful mammal on Earth. Now, as humans set their sights on extraterrestrial expansion, rodents—more specifically, mice—are once again in the vanguard.

The story of mice in space stretches back at least to 1900, the year Abbie Lathrop, a retired school teacher, began rearing rodents on her farm in Massachusetts. At first she intended to sell them as exotic pets, but quickly became a supplier to the research community instead. Biologists had developed an interest in Gregor Mendel's laws of inheritance, in which traits are determined by genes transmitted from one generation to the next. Mendel had discovered his laws using pea plants; now biologists wanted to apply them to mammals.

At Harvard, a student named Clarence Cook Little was assigned by his senior professor, William Castle, to test Mendelism in mice. He began in 1907, using animals from Lathrop's stocks. His first task: to inbreed the mice. It was known that the repeated mating of brother and sister could fix a certain number of traits, such as size, weight, and fur color. The inheritance of these traits could then be studied.

"Most animals can't be inbred," geneticist Kevin Flurkey told me recently. Rats, for example, endure health problems after three years of close mating. "But mice are much easier. They face no genetic depression, maybe because they lived in groups that already inbred in the wild." By 1911, Little had developed the first inbred strain, called DBA.

Two decades later Little would found the Jackson Laboratory, a pharmaceutical nonprofit giant that now distributes 3 million mice a year. It was there that mice would earn a place on the Mount Olympus of medicine. Though nearly every Nobel Prize awarded in medicine has relied on some sort of animal sacrifice—pigeons were used for the study of malaria, cats for brain mapping, cows for organ transplantation—no other animal has made a greater medical contribution to humanity than mice, especially mice from the C57BL/6 strain, known as Black 6.

Black 6 mice have been used to study diabetes, heart diseases, and bone-related problems. They have consumed alcohol, sniffed cocaine, and taken Viagra. Some have faced early separation from their mothers (to explore the effects of maternal absence in childhood); others were forced to become obese (to test metabolic drugs aimed at helping the overweight American). At the Massachusetts Institute of Technology, Black 6 mice were tested while listening to a Beethoven Symphony (the second movement from the Seventh). They appeared to enjoy it.

Black 6's supremacy, however, is fairly recent. The strain was created in 1921 from the mating of female 57 and male 52—two of Abbie Lathrop's mice—and wasn't particularly important during its first six decades of existence. As Karen Rader writes in *Making Mice*, a history of the Jackson Laboratory, rodents that entered scientific facilities at the turn of the 19th century "were far more likely to be stray creatures looking for food and shelter." Their fate would begin to change when scientists learned how to recombine DNA, in the 1980s.

To leverage the new technology for studying—and hopefully solving—the causes of genetic diseases, scientists needed a stable animal model, in which every single individual presented the same genetic traits. Mice, which had gone through brother and sister mating since the beginning of the century, were the right mammals at the right time.

What came next was a mouse boom. New methods of genetic manipulation led to new questions, which needed new kinds of mice to be solved. Humans invented anemic mice, transgenic mice with human DNA, mice that glowed in the dark, mice for studying autism, mice prone to cancer.

But among thousands of newly released mice, none achieved greater success than the Black 6. Maybe it was for its propensity to become deaf, or obese, or blind or old. Maybe it was because it was small and affordable

(about $20 per mouse at today's prices). It was also helped by what Flurkey described to me as a "snowball effect": More use generates more data, which, in turn, generates better answers. When starting a new experiment, a researcher will prefer solid ground. "If your senior scientist used it, you will want to replicate it," Flurkey said. In a few years, the black-furred 25-gram, 10-centimeter-wide Black 6 mouse became the common currency of clinical trials.

It brought medical advances in treatments for brain signaling, diabetes, and atherosclerosis. It contributed to Nobel victories in 1989 (retroviral oncogenes), 1997 (prions), and 2008 (HIV). Today, among the more than 7,500 strains sold by the Jackson Laboratory, 47 percent are Black 6. Major Tom, too, was a Black 6.

MAJOR TOM WAS BORN and reared at the Institute of Bioorganic Chemistry, in Moscow. At the age of about 3 months—when Black 6 mice are considered to be mature—he was taken, in the company of 299 siblings, to an animal facility at Moscow State University. It was a Wednesday, early in 2013—exactly 51 days before he would journey into space.

There the mouse first met Andreev-Andrievskiy, a young scientist at both the State University and the Institute of Biomedical Problems (IMBP), Russia's

Major Tom, Space Invader, Space Boy, Spider from Mars, and Ziggy Stardust were placed inside five cylindrical compartments, each the size of a big Coke bottle.

FEATHERWEIGHT A Black 6 mouse is weighed before flight.

ALL PHOTOS COURTESY OF IMBP/OLEG VOLOSHIN main agency for the support of human space flight. A specialist in the study of rodents, Andreev-Andrievskiy had joined the IMBP seven years earlier, shortly before the institute announced it would revive the Bion Space Project. From 1973 to 1997, the IMBP and Roscosmos (the agency responsible for designing rockets) had launched 11 Bion satellites, carrying mammals, fish, reptiles, insects, bacteria, and fungi into space. After a 16-year funding shortfall, this would be the first time they would work with mice, all male—and Andreev-Andrievskiy was assigned to head their training.

Major Tom, at the time, was known by his number: 50. On the day after arrival, he was weighed and examined. Then he had a microchip implanted under the skin of his back. As with 29 other mice, all picked at random, he also underwent heart surgery to install a catheter that would monitor his blood pressure. "The surgery took 15 to 20 minutes, under general anesthesia," Andreev-Andrievskiy explained. Mouse 50 recovered in about one week.

Forty-five days prior to the launch, the mice were randomly divided into 100 groups of three, each of which would be observed and occasionally replaced, in case of maladaptation. "Black 6 males usually cope when they are young, but when they grow old, they get more aggressive," Andreev-Andrievskiy said. "In space, which is a completely unusual environment, we needed the calmest ones." Mouse 50 was placed in the company of Mouse 51 and Mouse 173. They got along perfectly.

Two weeks later, physical training began. Each mouse was placed in a 60-centimeter-wide box so that scientists could analyze its locomotor and behavioral activities (generally, fearless animals are more exploratory). Then, the rodent had its equilibrium tested on a rotarod, a revolving bar on which it had to balance like a tightrope walker. Finally, it was held for one week in a high-tech cage equipped with a running wheel, where its movements were recorded.

There, the animal was tested for intelligence. First, it was presented with two simultaneous light beams emitted from one of the cage's walls. The lights differed in color and consequence. If the mouse chose the red light, for example, it would be rewarded with a pallet of dry milk. Choosing the green light would have no effect. Once the animal understood this dichotomy, scientists would invert the order, to test how quickly

the change was recognized. Finally, the candidate had to adapt to a paste diet—the same that it would be given in outer space.

Results were announced one week before launch. Out of the 100 trios, 53 were observed to have potential cosmonauts; 35 were assigned for ground control experiments; and 12 were discarded and sacrificed due to physical, intellectual, or social inabilities. "We worked with four criteria," Andreev-Andrievskiy explained. "We checked if they lived well together, if their implants worked, if they had learning abilities, and if they could run." A mouse that ran an astonishing 11 kilometers in a day was not chosen. "We selected the ones in the middle. We wanted the normal, not the extremes. It was not the Olympics," he said.

Then, the 53 trios of elite mice were placed in small plastic containers and transported, by car, to an airport near Moscow. They flew straight to the Baikonur Cosmodrome, a launch facility larger than Belgium, located at a Russian-leased territory in the deserts of Kazakhstan. The whole trip took about 24 hours.

In Baikonur, engineers from Roscosmos were making final adjustments to a Soyuz-2 rocket, fitting six small satellites that it was due to carry besides the Bion M-1 module. Scientists from the IMBP were also busy boarding the additional Bion crew, which was composed of eight gerbils, 15 geckos, 20 snails, and a whole menagerie of fish, plants, algae, bacteria, fungi, and microbes.

CAREFUL NOW (p.114) Scientists make final adjustments to the apparatus that will carry the mice. Andreev-Andrievskiy is second from left.

THE PAYLOAD The Bion M-1 biosatellite a few days before take-off.

Three days before launch, Andreev-Andrievskiy was authorized to place his mice inside the capsule. It was only then that the 15 flying trios were picked and Mouse number 50 baptized. "Five of the chosen mice had the heart device," he explained. "We named them after David Bowie songs, which we listened to a lot in those days."

On that same Tuesday, April 16, Major Tom, Space Invader, Space Boy, Spider from Mars, and Ziggy Stardust were placed with their respective trios inside five cylindrical compartments, each the size of a big Coke bottle, that would serve as their residences. The cages were each equipped with a video camera, a food dispenser, a lamp to simulate daylight, and a filter for accumulating debris (which would be carried away by a constant flow of air). Once there, most of the mice stuck together, piled up like football players to keep warm. Of the remaining trios, 15 were placed on standby just in case substitutions were needed (one group had to be changed before takeoff). The remaining ones were sacrificed.

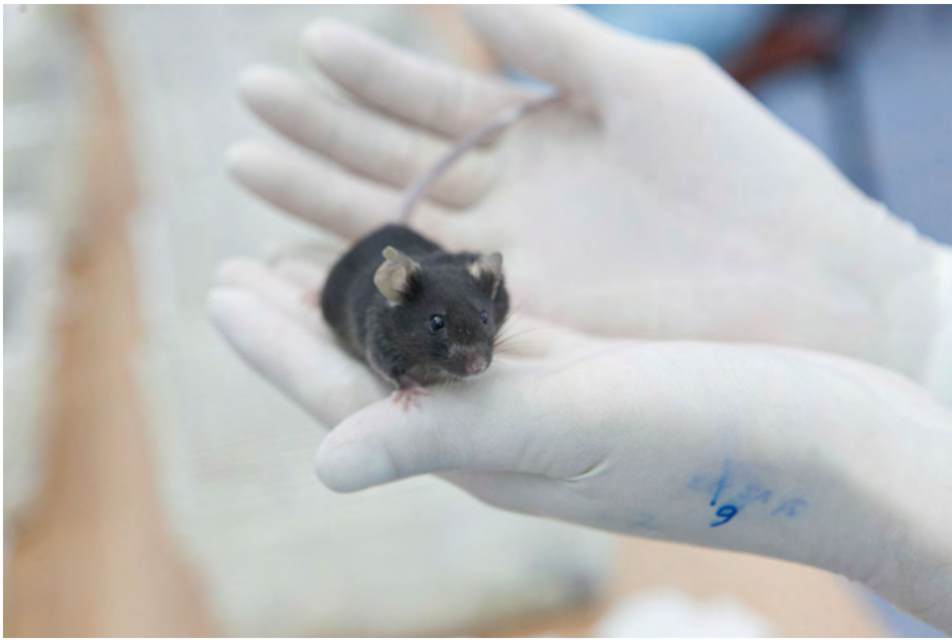
Andreev-Andrievskiy then placed the assemblage of cages on a luggage cart and pushed it toward a hangar. There, the machinery was lifted by a crane and fitted in the biosatellite. A video recorded by the IMBP shows dozens of reporters, engineers, and scientists gathering around the cages, while Andreev-Andrievskiy and his assistant, Anfisa Popova, stare at the scene with their arms crossed. The two would spend most of the following days seated in front of a screen, monitoring the animals by video.

On April 19, 4 p.m. Kazakh time, the five engines of Soyuz-2 were ignited. Andreev-Andrievskiy filmed the scene from an open field about 1 kilometer away. As the 300-ton machine started lifting off, he let his camera drop to the ground—and did not pick it up for the next minute. The recording shows the arid vegetation of Kazakhstan, accompanied by some effusive words in Russian and the sound of the receding rocket.

"It was very emotional," he said. "We hadn't slept for three days. I was too excited, but I couldn't afford crying."

For the 45 rodent cosmonauts, the time had finally come to show why they were chosen, from among 300 candidates, to head a $100 million space mission that involved scientists from six countries. It was their time to prove they were capable of surviving in a habitat with minimal radiation protection, no nest, no shelter, no running wheel, no sunlight, no dry food, no water, no medical assistance, and, most importantly, no gravity.

WHEN THE BLACK 6 genome was published in 2002, a *Nature* news article referred to it as "our greatest ally." Shirley Tilghman, a molecular biologist and then the president of Princeton University, preferred to describe it as a "Rosetta stone" for biomedical interpretation. Researchers wondered what role each gene



THE HERO Major Tom passed through a battery of locomotor, behavioral and intelligence tests before being selected for the Bion M-1 mission.

played—a question that would soon be turned into a $900 million project starring the Black 6 as protagonist.

Founded in 2007, the International Knockout Mouse Consortium was created to produce 20,000 variations of Black 6 mice, each either inactivating or overexpressing one of its 20,000 mapped genes. The reasoning behind the project was simple: Since mice and humans share 95 percent of their genetic material, a gene that is responsible for a given trait in mice has a reasonable chance of acting the same way in humans (though, in practice, it is usually a combination of genes that is involved).

At Jackson Laboratory, genes were knocked out based on a natural process called homologous recombination. Researchers were able to knock out 17,000 individual genes (3,000 others led to immediate embryonic death). The newly produced Black 6 stem cells were then frozen in liquid nitrogen. The project then began to turn the cells into actual mice. Researchers have now produced 3,500 new knockout mice in the United States. The goal is to reach 5,000 by 2016.

For this stage of the project—more complex and expensive than the genotyping—the responsibility was split among 18 institutions from 12 countries. At the Jackson Laboratory, for example, brothers and sisters of a given new strain are bred with each other for 20 generations (it's a way of decanting the unwanted information). After about two years, the mutant mouse is said to be stable, or genetically homozygous. From there on, every new mouse will be a clone. Researchers then spend 16 weeks phenotyping the animal. During this period, the rodent goes through 2,000 behavioral, physical, and immunological exams to evaluate the exact effect caused by the gene modification.

If that sounds like a lot of work—it is. Monica Justice, the head of genetic research at the Hospital for Sick Children, in Canada, has doubts about the project's future. She was, until last year, the director of knockout production at Baylor College of Medicine, one of three institutions financed by the National Institutes of Health to phenotype mutant mice in the U.S. "It's really expensive to do this, and people are not sure they will get enough information to make it worthwhile," she told me. "There is still a need for the project, but it's almost being suppressed by RNA-guided genome editing. People are making mutation so quickly and easily that they just want to do it in their own labs."

Justice is referring to Crispr/Cas9, a form of gene editing developed in 2012 by researchers Jennifer Doudna, Emmanuelle Charpentier, and Feng Zhang, who are often referred to as future Nobel winners. The technique can generate a homozygous knockout mouse in one or two generations, as opposed to the 20 needed with homologous recombination. First, researchers choose a piece of DNA they want to cut from a cell. Then they synthesize a corresponding piece of RNA, and attach it to a bacterial enzyme called Cas9, whose function is to cut the cell's DNA. Once it's done, the cell tries to repair the cut, often in a way that ends up disabling the gene.

This is not the only difference between Crispr and homologous recombination. Since homologous recombination was less effective, it had to be done on a large scale, relying on embryonic stem cells (which are found on the order of hundreds in a single mouse embryo.) Then the mutated stem cell had to be implanted in the embryo of another mouse. The resulting animal was a mixture—which could only be "purified" after two years of inbreeding. Crispr/Cas9, on the other hand, is so efficient that it can be applied directly in the zygote, the very first cell formed after sexual reproduction. From there on, every subsequent cell—including stem cells—will contain the gene mutation: The animal leaves the womb ready to use.

"You are building a magnificent bicycle, and a Model T passes by you," Michael Wiles, a senior director at the Jackson Laboratory, told me, illustrating the difference between the two techniques. "Now, in three months, you can have mice with the exact genetic modification, costing 90 percent less than it used to cost. That is science fiction."

Whether it is through homologous recombination or Crispr, the new breeds of Black 6 mice are unlike any seen before: Where previous iterations bred for an individual trait, researchers are now breeding the mice to express or suppress individual genes or groups of genes. Rather than studying gross or qualitative effects, researchers are gaining the ability to peer directly into the genetic mechanisms invoked by diseases, or by environments—like space.

MICE ARE NOT NEW to space exploration. In 2009, six—some carrying foreign DNA (transgenic), some unaltered (wild type)—were sent for a three-month stay at the International Space Station. Half died and were placed in a refrigerator until the return. In 2011, 24 females—all Black 6—had the honor of boarding Atlantis during the shuttle's final mission (they were euthanized five hours after landing.) No mission, however, has taken as much preparation time, orbited as high, or involved as many mice (and humans) as Major Tom's. "It was vastly more important," Richard Boyle, a senior scientist at NASA who was part of the Bion M-1 team, told me. "Bion was real science."

When one mouse dies in the cage, the others just eat it. They usually begin with the brain and the intestines.

From 1973 to 1997, the Soviet Union launched 11 Bion missions, transporting 212 rats and 12 rhesus monkeys into space—along with insects, amphibians, reptiles, and human cells. The missions led to findings on the muscular-skeletal system, cardiac metabolism, vestibular function, and stress response—all of which were applied so that humans could spend longer times in space. "The main result," Vladimir Sychev, a 63-year-old scientist, and deputy director at the IMBP, said, "is that we can now have a cosmonaut spending one and a half years in weightlessness." But there is much still to be learned, and the Bion flights, interrupted eight years after the fall of the Soviet Union, were only resumed with Major Tom's mission, in 2013.

I met Sychev in January, at the IMBP headquarters, just outside Moscow. Our conversation took place in a large conference room that contained a tube television, a fake tree, and some crystal chandeliers. He spoke in Russian, and wore a pin with the symbol of the institution attached to his suit.

"We have great experience in orbital flight, but there are some processes which we still cannot understand," he continued, translated by an interpreter. "Now we have the means of understanding the effects on the molecular level." Humans, who vary in weight, size, skin color, and myriad other factors, are too genetically different to serve as an experimental model. If Bion M-1 had transported nothing but human tissues, its conclusions could not be generalized. The Black 6 mouse—which had its genome mapped, its genes knocked out, and its molecular paths studied—was one of the best possible animals to provide such insights.

"For simple things, tissue works," Andreev-Andrievskiy told me. "But genetic effects always arise by an interplay of different systems, so we needed an actual animal." While microgravity and radiation start affecting the mice as soon as they leave the atmosphere, "the physical effects appeared much later."

The Earth's atmosphere and magnetic field protects us from 99.9 percent of the sun's radiation. On an eventual human trip to Mars, which would take six to eight months under no such shield, the astronauts' chances of undergoing genetic mutation (and all its hazardous physical consequences) would enormously increase. "Radiation is likely the show-stopper, unless we can protect the individual," says Boyle. Major Tom's genes might offer insight into how to keep humans safe.

Since Black 6 mice live no longer than three years, the 30 days Major Tom spent in outer space correspond to two years of a human life. Bion M-2 is planned for 2019. It will orbit at 1,000 kilometers, where the level of radiation will be almost 30 times higher.

THE RIGHT STUFF A rodent cosmonaut peers out of the compartment where he will spend 30 days in space (top). He will be carried there by a Soyuz 2 rocket, pictured here en route to the launch site (bottom).

MIGHTY MICE Forty-five mice lift off from the Baikonur Cosmodrome, along with a variety of other creatures.

TEN MINUTES AFTER BEING LAUNCHED, Major Tom escaped the Earth's atmosphere. The rocket's engines went off, the effects of microgravity went on, and he suddenly began to fly, bumping into his cage mates. The craft rose smoothly and silently, passing by satellite debris, crossing the orbit of the International Space Station, and finally reaching an altitude of 575 kilometers. Peace reigned as the internal temperature stabilized at 72 degrees Fahrenheit (22 degrees Celsius). Then, on the second day of the mission, two fatalities occurred.

"What might help explain the deaths?" Andreev-Andrievskiy later wrote, with 12 other scientists, in a study published in *PLoS ONE*. "There was no evidence of fighting, biting, or agonistic behavior in any of the video samples, so we do not believe that any of the injuries resulted from aggression among the males." It was concluded that the two mice probably died after getting their tails stuck in the feeder.

On the ninth day, a new casualty, the same *causa mortis*. On the tenth, a gross malfunction of the food system affected five cages, resulting in 15 dead mice. Eleven more would perish—including mouse 51, from Major Tom's team—by the end of the trip. "When one mouse dies in the cage, the others just eat it," Andreev-Andrievskiy explained, matter-of-factly. "Like most animals, they usually begin with the brain and the intestines. This is what happens when they kill each other in a fight. But they did not fight in space, which was a surprise."

Other disappointments would take place during the mission. Due to a failure of the oxygen supply, all of the gerbils died by the end of the first week. When the aquarium lights stopped working, interrupting the process of algae photosynthesis, all of the fish and crustaceans also died. The 15 geckos and the 20 snails survived. The worms died, eaten by the geckos, as planned.

Andreev-Andrievskiy spent some of that month in Baikonur, monitoring the vivarium mice (which would be compared to the returning cosmonauts), and interpreting the small trickle of information arriving from the spacecraft. "Our main data came from the five mice that had the heart implants," he explained. "We could more or less derive from oxygen consumption if the others were alive." The cage videos—which cut off after the first 10 days due to a buildup of dirt on the lens—were only made available after the return.

When he did return, Major Tom was fatter than when he left. The weight gain, caused by the lack of gravity, the inactivity, and the excess of paste food, was also noticed in 75 percent of the team (in his case, it was aided as well by the ingestion of brain and intestines from Mouse 51). Post-flight lethargy was another common problem. "Examination directly at the landing site revealed gross motor function impairment," Andreev-Andrievskiy wrote in his 2014 *PLoS ONE* study. "The mice could not maintain steady posture and their fore and hind paws were positioned more to their sides, rather than directly under their trunk; the mice did not move even when prodded." Locomotor activity would begin to recover after six hours.

Recovery, however, was not exactly what the scientists wished for: Every minute spent by the animals in

A WARM RECEPTION The heat-scored Bion M-1 satellite, freshly returned from space, is greeted by seven military helicopters.

normal gravity represented one less minute of information about the deleterious health effects of their experience in space. As soon as he finished counting the survivors and conducting the initial physical testing, Andreev-Andrievskiy got back in the helicopter, and rushed the mice to the Baikonur Cosmodrome.

Events followed very quickly. From a nearby airport in Orenburg, they took a military airplane that flew straight to Moscow. From the airport, they got into an ambulance that used its sirens to bypass the Sunday afternoon traffic jams. "It looked like a Hollywood movie," he recalled.

Then the mice were separated. Eleven of them were left at the IMBP, to be euthanized for necropsy, while five others—including Major Tom—remained in the ambulance, which headed with Andreev-Andrievskiy to the Kurchatov Institute, in north Moscow. There, they would be analyzed in the same cages they had used, during training, to keep track of their daily movements. After that week passed, Major Tom and his mates were taken back to the IMBP, where they met the same fate endured by the others. Andreev-Andrievskiy, who was outvoted in his idea of keeping some of the mice alive, did not take part in the euthanasia. "I had to accept what most of the scientists wanted, but I preferred not watching it. I felt very personal about those animals."

It was the end of a glorious trajectory. Six months had passed since Major Tom was born in a lab, faced heart surgery, endured physical training, adapted to paste food, learned how to fly, and came back from space to tell humans, with his body, how tough life is out there. On Sunday, May 26, 2013, Major Tom—or Mouse number 50—had his neck broken through cervical dislocation. He was then decapitated.

The moment a mouse model dies is the moment scientific knowledge is born. As planned, Major Tom's organs were dissected and split among specialists from six countries, resulting in 70 studies. His brain was subdivided in smaller parts—frontal cortex, visual cortex, hypothalamus, hippocampus, striatum, and substantia nigra—some of which were sent to Vladimir Naumenko, a senior researcher from the Russian Institute of Cytology and Genetics. In a study published in July 2014, Naumenko concluded that "spaceflight decreased the expression of crucial genes involved in dopamine synthesis." Such a decrease, aside from deregulating muscle tone, can trigger diseases such as Parkinson's, Alzheimer's, depression, and schizophrenia. Because of these observations, humans on a trip to Mars may need to take antidepressants to control their dopamine levels and stave off potentially devastating illness.

Studies of the returning mouse cosmonauts also addressed the effects of microgravity on bone marrow, insulin receptors, and sperm cells (sperm cells move more quickly after exposure to space, though it's not yet clear why). Scientists observed a reduction in the mice's ability to contract and dilate cerebral arteries (which could explain why astronauts suffer from eyesight impairment when they return from space). These results depend on genetic analyses that would not have been possible if the mouse genome had not been mapped and studied in fine detail.

Other animals yielded their own results. Snails, which have a simple and well-studied nervous system, allowed scientists to study vestibular readaptation to normal gravity, which could help illuminate what happens to the human brain in the 24 hours after spaceflight. Geckos revealed insights into the muscular system, potentially leading to the development of clothing that imitates tactile stimuli, helping astronauts prevent muscle loss.

Andreev-Andrievskiy did not attend the final experiments. By then, he was already dealing with the ground control mice, which had been waiting, in their cages, ever since he and Major Tom had left for Baikonur. Things started from zero again: He picked 45 rodents, which were then placed, in trios, in the same apparatus that was used for the space mission. For the following month, those mice would see no sunlight, would have no running wheel, and would eat no dry food. For the sake of comparison, conditions would simulate the ones faced by Major Tom, aside from the crucial fact that everything would be endured under normal gravity.

No mice from that group were named after David Bowie songs.

ROBERTO KAZ is a journalist from Brazil. This feature was written as a Master's thesis at Columbia University's School of Journalism.

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Jane McGonigal

The alternate-reality game designer and author of Reality Is Broken *and* SuperBetter *reflects on the themes in* Nautilus

INTERVIEW BY YVONNE BANG

GAME ON

In the middle of writing my first book about using games to solve big global problems, I got a serious concussion. I couldn't work on my book. I experienced a lot of things that people with trauma experience, like loneliness and suicide ideation. After a month at my lowest point, I had that light bulb. I'd been researching the gameful mindset for eight years: "My God, I should use this to solve my problems!"

CONCUSSION SLAYER

I created a game called Jane the Concussion Slayer. I identified and battled the bad guys. These were anything that could trigger my symptoms and slow down the healing process. I collected "power-ups." These were anything that I could do on even my worst day to feel just a little bit good or happy or powerful. After just a few days of playing, it gave me this sense of possibility and optimism. My cloud of anxiety and depression started to lift.

SUPERBETTER

I put up a blog post and a short video online explaining how to play. Soon I started hearing from people all over the world who were adopting their own secret identities, recruiting their allies, and fighting their own bad guys. Not everybody has a concussion, and not everyone wants to be "the slayer," so I renamed the game SuperBetter. In a control study, we found players became significantly less depressed. Even more interestingly, the more depressed people were, the more they played and the more significantly they improved.

POWER TO THE GAMERS

There's no faster way to scale up an idea than to reach out to gamers. We have 1 billion people playing video games today on connected devices. They're playing on phones and on tablets. Gamers are more global than Facebook. They can scale anything because of their sheer size and their connectedness.

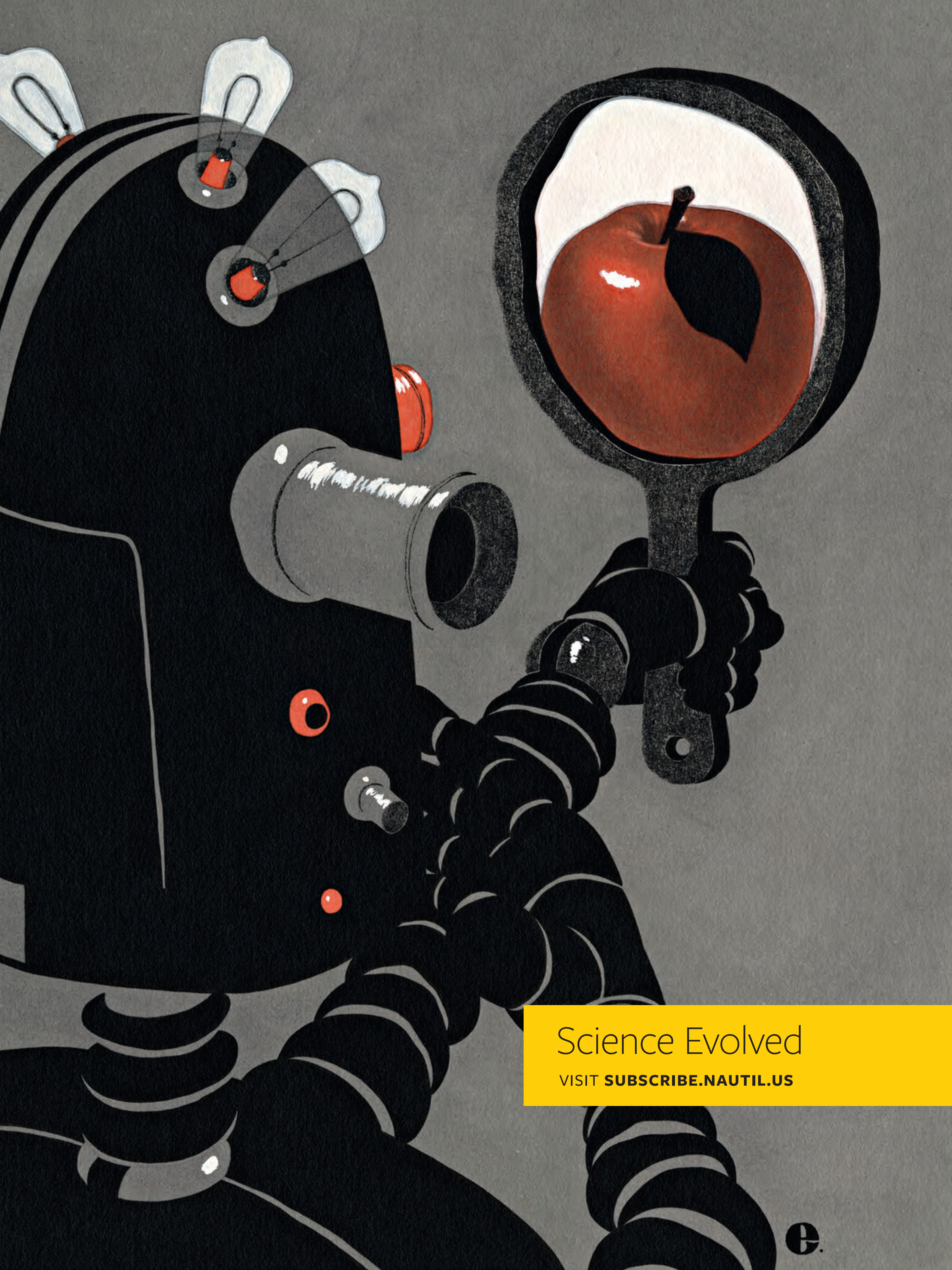
EPIC SCALE

Treating depression in novel and innovative ways is one of the biggest epic scale challenges. That's where I'm trying to take SuperBetter. We need people to get excited about this idea. We need people to take this idea and develop it in different contexts and different cultures.

DANCING IN THE STREETS

2050 is a long enough timeline for everything to be radically different. But the problems we're trying to solve in 35 years will be the same. Poverty. Disease. Depression. By then we'll have such a different approach. Personalized medicine, nanobots doing surgery on our bodies while we dance in the streets.

ILLUSTRATION BY ANDY FRIEDMAN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