

NAUTILUS

50 **EMERGENCE**
More than the sum

51 **LIMITS**
Imagining the possible



How a City Grows

YOUR TOWN'S HIDDEN SCALING LAWS p.20

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Scale Models

VIEWED FROM SPACE, Earth's cities have a distinctly biological aesthetic. At night, thin tendrils stretch out like axons connecting city-neurons together. Ring roads surround gridded or concentric circuitry.

The images remind us that, just as colonies of cells make us up, we in turn make up bigger colonies. The human body is just one stop on the hierarchy of biological structure.

In this issue's cover story, the particle-theorist turned city-theorist Geoffrey West makes this instinct quantitative. He describes how cities, like all organisms, follow scaling laws. An animal's metabolic rate scales non-linearly with size, and so do a city's vital statistics—creative output, crime, and so on.

The non-linear nature of these laws makes comparisons across scales tricky. Per-capita comparisons of cities, for example, are problematic. At the same time, their universal nature creates startling similarities, whether it is city networks that look like stained tissue samples, or brains that look like galaxy clusters (page 48).

West's observations are cause for both pride and humility. We are building complex, organic machines on unimaginable scales. And they are just as constrained and vulnerable as a cell in a petri dish.

Welcome to the July/August 2017 *Nautilus* print edition.

—Michael Segal
Editor in Chief

NO REACTION NO PROGRESS

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Contents



Preludes

- 14 *Uber and driverless cars; raccoons wreaking havoc; a strange new language; and why robots need to boogie*

Themes

Each print edition identifies different themes in science and explores them from multiple perspectives.

Cover Story

- 20 **SOCIOLOGY**
Why New York Is Just an Average City
Understanding any city requires understanding how all cities scale
BY GEOFFREY WEST

- 32 **Emergence**
More than the sum

- 54 **Limits**
Imagining the possible

- THE LAST WORD**
96 **Jack Gilbert**
The faculty director of the Microbiome Center and coauthor of Dirt Is Good reflects on the themes in Nautilus

COVER Wenjia Tang
BACK COVER Paulo D. Campos

50

Emergence

“Emoji, today, dwarfs even the reach of English.”

—Vyvyan Evans, p. 34

SOCIOLOGY

34 Why You Need Emoji

Emojis are the body language of the digital age

BY VYVYAN EVANS

TECHNOLOGY

40 How the Oil Pipeline Began

Pipeline fights have a longer history than you think

BY JONATHAN WALDMAN

MATH

48 The Strange Similarity of Neuron and Galaxy Networks

Your life's memories could, in principle, be stored in the universe's structure

BY FRANCO VAZZA & ALBERTO FELETTI



51

Limits

“Remember that your brain is always guessing,
and sometimes its guesses are wrong.”

—Lisa Feldman Barrett p. 68

ANIMALS

56 Where the Wild Things Go

The remarkable travel itineraries of animals

BY OLIVER UBERTI

PSYCHOLOGY

68 Emotional Intelligence Needs a Rewrite

Think you can read people's emotions? Think again.

BY LISA FELDMAN BARRETT

ENVIRONMENT

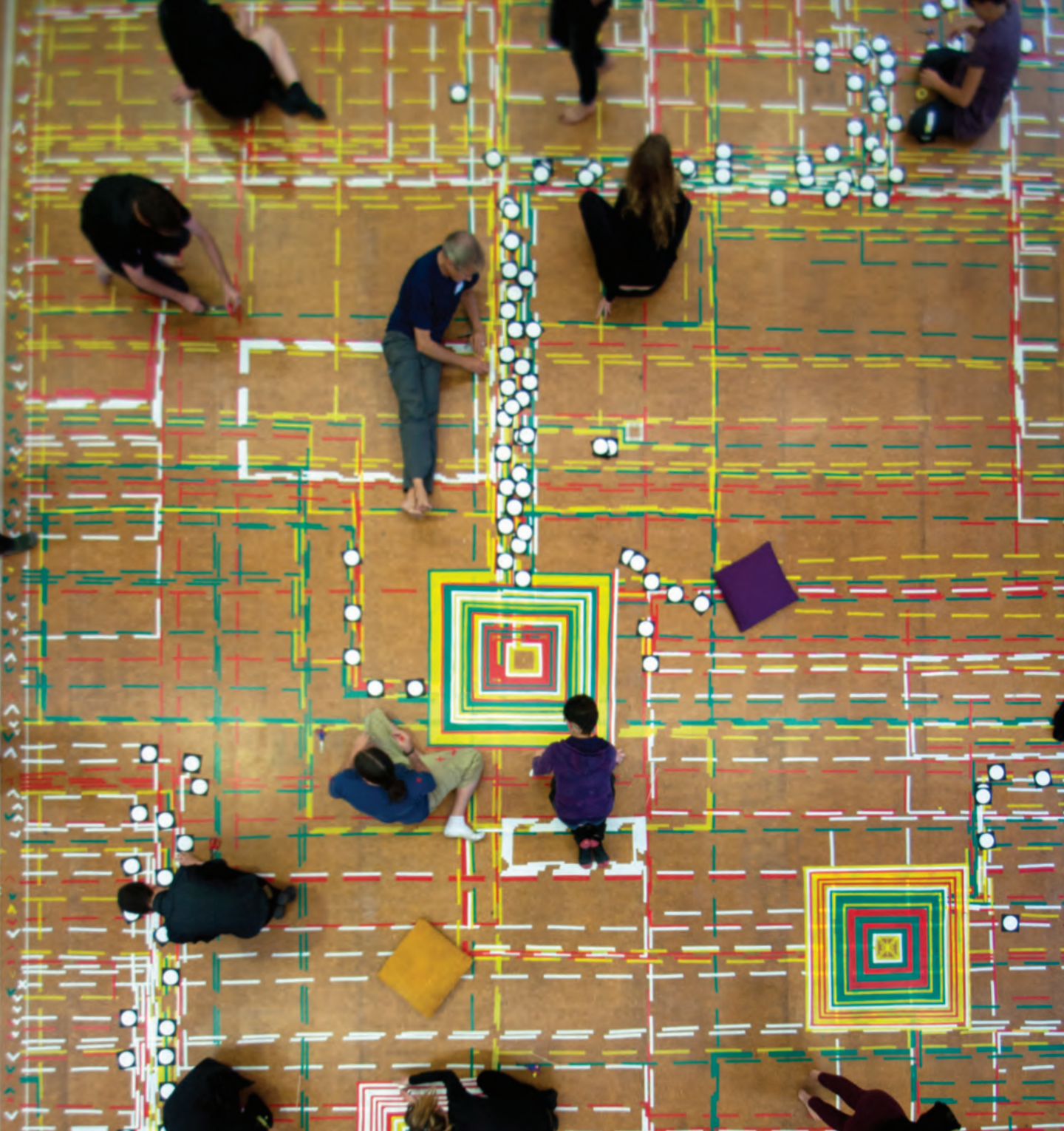
74 Reinventing Staten Island

*The ecological philosophy of turning a garbage dump
into a park*

BY MADELINE GRESSEL

THEME ART Francesco Izzo



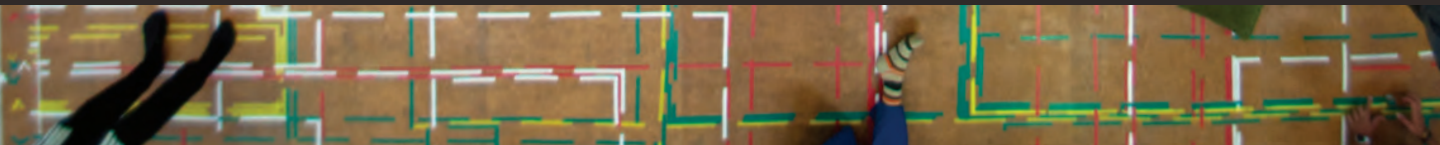


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Image: *Experiment Two* from the "Drawing on Complexity" series by Briony Barr. In consultation with physicist Andrew Melatos, Barr creates different rules, feedback loops, and boundary conditions for collaborative drawings that are real-time versions of agent-based models.





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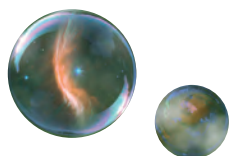
Letters

Reader responses to the May/June 2017 print edition.

“WHY YOUR BRAIN HATES OTHER PEOPLE”

Great article, with great research to back it up. I think a significant amount of people know they're biased but don't care because they truly feel they are better. I wish there was some mention of this. It was probably a good thing to genetically have an Us/Them mentality before we had agriculture and society—when people did have to fight over hunting ground and mates. But in a post agriculture and largely civilized world these genes just cause the human species pain.

—Adam Miller



“THE INFLATED DEBATE OVER COSMIC INFLATION”

There are more critics to the inflationary paradigm than this article claims. But some critics of the inflationary paradigm go too far in claiming that it should be completely abandoned, and some of its advocates go too far in claiming it should be thought of as a settled science. The truth is between these two extremes and numerous critics and advocates of the inflationary paradigm fail to realize that non-eternal inflation is much easier to realize than previously thought.

Non-eternal inflation is predictive, explanatory, has no multi-mess and no measure problems.

—Louis Wilbur

“WHEN NEUROLOGY BECOMES THEOLOGY”

What if the brain is stimulated not by just the sensory inputs, but by many subtle bits of information from the endocrine system, the blood, and so on. These multiple, intertwined flows of influence, coiled with memory, may be a partial explanation of both mind and agency. Essentially, I'm suggesting that the brain is not the sole place the mind occupies, but it is the whole body, including experience and memory, that together create and nourish the mind.

—Frederick Cass

Has anyone given a definition of consciousness? I have never seen even an attempt to define it. My impression is that the standard is to assume that each of us knows what consciousness is, simply from personal experience. Might a person in a coma be conscious? Is a housefly conscious? Is there a test for consciousness of an object/being? Until we can say with some precision what we are talking about, the hard problem of consciousness will be not only hard, but intractable.

—Jesse Jones



“THE IMPOSSIBLE MATHEMATICS OF THE REAL WORLD”

Wonderful article! At some points I wondered “and what about ...” and then that topic was addressed in the next paragraph. So “close” not only counts in horseshoes and hand grenades, but sometimes in mathematics, too. I live and learn.

—Kai Frederking

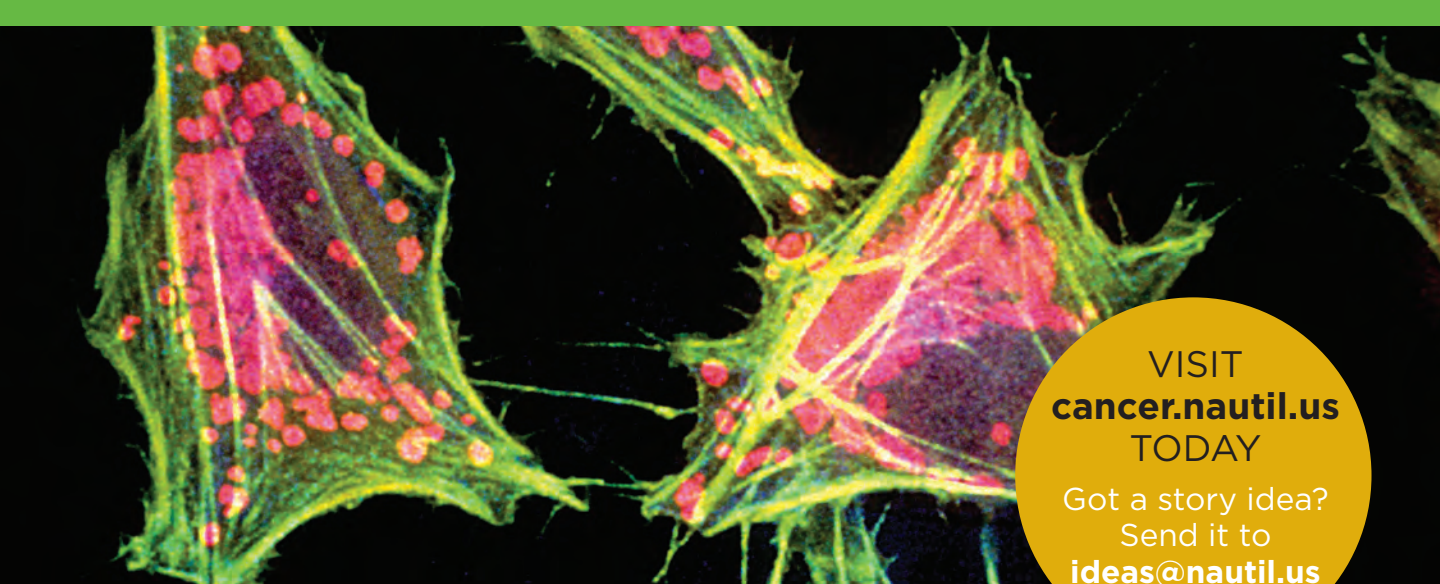
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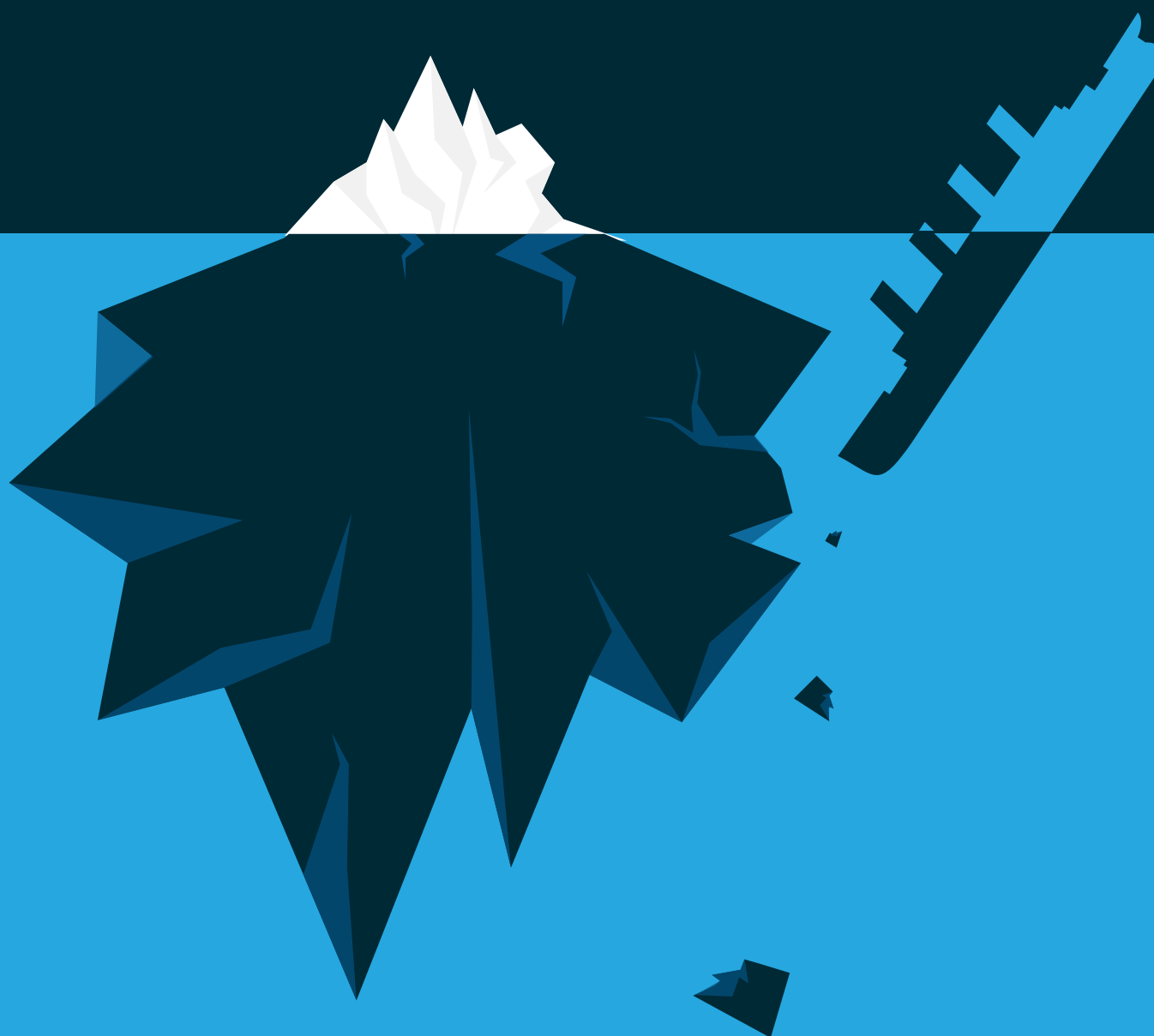
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The eye sees only what the mind
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Preludes



TECHNOLOGY

Why Uber Needs Self-Driving Cars

UBER HAS COME a long way, from a limited launch in San Francisco in 2010, to offering rides in more than 450 cities worldwide today. Within five years the company had provided 1 billion people with rides, and in May of 2017 Uber passed 5 billion trips taken. But are there limits to how much Uber can scale? There might be—us.

“The natural end point has to rely on autonomous driving technology”—not humans, says Emilio Frazzoli, director of the Transportation@MIT Initiative. He thinks robots could be taking the wheel in the next 15 years, certainly within the next 30. The reasons, he says, are both economical and cultural.

First, more than 50 percent of an Uber ride’s cost goes toward paying the human behind the wheel, Frazzoli says, and that’s money that could be going into Uber’s pocket. Replacing human operators has already begun in Singapore, a city that relies heavily on public transit. It’s not widely advertised, Frazzoli says, but the

Getting drivers will likely always be more of a headache than finding more riders.

subway trains there “are completely automated. They are just horizontal elevators.”

Felix Oberholzer-Gee, a professor at Harvard Business School, agrees. Uber, he says, is a perfect example of a business that benefits from network effects, where the value of its service increases with more use. But, unlike other companies that benefit from strong network effects, Uber has to bring together two different types of users and networks: drivers and riders. Getting rid of human drivers, he says, “will make the platform even stronger.”

Plus, for reasons from supply to quality control, Oberholzer-Gee

says getting drivers will likely always be more of a headache than finding more riders. With autonomous vehicles, he says, “You could have a guaranteed supply of one of the sides, and particularly of the side that is harder to manage.” Uber might already be trying to learn how little they can pay their drivers. “They want to test the bottom line,” a Chinese Uber driver told *MIT Technology Review*, “just to see how much lower they can go before you quit.”

Second, Uber’s urban saturation is making a lot of people rethink the idea of owning a car, Frazzoli says, “versus just taking an Uber.” That’s no accident: As Uber’s general manager in Vietnam told *Reuters*, “Our goal is to replace private car ownership.”

Stowe Boyd, lead researcher at GigaOM Research, which specializes in emerging technology, thinks more and more people will eschew owning personal vehicles once self-driving cars arrive. They will “radically decrease car ownership,” he told Pew Research Center. “Perhaps 70 percent of cars in urban areas would go away.”

In an apparent attempt to bring this about, Uber hired 50 researchers from Carnegie Mellon’s National Robotics Engineering Center—a third of the department’s staff—for a developmental project on self-driving cars.

If the custom of car ownership dramatically dissolves, then Uber’s mass of potential drivers will, too. Driver scarcity will serve as another forcing function on Uber’s business model, further compelling it to evolve toward autonomous cars.

Oberholzer-Gee, however, doesn’t think it would be in Uber’s best interest to manufacture its own fleet of self-driving cars. That would change its strategy from, he says, “a very asset-light business model that Wall Street and the investors love, to sitting on billions and billions of dollars of invested assets.” That is a particularly difficult proposition given the dramatic fluctuations that happen to ride demand and availability. A large fleet of vehicles is needed at peak times, but a fleet that sits idle during off hours is just an added expense. “Regular drivers and

autonomous vehicles have similar properties that I think make the Uber model difficult to scale,” says Oberholzer-Gee.

Say Uber (which declined to comment for this story) does decide to ditch its human drivers and opts not to operate its own fleet of self-driving cars: Who would do it for them? Oberholzer-Gee suggests that a large car manufacturer could be ideal. But then again, maybe it will be autonomous car owners themselves that will make up the next generation of Uber “drivers.”

—Jon Kelvey

ANIMALS

How a Cartoon Created a Real-Life Invasive Army

TALES OF MONSTERS invading Japan are a longstanding tradition, usually involving menacing creatures rising from the sea to wreak havoc. Now, the country is engaged in just such a war, with an army of invasive creatures—raccoons.

Our story begins when a young Wisconsin boy named Sterling North adopts an orphaned baby raccoon and names him Rascal. The boy and the raccoon were inseparable best friends, and for a year did everything together. But Rascal became more mischievous as he aged, and drew the attention and aggression of other raccoons. North realized that he would have to release his best friend. A life inside a cage was no life for a raccoon.

The true story of Sterling North and Rascal was the basis for North’s 1963 memoir, *Rascal: A Memoir*



of a *Better Era*. The story became a Disney movie, and then an anime series called *Araiguma Rasukaru*, which aired in Japan in 1977.

Raccoons are not native to Japan. But when *Araiguma Rasukaru* aired, Japanese children wanted their own pet raccoons. At the peak of their popularity, Japan imported more than 1,500 North American raccoons each year. The government eventually banned importing them or keeping them as pets, but it was too late.

Life imitated art when some of the Japanese children who had kept pet raccoons released them into the wild. Other raccoons simply escaped. Still others were released due to frustration. Raccoons are friendly when young, but become more aggressive and harder to control as they age, posing a potential threat to humans.

Raccoons have since proliferated in Japan, where they have no natural predators. By 2004, they had spread to at least 42 of 47 prefectures. They steal food from livestock, rob fish from farms, and damage crops. Raccoons were responsible for more than \$300,000 of agricultural damage each year on the island of Hokkaido alone, according to a 2004 study by Tohru Ikeda, of Hokkaido University, and colleagues.

The masked invaders have also taken a toll on Japan's ecology, preying on some native animals, insects, and fish, and competing with others for food and territory. And, raccoons are known vectors for the spread of infectious diseases, particularly rabies.

Following the passing of a law

protecting native Japanese ecosystems in 2004, local governments began culling invasive raccoon populations. Predictably, there was public backlash.

This is one unfortunate consequence of fame. A species once beloved by a country's children thanks to a popular cartoon has in the space of just a few decades become a public nuisance, a source of significant agricultural economic losses, a possible vector for disease transmission, and a threat to other threatened and vulnerable species.

There is no good solution to the problem of invasive raccoons in Japan. Left uncontrolled, they will continue to cause problems. But the alternative—mass culls—can't garner public support, and most research indicates that culls aren't actually all that effective anyway. In the end, the best antidote against the anthropogenic origins of animal invasions is wildlife education, so people learn that raccoons are best left in their natural North American habitats—and on TV.

—Jason G. Goldman

LINGUISTICS

A Language That Breaks the Rules

LANGUAGES, LIKE HUMAN BODIES, come in a variety of shapes—but only to a point. Just as people don't sprout multiple heads, languages tend to veer away from certain forms that might spring from an imaginative mind. For example, one core property of human languages is known as duality of patterning: Meaningful linguistic units (like words) break down into smaller meaningless units (sounds), so that the words sap, pass, and asp involve different combinations of the same sounds, even though their meanings are completely unrelated.

It's not hard to imagine that things could have been otherwise. In principle, we could have a language in which sounds relate holistically to their meanings—a high-pitched yowl might mean "finger," a guttural purr might mean "dark," a yodel might mean "broccoli," and so on. But there are stark advantages to duality of patterning. Try inventing a lexicon of tens of thousands of distinct noises, all of which are easily distinguished, and you will probably find yourself wishing you could simply re-use a few snippets of sound in varying arrangements.

The dominant thinking until fairly recently was that universal linguistic properties reflect genetic

The sign for "lemon" resembles the motion of squeezing a lemon.

predispositions. Under this view, duality of patterning is much like an opposable thumb: It evolved within our species because it was advantageous, and now exists as part of our genetic heritage.

What to make, then, of the recent discovery of a language whose words are not made from smaller, meaningless units? Al-Sayyid Bedouin Sign Language (ABSL) is a new sign language emerging in a village with high rates of inherited deafness in Israel's Negev Desert. In this language, words correspond to holistic gestures, much like in our imaginary sound-based language.

To linguists, this is akin to finding a planet on which matter is made up of molecules that don't decompose into atoms. ABSL contrasts sharply with other sign languages like American Sign Language, which creates words by re-combining a small collection of gestural elements such as hand shapes, movements, and positions.

ABSL provides fodder for researchers who reject the idea of a genetic basis for the similarities found across languages. Instead, they argue, languages share certain properties because they all have to solve similar problems of communication. The challenge, then, is to explain why ABSL is an outlier—if duality of patterning is the optimal solution to the problem of creating a large but manageable collection of words, why doesn't ABSL use it?

One possible explanation is that the vocabulary of ABSL hasn't yet reached a critical mass that would force it into a more combinatorial system for word creation.

This doesn't look like the full story though. In a study by Tessa Verhoeve of the University of Amsterdam, people tried to reproduce a “language” of 12 sounds made on a slide whistle. Each person's attempts served as the new version to be learned by the next subject, so that each new learner represented a “generation” in the life of the language. Over just 10 generations, learners began to change the original sounds to involve combinations of smaller sound patterns. The later iterations of the language were easier to learn than the original, suggesting there's a learning advantage to breaking down even a very small number of complex sounds into smaller ingredients.

The signs of ABSL may be easier to learn because many of them are concretely related to what they symbolize—for example, the sign for “lemon” resembles the motion

of squeezing a lemon. A study led by Gareth Roberts of Yeshiva University found that both large vocabularies and abstract symbols encouraged the birth of duality of patterning in artificial languages. Concreteness may be easier to achieve in a gestural language than an auditory one, simply because you can illustrate more ideas using your hands than by making sounds with your mouth.

Researchers don't yet know why ABSL looks as it does, but studies may help solve this puzzle, as may the evolution of ABSL itself; Sandler and her colleagues see hints that ABSL is on the cusp of evolving a more combinatorial system. This language may eventually tell us something profound about how languages emerge from the human mind, and why so many of them share some important similarities.

—Julie Sedivy

ONE QUESTION



Linda Boff

Are you optimistic about communicating science to the public?

Chief Marketing Officer of General Electric

It is amazing to me how the right engagement, the right storytelling, the right cultural relevance can get across things that people would otherwise say, “I don't understand that.” The movie *Hidden Figures* is one case in point. My favorite example of all time, though, which is not a science example, is the movie *The Big Short*. They found funny ways to tell you about really complicated financial things that make your head hurt and that people don't care about. So I think it is possible, but I think it is about starting a conversation.

ARTIFICIAL INTELLIGENCE

Why Robots Can't Dance

ROBOTS NEED TO DANCE, if you believe David Chapman. The first researcher to apply computational complexity theory to robot planning, he showed mathematically that there was no feasible, general method of enabling AIs to plan for all contingencies. He concluded that human-level AI might be possible in principle, but none of the available approaches had much hope of achieving it.

In 1990, Chapman suggested a fresh research challenge: dancing. Dancing, he wrote, was important because “there’s no goal to be achieved. You can’t win or lose. It’s not a problem to be solved.” Dancing robots require a sharp change in priorities for AI researchers, whose techniques were built around rigidly structured tasks with unambiguous end goals.

In a conversation with *Nautilus*, Chapman explained why robots need to dance before they can learn.



Dancing and making breakfast are still well beyond the state of the art.

What makes a dancing robot interesting?

Human learning is always social, embodied, and occurs in specific practical situations. Mostly, you don’t learn to dance by reading a book or by doing experiments. You learn it by dancing with people who are more skilled than you. Imitation and apprenticeship are the main ways people learn.

I aimed to shift emphasis from learning toward development. “Learning” implies completion: once you have learned something, you are done. “Development” is an ongoing, open-ended process. There is no final exam in dancing after which you stop learning.

Wasn’t that quite a shift from the traditional approach to learning?

Yes. In its first few decades, artificial intelligence research concentrated on tasks we consider signs of intelligence because they are difficult for people, like chess. It turned out that chess is easy for fast-enough computers. Early work neglected tasks that are easy

for people: making breakfast, for instance. Such easy tasks turned out to be difficult for robots.

Recent research has made progress on practical, real-world problems, but still makes no use of the social and bodily resources critical to human learning.

Does building a physically embodied robot add a lot of challenges?

We can never make an entirely accurate model of the real world. It’s just too messy. A spoonful of jam has no particular shape. It’s sticky, squishy, and somewhat runny. Our bodies are the same. Muscles are bags of jelly with stretchy strings in them. Bones are irregular shapes with elastic tendons, so joints exhibit complex patterns of “give” as they approach their limits.

Using physical simulation, you can make an animated human figure dance on the screen. It might look impressively realistic. But these methods don’t work well enough for robots to do most ordinary human tasks. Dancing and making breakfast are still well beyond the state of the art.

What do you think of the deep learning approach to AI?

Deep learning, which has had some spectacular recent successes, is more flexible than the older approaches. It builds models that are statistical and implicit, rather than absolute and logical. However, this requires enormous quantities of data, whereas people often learn from a single example. It will be fascinating to discover the scope and limitations of deep learning.

—Uri Bram

Hamatreya

By Ralph Waldo Emerson

POETRY
IN AMERICA

Bulkeley, Hunt, Willard, Hosmer, Meriam, Flint,
Possessed the land which rendered to their toil
Hay, corn, roots, hemp, flax, apples, wool, and wood.
Each of these landlords walked amidst his farm,
Saying, "'Tis mine, my children's and my name's.
How sweet the west wind sounds in my own trees!
How graceful climb those shadows on my hill!
I fancy these pure waters and the flags
Know me, as does my dog: we sympathize;
And, I affirm, my actions smack of the soil."

Where are these men? Asleep beneath their grounds:
And strangers, fond as they, their furrows plough.
Earth laughs in flowers, to see her boastful boys
Earth-proud, proud of the earth which is not theirs;
Who steer the plough, but cannot steer their feet
Clear of the grave.
They added ridge to valley, brook to pond,
And sighed for all that bounded their domain;
"This suits me for a pasture; that's my park;
We must have clay, lime, gravel, granite-ledge,
And misty lowland, where to go for peat.
The land is well,—lies fairly to the south.
'Tis good, when you have crossed the sea and back,
To find the sitfast acres where you left them."

Ah! the hot owner sees not Death, who adds
Him to his land, a lump of mould the more.
Hear what the Earth say:—

EARTH-SONG

"Mine and yours;
Mine, not yours.
Earth endures;
Stars abide—

Shine down in the old sea;
Old are the shores;
But where are old men?
I who have seen much,
Such have I never seen.

"The lawyer's deed
Ran sure,
In tail,
To them and to their heirs
Who shall succeed,
Without fail,
Forevermore.

"Here is the land,
Shaggy with wood,
With its old valley,
Mound and flood.
But the heritors?—
Fled like the flood's foam.
The lawyer and the laws,
And the kingdom,
Clean swept herefrom.

"They called me theirs,
Who so controlled me;
Yet every one
Wished to stay, and is gone,
How am I theirs,
If they cannot hold me,
But I hold them?"

When I heard the Earth-song
I was no longer brave;
My avarice cooled
Like lust in the chill of the grave.



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The Mayflower through Emerson
Whitman and Dickinson



Why New York Is Just an Average City

Understanding any city requires understanding how all cities scale

BY GEOFFREY WEST

H

OW RICH, CREATIVE, OR SAFE can we expect a city to be? How can we establish which cities are the most innovative, the most violent, or the most effective at generating wealth? How do they rank according to economic activity, the cost of living, the crime rate, the number of AIDS cases, or the happiness of their populations?

The conventional answer is to use simple per capita measures as performance indices and rank order of cities accordingly. Almost all official statistics and policy documents on wages, income, gross domestic product (GDP), crime, unemployment rates, innovation rates, cost of living indices, morbidity and mortality rates, and poverty rates are compiled by governmental agencies and international bodies worldwide in terms of both total aggregate and per capita metrics. Furthermore, well-known composite indices of urban performance and the quality of life, such as those assembled by the World Economic Forum and magazines like *Fortune*, *Forbes*,¹ and *The Economist*,² primarily rely on naive linear combinations of such measures.

But, since we have quantitative scaling curves for many of these urban characteristics and a theoretical framework for their underlying dynamics, we can do much better in devising a scientific basis for assessing performance and ranking cities.

The ubiquitous use of per capita indicators for ranking and comparing cities is particularly egregious because it implicitly assumes that the baseline, or null hypothesis, for any urban characteristic is that it scales linearly with population size. In other words, it presumes that an idealized city is just the linear sum of the activities of all of its citizens, thereby ignoring

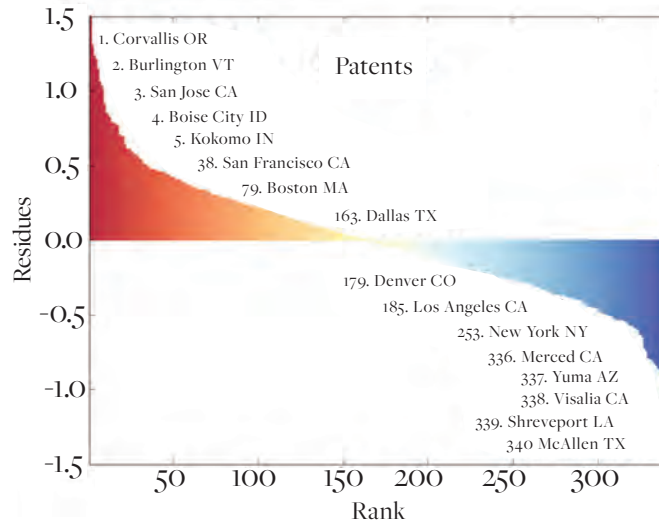
ILLUSTRATIONS BY JESSICA LIN

its most essential feature and the very point of its existence, namely, that it is a collective emergent agglomeration resulting from nonlinear social and organizational interactions. Cities are quintessentially complex adaptive systems and, as such, are significantly more than just the simple linear sum of their individual components and constituents, whether buildings, roads, people, or money. There is an approximately 15 percent increase in all socioeconomic activity with every doubling of the population size, which happens almost independently of administrators, politicians, planners, history, geographical location, and culture.

In assessing the performance of a particular city, we therefore need to determine how well it performs relative to what it has accomplished just because of its population size. By analogy with the discussion on determining the strongest champion weightlifter by measuring how much each deviated from his expected performance relative to the idealized scaling of body strength, one can quantify an individual city's performance by how much its various metrics deviate from their expected values relative to the idealized scaling laws. This strategy separates the truly local nature of a city's organization and dynamics from the general dynamics and structure common to all cities. As a result, several fundamental questions about any individual city can be addressed, such as how exceptional it is relative to its peers, what timescales are relevant for local policy to take effect, what are the local relationships between economic development, crime, and innovation, to what extent is it unique, and to what extent can it be considered a member of a family of like cities.

My colleagues Luis, José, and Debbie carried out such an analysis for the entire United States urban system consisting of 360 Metropolitan Statistical Areas (MSAs) for a suite of metrics.³ A sample of the results is presented in *Innovation in Cities* (on page 23), where the deviations from scaling for personal income and patent production for cities in the U.S. in 2003 are plotted logarithmically on the vertical axis against the rank order of each city. We called these deviations Scale-Adjusted Metropolitan Indicators (SAMIs). The horizontal axis across the center of these graphs is the line along which the SAMI is zero and there is no deviation from what is predicted from the size of the city. As can be seen, every city deviates to some extent from its expected values. Those to the left denote above-average performance, whereas those to the right denote below-average performance. This provides a meaningful ranking of a city's individuality and uniqueness beyond what is effectively guaranteed just because it's a city of a certain size. Without delving into details of this analysis, I want to make a few salient points about some of the results.

First, compared with conventional per capita indicators, which place seven of the largest 20 cities in the top 20 in terms of their GDPs, our science-based metrics rank none of these cities in the top 20. In other words, once the data are adjusted for the generic superlinear effects of population size, these cities don't fare so well. Mayors of these cities who take credit and boast that their policies have led to economic success as evidenced by

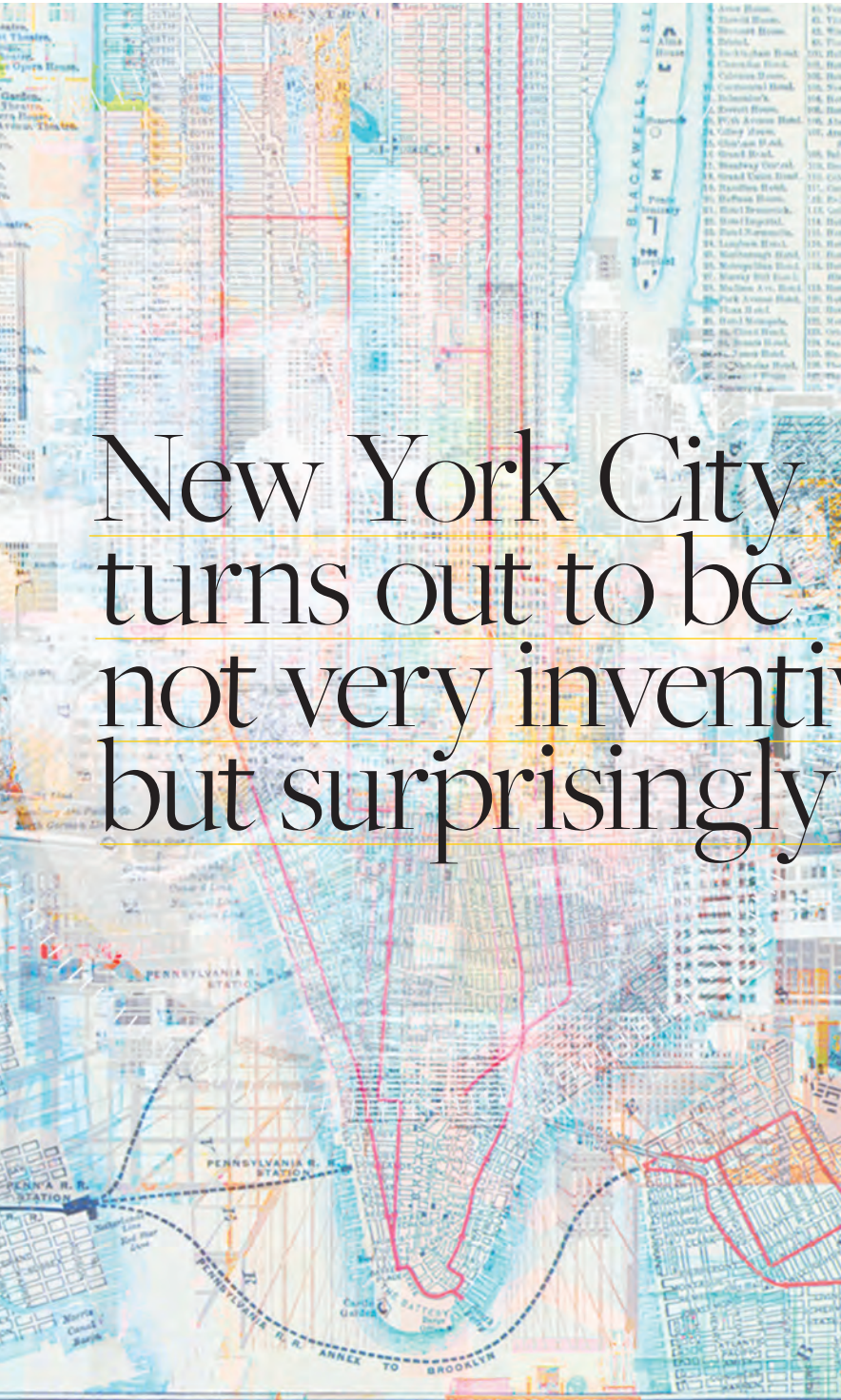


INNOVATION IN CITIES Deviations in the number of patents produced in U.S. cities in 2003 relative to the expected number from scaling laws given the size of the city, plotted against their rank. Those to the left are overperformers with Corvallis being ranked first, whereas those to the right are underperformers with McAllen being ranked last.

their city's being near the top of the per capita GDP rankings are therefore giving a misleading impression.

Amusingly from this point of view, New York City as a whole turns out to be quite an average city, marginally richer than its size might predict (rank 88th in income, 184th in GDP), not very inventive (178th in patents), but surprisingly safe (267th in violent crime). On the other hand, San Francisco is the most exceptional large city, being rich (11th in income), creative (19th in patents), and fairly safe (181st in violent crime). The truly exceptional cities are typically smaller, such as Bridgeport for income (due to all those bankers and hedge fund managers from New York City living in the suburbs); Corvallis (home of a Hewlett-Packard research lab and a respectable university, Oregon State), and San Jose (which encompasses Silicon Valley—what more need be said?) for patents; and Logan (the Mormon culture?) and Bangor (who knows?) for safety.





New York City turns out to be not very inventive, but surprisingly safe.

BESIDES BEING SAFE, New York City does distinguish itself another way: In New York the most abundant business type is offices of physicians. Weird, especially because physicians are ranked only fifth in Phoenix, which has a huge retirement community of decrepit old farts like me, and seventh in San Jose, which is possibly less surprising given all those young obsessive-compulsive California joggers and health enthusiasts.

Just as with other metrics, the types of businesses that a city hosts scale according to universal laws with the size of the city. While all cities necessarily have a similar essential core of businesses—lawyers, doctors, restaurants, garbage collectors, teachers, administrators, and so on—only a very few have specialized subcategories such as maritime lawyers, tropical disease doctors, blacksmiths, chess store proprietors, nuclear physicists, and hedge fund managers. The deviation of a city’s business types from what is expected based on universal scaling laws is then a reflection of its individuality and distinctive characteristics.

The challenge of formally categorizing businesses has been addressed, at least in North America, by the compilation of an extraordinary data set that includes the records of almost all business establishments in the U.S. (more than 20 million). This is the result of an impressive collaboration between the United States, Canada, and Mexico, and is called the North American Industry Classification System (NAICS). An establishment is just any single physical location where business is conducted. Consequently, individual businesses that are part of a national chain, such as a Walmart store or a McDonald’s franchise, would be counted as separate establishments. Establishments are often viewed as the fundamental units of economic analysis because innovation, wealth generation, entrepreneurship, and job creation all manifest themselves through the formation and growth of such workplaces. The NAICS classification scheme employs a six-digit code at the most detailed industry level. The first two digits designate the largest business sector, the third digit designates the subsector, and so on, thereby capturing economic life at an extraordinarily fine-grained level.

My colleagues Luis, José, and Debbie carried out an analysis of these data with our postdoc Hyejin Youn taking the lead role. Youn has now established herself as an expert in innovation technology. As we saw in the analysis of other urban metrics, the data reveal surprisingly simple and unexpected regularities. For instance, the total number of establishments in each city regardless of what business they conduct turns out to be linearly proportional to its population size. Double the size of a city and on average you’ll find twice as many businesses. The proportionality constant is 21.6, meaning that there is approximately one establishment for about every 22 people in a city, regardless of the city size. Or to put it slightly differently, on average a new workplace is created each time the population of a city increases by just 22 people, whether in a small town or a large metropolis. This is an unexpectedly small number and usually comes as quite a surprise to most people, even those dealing in business and

A new workplace is created each time the population increases by just 22 people.

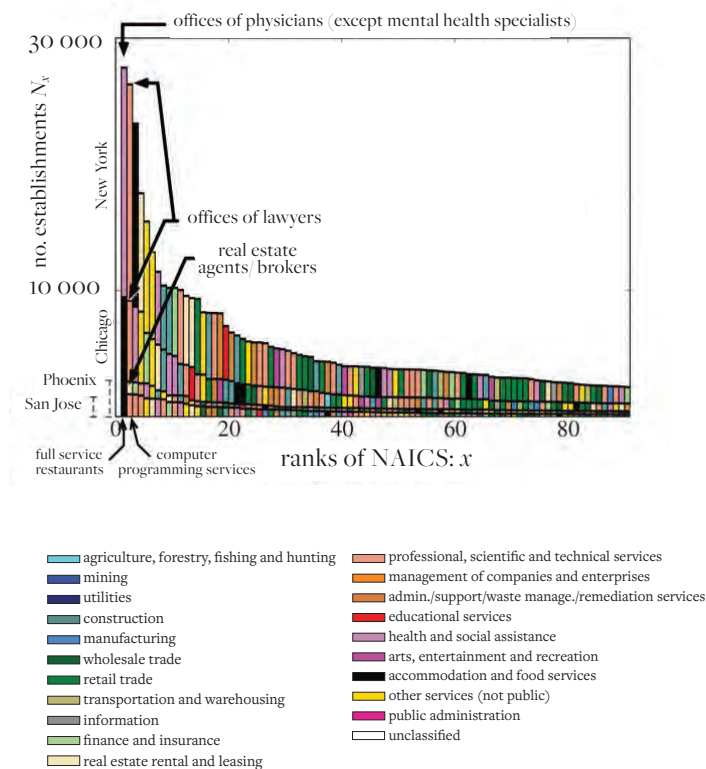
commerce. Similarly, the data also show that the total number of employees working in these establishments also scales approximately linearly with population size: On average, there are only about eight employees for every establishment, again regardless of the size of the city. This remarkable constancy of the average number of employees and the average number of establishments across cities of vastly different sizes and characters is not only contrary to previous wisdom, but also rather puzzling when viewed in light of the pervasive superlinear agglomeration effects that underlie all socioeconomic activity, including per capita increases in productivity, wages, GDP, and patent production.⁴

To get a deeper understanding of this and to reveal the business character of a city, it's illuminating to ask how many different types of businesses there are in a city. This is like asking how many different species of animals there are in an ecosystem. The simplest coarse-grained measure of economic diversity of a city is obtained by just counting the number of distinct types of establishments it has as a function of its population size. The data confirm that diversity systematically increases with population size at all levels of resolution, as defined by the NAICS data set. Unfortunately, the classification scheme is unable to capture the full extent of economic diversity in the largest cities because it is unable to differentiate among very closely related types of establishments such as, for instance, between a northern and southern Italian restaurant. However, an extrapolation of the data strongly suggests that if we could measure diversity to the finest possible resolution it would scale logarithmically with city size.

Compared with the usual canonical power law behavior that most metrics obey, this represents an extremely slow increase with population size. For instance, an increase of the population by a factor of 100 from, say, 100,000 to 10 million results in the addition of 100 times as many

businesses but an increase of only a factor of two in their diversity. To put it slightly differently: Doubling the size of a city results in doubling the total number of establishments, but only a meager 5 percent increase in new kinds of businesses. Almost all of this increase in diversity is reflected in a greater degree of specialization and interdependence involving larger numbers of people, both as workers and as clients. This is an important observation because it shows that increasing diversity is closely linked to increasing specialization, and this acts as a major driver of higher productivity following the 15 percent rule.

A more detailed way of assessing economic diversity is to dig deeper and examine the specific component types of establishments that constitute the business landscape of individual cities. How many lawyers, doctors, restaurants, or contractors are there in each city, and how many of



CITY BUSINESS The number of establishments ranked in descending order of their frequencies (from common to rare) for New York City, Chicago, Phoenix, and San Jose. Establishment types are referred to by their NAICS classification.



Increasing diversity is closely linked to increasing specialization.

these are corporate lawyers, orthopedic surgeons, Indonesian restaurants, or plumbing contractors? As an example of such an analysis, City Business (on page 27) shows the abundances of the 100 leading business types for a selection of cities in the U.S. These are plotted in a classic rank-size format. When giving a talk, I preface the showing of this graph by asking the audience what they think is the most abundant business type in New York City. So far, no one has yet come up with the correct answer, including audiences of business and corporate gurus operating in New York City itself. It's amazing what you can learn from taking a simple analytic, principled approach to problems.

The answer, as mentioned, is physicians. Less surprising is that after physicians, the next highest ranked in New York are offices of lawyers, followed by restaurants. In fact, restaurants rank high in all cities, being first, for example, in Chicago, Phoenix, and San Jose. Eating out, whether at a fancy Four Seasons restaurant or at a McDonald's fast-food stop, is clearly a major component of the socioeconomic activity of Americans. More generally, it's interesting to speculate what these sorts of rankings say about a city. For instance, after restaurants Phoenix ranks real

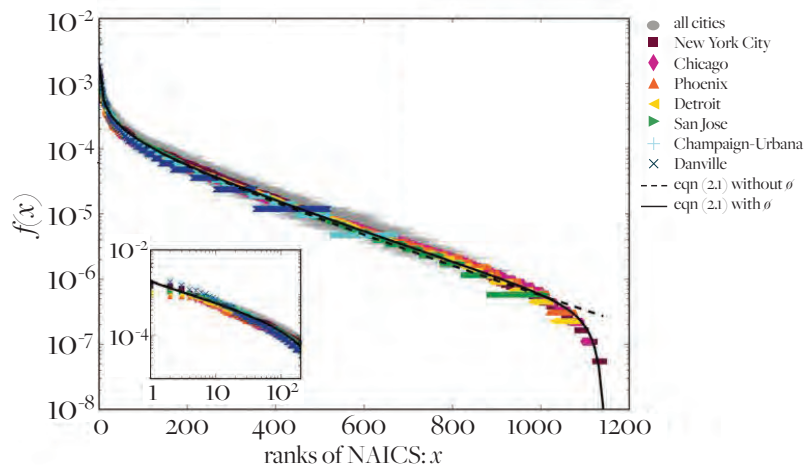
estate second, which is perhaps not surprising in a rapidly growing city, whereas San Jose, the home of Silicon Valley, predictably ranks computer programming second.

It's obvious why lawyers and restaurants would rank high in New York, but what is it about New York that there should be such a large abundance of doctors? Is life in the Big Apple that stressful and unhealthy? If you find this intriguing, you can see the analogous decomposition of economic activities in your favorite city in the supplementary material to our paper posted on the web. Clearly, for those running a city or thinking about its future or investing in its development, knowing these sorts of details about the composition of their business landscape provides an important input.

In contrast to the inherent universal properties of cities that are manifested in the scaling laws, these rank-size distributions of business types reflect a unique fingerprint of the city. They are the hallmark of each city and obviously do depend on its history, geography, and culture. It is therefore all the more remarkable that, despite the unique admixture of business types for each individual city, the shape and form of their distribution is mathematically the same for all of them. So much so, in fact, that with a simple scale transformation inspired by theory their rank abundances collapse onto a single unique universal curve common to all cities, as shown explicitly in Business Types (on page 30). When one considers the vast range of income, density, and population levels, let alone the uniqueness and diverse cultures that vary so widely in cities across the U.S., this universality is quite surprising.

What is particularly satisfying is that this unexpected universality, as well as the actual form of the universal curve and the logarithmic scaling of diversity, can all be derived from theory. The universality is driven by the constraint that the sum total of all the different businesses in a city scales linearly with population size, regardless of the detailed composition of business types or of the city. The snakelike mathematical form of the actual distribution function in the chart can be understood from a variant of a very general dynamical mechanism that has been successfully used for understanding rank-size distributions in many different areas, ranging from words and genes to species and cities. It goes under many different names, including preferential attachment, cumulative advantage, the rich get richer, or the Yule-Simon process. It is based on a positive feedback mechanism in which new elements of the system (business types in this case) are added with a probability proportional to the abundances of how many are already there. The more there are, the more of that type are going to be added, so more frequent types get even more abundant with increasingly higher probability than less frequent types.^{5, 6, 7}

This may be one of the most important universal scaling laws for cities. Successful companies and universities attract the smartest people, resulting in their becoming more successful, thereby attracting even smarter people, leading to even greater success and so on, just as wealthy people



BUSINESS TYPES Universal per capita rank-abundance curve of establishment types for all 366 metropolitan statistical areas of the United States; shown explicitly are New York City, Chicago, Phoenix, Detroit, San Jose, Champaign-Urbana, and Danville. The inset shows the first 200 types plotted logarithmically, obeying an approximate Zipf-like power law behavior.

attract favorable investment opportunities that generate even more wealth which they further invest to get even more wealthy. Hence the catchphrase the rich get richer and its implied, but usually unstated, corollary the poor get poorer to characterize this process. Or, as so articulately put by Jesus according to the Gospel of Matthew in the New Testament:

For everyone who has will be given more, and he will have an abundance.
Whoever does not have, even what he has will be taken from him.

This surprising declaration has been used by some fundamentalist Christians and others as justification for rampant capitalism—a sort of anti-Robin Hood slogan supporting the idea of taking from the poor to give to the rich. But while Jesus's remarks are a good example of preferential attachment, the quote is, not surprisingly, taken out of context.

It is often conveniently forgotten that Jesus was actually referring to knowledge of the mysteries of the kingdom of heaven and not to material wealth. He was expressing a spiritual version of the very essence of diligent study, knowledge accumulation, and research and education as expressed by the ancient rabbis: He who does not increase his knowledge decreases it. ☺

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50

“PSYCHOLOGY IS NOT APPLIED BIOLOGY,” the physicist and Nobel Laureate Philip Anderson wrote in 1972, “nor is biology applied chemistry.”

Anderson was bemoaning the fallacy of moving from the reductionist hypothesis (that all natural phenomena obey the same set of fundamental laws) to the constructionist hypothesis (that we can start from those laws and “reconstruct the universe”).

In fact, he argued, at each level of complexity in nature, “entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.” In other words, we should expect new scientific foundations to emerge from complex systems.

His paper in *Science* went on to be cited nearly 3,000 times and helped make emergent phenomena an object of study in themselves. But it was far from the beginning of the field, which stretches back at least to Aristotle’s observation in *Metaphysics* that “the whole is something beside the parts.”

That the reductionist program has mostly overshadowed emergence is to be expected—in a sense, reductionism had to come first. But we may finally be ready for the next act.

Welcome to “Emergence.”

—MS

“An evolving galaxy does not care about the dance of electron orbitals within atoms.”

FRANCO VAZZA & ALBERTO FELETTI

“The Strange Similarity of Neuron and Galaxy Networks” p.48

Emergence

MORE THAN THE SUM



Why You Need Emoji

Emojis are the body language of the digital age

BY VYVYAN EVANS



THE USE OF EMOJIS has become a global phenomenon. By 2015, over 6 billion emojis¹ were being sent every day by over 90 percent of the world's online population.² Emoji, today, dwarfs even the reach of English.

For some, emojis are prompting warnings about the death of real language. Professional art critic and contrarian Jonathan Jones, writing in *The Guardian* newspaper in 2015, contended that “After millennia of painful improvement, from illiteracy to Shakespeare and beyond, humanity is rushing to throw it all away.” Emoji is, he proclaimed, a “huge step back for humanity.” His derision is clear: “Use emoji if you want to, I’ll stick to the language of Shakespeare.”

But is language really the prime mover and shaker in our everyday world of communication?

Take the quotidian, face-to-face interaction, when we gossip, pass the time of day, or otherwise engage in idle banter—on one estimate as much as 70 percent of our daily interactions are spent in this way. While

these exchanges doubtless involve language—the words that we utter, in some semblance of grammatical order—they also involve a specific mode of delivery: speech. Yet spoken language lacks the white spaces, on the written page, that help us decipher where one word begins and another ends; also absent are the punctuation marks and other niceties of the writer’s handbook, that enable us to tell how the words are being marshaled into groups of ideas: clauses and sentences.

In speech we have, instead, prosody: features of stress, pitch, volume, pauses, and accelerations and decelerations; it is these that enable us to interpret a verbal stream as comprising distinct words and intonation units. Rhythm and meter provide cues as to how information is being organized. And the rise or fall of a speaker’s intonation helps us figure out whether “You’re not from around here,” is a question, or telling us to get lost. There are other modes too: eye-gaze, facial expression, gestures, and other features of “body language.”

On one estimate, only 30–35 percent of the social dimensions of meaning, in our daily interactions with others, come from language, with up to a staggering 70 percent deriving from nonverbal cues. This includes visual cues such as the other person's body language, facial expression, and gestures, as well as how close they stand to us—we've all experienced the discomfort of the individual who occupies too much of our personal space for comfort; our emotional response is, invariably, likely to be negative. We also respond to their physical appearance, their dress, and the environment in which we encounter them, which provides information about their occupation or mode of living.

We also draw information from touch—I once knew a successful businessman who claimed to be able to tell how reliable a potential partner or client was from how they shook his hand. Grip strength, the feel of the other's palm, and the other actions associated with nothing more complex than a handshake may provide all we believe we need to make far-reaching conclusions about a potential business partnership.

But is there any truth to this anecdote? According to research, there really is: The strength of our handshake gives away telltale signs about our personality. In one of the first studies of its kind, researchers investigated the relationship between handshake strength and personality. In the study, 112 subjects shook hands with four trained coders—twice with each coder—in order to assess grip strength of the handshake. The subjects also completed assessments of personality traits. The research found that a strong handshake, across both sexes, correlates with being an extrovert and emotionally expressive. In contrast, a weak handshake tends to correlate with introversion, and being less emotionally expressive.

We also derive information from observing self-touch: Someone touching their hair might be bored, or perhaps even signaling romantic interest. And we glean information from how others manage temporal passage in our interactions with them—time between turns in an exchange—as well as eye contact, pupil dilation—especially in assessing the likelihood of potential romantic encounters—and even blink rate.

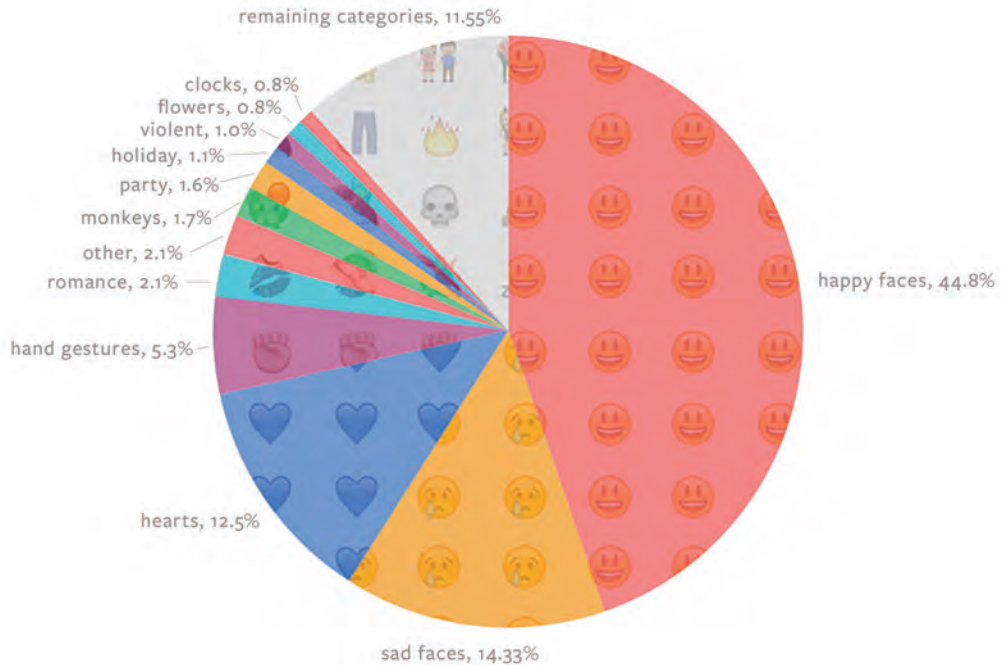
All these dimensions of nonverbal communication were studied by the late American anthropologist Ray Birdwhistell, a pioneering figure in research

Digital text alone is impoverished and, on occasion, emotionally arid.

on nonverbal communication. He founded the field of kinesics, as he dubbed it, which involved the study of the role of “facial expression, gestures, posture, and gait, and visible arm and body movements” in conveying social meaning. Based on extensive research, Birdwhistell estimated that we may be able to both produce and recognize as many as 250,000 distinct facial expressions; viewed through this lens, it is perhaps no accident that emoji, with its bewildering array of yellow faces ranging from the various permutations on a smile through to the various confused, unamused, sad, and angry faces, are so apt for visual communication in textspeak.

The other dimension of nonverbal communication involves paralinguistic features of speech, first studied by American linguist George Trager. Paralinguistics is the study of the features that accompany spoken language, a consequence of its medium of production; this can influence, and even alter, the meaning of the words we utter. Paralinguistic features, as intimated above, range from vocal signals, such as laughter, to speech prosody. Prosodic features include rhythm, relative volume, pitch, intonation, and the pitch range the voice operates in—higher for women, on average, than men.

As a significant proportion of the meaning of a communicative message in social interaction derives from nonverbal cues, it stands to reason that text alone—the linguistic mode—conveys only a relatively small proportion of the information we have access to, in spoken exchanges. There's a gaping lacuna in what digital talk, alone, can convey. Much of the information relating to emotional expression, projection of personality, the nuancing that accompanies words in spoken language, is missing. It's hardly surprising,



HAPPY TEXTING According to a 2015 survey, about 45 percent of all emojis used are some sort of happy face. In fact, the top three categories of emojis are all emotional cues—happy, sad or angry, and love.

therefore, that we can all, on occasion, fall foul of the angry jerk phenomenon: A rushed email, or a casual SMS can sound detached, snotty, or worse. It lacks the nonverbal cues that fill out and complement our face-to-face interactions. As the usual resources that allow our empathy to get off the ground are missing, we're at an immediate disadvantage in trying to put ourselves in the sender's shoes.

The rich, communicative context available in face-to-face encounters is largely absent from digital communication. Digital text alone is impoverished and, on occasion, emotionally arid. Textspeak, seemingly, possesses the power to strip all forms of nuanced expression from even the best of us. But here emoji can help: It fulfills a similar function in digital communication to gesture, body language, and intonation in spoken interaction. Emoji, in text messaging and other forms of digital communication, enables us to better express

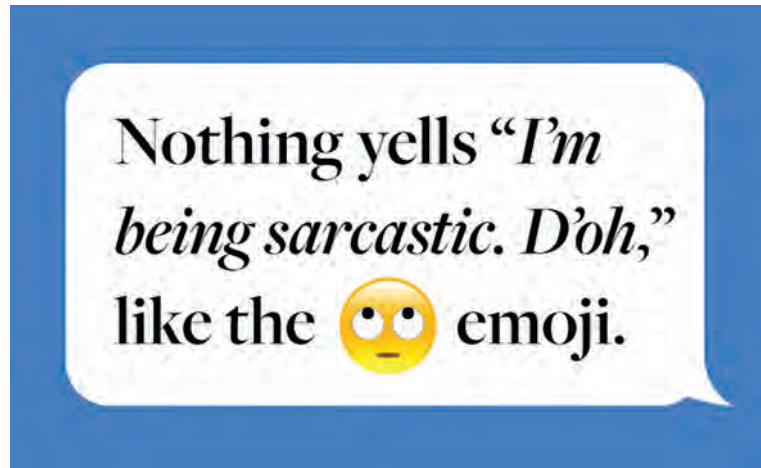
tone and provide emotional cues; and this enables us to better manage the ongoing flow of information, and to interpret what the words are meant to convey.

In fact, the idea that digital text, used alone, sucks away the nuancing has even been given its own name: Poe's law. Based on comments made originally by Nathan Poe on how to parody fundamentalist views, Poe's law is now an Internet adage, widely cited on web forums and chat rooms; it even has its own Wikipedia page. According to the British newspaper *The Daily Telegraph*, Poe's law states the following: "Without a winking smiley or other blatant display of humour, it is impossible to create a parody of fundamentalism that someone won't mistake for the real thing." In short, when poking fun in digital communication, emojis are best used for avoidance of doubt; nothing yells "I'm being sarcastic, D'oh," like the rolling eyes emoji.

IT IS NO FLUKE, therefore, that I have found, in research on emoji usage in the United Kingdom that I conducted on behalf of TalkTalk Mobile, that 72 percent of British 18- to 25-year-olds believe that emoji makes them better at expressing their feelings. Far from leading to a drop in standards, emoji is enabling people—especially the young—to become better communicators in their digital lives. The advent of emoji can be seen, from this perspective, as empowering, a force for good in 21st-century communication.

A case in point is research commissioned by the dating site Match.com in the United States. In the fifth annual Singles in America report, researchers investigated the relationship between emoji usage and sexual conquests—the first survey of its kind to do so. The survey polled over 5,600 singles—all non-Match.com subscribers—whose socio-economic and ethnic profiles were representative of the national population. And results were striking: The more emojis a singleton uses in their digital communication, the more dates they get to go on; further, the more sex they have. A striking 54 percent of those who used emoji had sex, compared with 31 percent that didn't. Even more striking: For women, emoji usage correlates with sexual satisfaction. The finding was that female singletons that use kiss-themed emojis have more orgasms than other women.

Clearly, and as any psychologist worth their salt will warn us: Correlation doesn't entail causation. Finding that two things seem to go together doesn't mean one causes the other. You can't simply start using emoji in your text messaging and expect to start being invited out on more dates (if only!). Rather, emoji usage is indicative of something else. Using emoji enables your potential date to better gauge your message: Emoji facilitates a better calibration and expression of our emotions in digital communication. Helen Fisher, a biological anthropologist at Rutgers University and Chief Scientific Advisor to Match's annual Singles in America survey, commented as follows on these



findings: “Here we have a new technology that absolutely jeopardizes your ability to express your emotion ... there is no more subtle inflection of the voice ... and so we have created another way to express emotions and that is the emoji.”

In essence, it is not emoji usage per se that gets you more dates: Rather, emoji users are more effective communicators. Their messages have more personality, and better convey the emotional intent of the text message. In turn, this leads to greater emotional resonance in the recipient.

In general terms, the predominant global usage of emoji does relate to emotions. In a survey conducted by London-based software developer, SwiftKey media, over 1 billion items of text-based data were analyzed from users spread across 16 different languages. Interestingly, the top three emoji categories all directly related to emotional expression.³ Happy faces, which include winks, kisses, smiles, and grins, accounted for 45 percent of all emoji usage. Sad faces (including angry faces) made up 14 percent of all usage. Heart emojis—of all colors, including the broken heart emoji—made up 12.5 percent of usage. Over 70 percent of emoji usage directly relates to emotional expression of some kind. This finding resonates with my own research that shows emoji to be a powerful means of expressing emotion, which, users report, enables them to better connect with others in digital communication.

While emojis can substitute for words in our digital

messages, a delicate hand is nevertheless required in how we choose to use emoji. In discussing the etiquette of emoji and dating, one 20-something, writing in *The Thought Catalog*, reports how the rush to using emoji can be as bad for your dating prospects as turning up late, or talking about your ex on the first date:

A guy once asked me out with almost nothing but emoji, which was cute and all, but I was a little turned off because what would happen when we had to rely on words instead of characters? It was a tough call: I didn't want to ruin my chance with a fun-loving and care-free guy all over a couple of symbols, but his excessive use tore apart the first impression that I had had of him. He had rushed into the emoji relationship.

Enough said! 😊

VYVYAN EVANS is an expert on language and communication. He's published 14 books on language, meaning, and mind, including *The Crucible of Language: How Language and Mind Create Meaning*. His writing has been featured in *The Guardian*, *Newsweek*, *New Scientist*, and *Psychology Today*, among other publications.

Excerpted from *The Emoji Code: The Linguistics Behind Smiley Faces and Scaredy Cats* by Vyvyan Evans, to be published on Aug. 1, 2017 by Picador. Copyright © 2017 by Vyvyan Evans. All rights reserved.

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How the Oil Pipeline Began

Pipeline fights have a longer history than you think

BY JOHNATHAN WALDMAN

SOON AFTER COLONEL EDWIN DRAKE struck oil, 70 feet down, in Titusville, Pennsylvania, on Aug. 27, 1859, he had a problem. He had nowhere to store the dark green liquid, and no good way to move it. Until then, locals had collected smaller quantities of oil from seeps and puddles and pits, by wringing it out of saturated wool blankets and scraping it off of wooden boards and collecting it in buckets, and they stored it easily in washtubs and whiskey barrels. But Drake's well produced 1,000 gallons a day, and subsequent wells produced much more. The nearest railroad was 16 miles to the north, in Corry, just shy of the New York border. The roads there, ill-maintained lumber trails, were barely passable. So, for half a decade, before the Atlantic and Great Western Railroad arrived from the east, and the Allegheny Valley Railroad arrived from Pittsburgh, Drake and the oil men who followed him—finding themselves in possession of so much oil—filled up hundreds of thousands of oak barrels, and delivered them to refineries by horse and by barge. It's hard to say which method was worse.

Behind teams of horses, men in tall rubber boots hauled one-ton loads of oil—six barrels to the wagon—south 15 miles to Oil City, where the barrels were transferred to barges on the Allegheny River. The men were teamsters. They charged \$3 to \$4 per barrel, nearly the value of each barrel's contents. The fluctuating delivery rates depended on the depth of the oily mud the teamsters had to wade through. The teamsters were numerous, and busy; in those early years, 2,000 wagons might cross one Titusville bridge in a day. They were also profane, and demanding. The journalist Ida Tarbell called them tyrants and plutocrats.

Oil Creek, the local waterway, was insufficient on its own to carry the oil and make the teamsters unnecessary. It needed enhancing. Boatmen did this by damming its tributaries, and loading barrels onto flatboats while they waited. The smallest boats held 20 barrels; the largest 1,000. Every week or so, on "freshet days," the oilmen opened the flood gates, and sent the oil forth, in exciting but perilous little torrents of water. Twenty-thousand barrels of oil made their way south.

Colliding into each other, and the shore, the boats regularly yielded their contents to the water. In a typical freshet, 1,000 or so barrels didn't survive, but still, locals celebrated gaily. Spilled oil soaked the creek, and lined its banks all the way to the Allegheny River. From there, the surviving oil barrels easily made their way, in bigger barges, down to Pittsburgh.

Whether the oil journeyed by land or by water, the coopers didn't complain. They were as busy as the teamsters. By 1870, when the region was producing a Drake's-well-worth of oil every few minutes, one cooperage in Oil City made 1,000 barrels a day. Such shops made pyramids of barrels, as tall as a few horses. Coopers came by the scores. There were more coopers making 42-gallon hooped barrels—each with a distinct company logo on the top—than there were roustabouts (or oil workers).

When the railroad finally arrived in 1862, barrels were loaded onto flat cars, only to slosh around and leak en route. Of each barrel's 42 gallons, only 40 made the trip. Beginning in 1865, the oil was dumped into specially made wooden tank cars, consisting of 2,000-gallon tubs. The modification made shipping easier, but no less dangerous; a severe fire hazard remained. One old oil man, W.H.H. Fithian, recalled in 1906, "Hardly a day passed but that somebody was not killed or injured" on the railroad. Most oil men, he wrote, called the area "The valley of the shadow of death." In 1869, big metal cylinders of equivalent volume, with baffles, replaced the wooden tanks, and before long, they doubled in capacity. Still, there was too much oil. "A man with a thousand-barrel well on his hands," Tarbell wrote, "was in a plight." Raymond Foss Bacon, in his 1916 treatise, *The American Petroleum Industry*, put it even better: "The magnitude of the petroleum industry made it necessary to find some mode of transportation even cheaper than a railroad."

The pipeline was just the thing.

THE FIRST OIL PIPELINE existed only in imagination. A West Virginian brigadier general named Samuel Karns, who'd worked for the Corps of Engineers, had a salt well in Burning Springs. When it started pumping



NO RUSH Oil out for delivery on horse-drawn wagons in Texas.

crude oil, he proposed a 6-inch pipe, 35 miles long, running downhill to the Ohio River at Parkersburg. This was in November of 1860. It was never built. A year later a man from Erie proposed building a wooden pipeline from Titusville to Oil City. It, too, was never built.

A Pennsylvania oilman named J.L. Hutchinson was the first to actually build one, in 1862. It ran over a hill, to a refinery, and worked on the principle of a siphon: as long as the outlet was lower than the inlet, liquid would flow. Except it didn't work—because the pipe was not airtight. Most people, in fact, thought pumping oil through a long metal pipe was a “visionary scheme,” its funders crazy, the endeavor certain to fail. Stitching together hundreds of pieces of metal, with nary a leak, seemed impossible.

The next summer, Hutchinson tried again, building a 2-mile line. Although it leaked, the combination of pumps and pipes worked well enough that the Humboldt Mining and Refining Company, to which the line ran, proudly claimed success. Its 1864 prospectus declares: “An oil-duct has been constructed, leading from the Tarr farm to the Humboldt refinery, with

power to convey 800 barrels of oil through it in twenty-four hours. ... The Company can now pump the oil from Oil Creek over the hills through the iron pipes ... at half the expense of former times.” *Harper's* reported on the novelty of pumping oil “in tubes.” Hutchinson's next attempt, though, failed. When he built a 3-mile line the following year, from a well to the railroad, it leaked so much it didn't matter how powerfully oil was pumped through it.

When Samuel Van Syckel proposed sinking his oil money into a 5-mile pipeline, he was ridiculed. His friends discouraged him, pitied him, and called the idea folly. Strangers made him the butt of their jokes. They'd ask, “Do you intend to put a girdle around the world?” and “Can you make water run uphill?” He was so humiliated that he ate alone, and left by the back door.

A.W. Smiley, who later worked as a timekeeper and paymaster on Van Syckel's pipeline—which succeeded—attributed the achievement to ingenuity, but also to youthful ambition and self-conceit. Really, though, it was fastidiousness. Another old pipeliner recalled,

The pipeline promised the termination of teamsters' employ. That little tube threatened their entire industry, and they fought it hard.

“it is no longer surprising that so many of the early pipe lines, which had their origin in optimism, ended their careers in bankruptcy. The real surprise is that any escaped the common fate of the many.”

When, in 1865, Van Syckel finished his line, of 2-inch pipe screwed together, from a well to the railroad, it worked. People began to notice. With three Reed & Cogswell single-piston steam pumps, his line was seven times more capacious than Hutchinson's best. It did the work of 300 teams working 10 hours a day. The Pithole Record called it a “considerable novelty” and later called it “one of the most wonderful of the many wonders.” Tarbell called the day Van Syckel's pipeline began to run the second most important event in the history of Pennsylvania's oil region, ranking it just behind the day oil was discovered. She said it began a revolution.

While the first successful—which is to say not astoundingly leaky—pipeline promised oil companies delivery rates of only \$1 per barrel, it also promised, to teamsters, the termination of their employ. That little tube threatened their entire industry, and they fought it hard. Having successfully lobbied against the wooden pipeline proposal of 1861, they put up signs around town decrying Van Syckel's pipe. Then they attacked it with pickaxes. They tied chains to it, and pulled it apart with horses. After the sheriff sent out armed deputies to guard the pipeline, Smiley and his colleagues were “threatened with transportation to a warmer clime.” The teamsters, infuriated with the way things were developing, sent a threatening anonymous letter to the head of an oil company. At 2 a.m., an armed mob

of teamsters stormed one company's tanks, and set five ablaze. Someone telegraphed the governor, asking for help. Van Syckel sent for rifles from New York. The railroaders got mad, too. Employees of the West Penn Railroad Company, sensing a threat from a pipeline that crossed their road, tore it up. The pipe was relaid, and the railroaders destroyed it again.

The pipeline men gave up, and in a nod to the teamsters they'd obviated, settled on transporting oil from the first half of their pipeline, across the railroad tracks in 25-barrel wagons, and into the second half of their pipeline. In this bipartisan fashion, they could do about 8,000 barrels a day. The teamsters eventually left town en masse. Soon enough, pipeline companies raised their prices, minimally undercutting the bids from the bygone teamsters.

THE EARLIEST PIPELINES led from wells to local refineries, and then, as John D. Rockefeller consolidated the refineries, straight to railroads. There were dozens of them, in parallel, supplied by places like the Oil Creek Tube Works. By 1872, the Pennsylvania region's 1,200 wells were producing 6 million barrels of oil a year, all of it gathered through pipelines. Soon enough, the pipelines began to compete with the railroads, and, taking a cue from Rockefeller, consolidated. Fairview Pipe Line was first to do so. It became the United Pipe Line Association, and eventually part of Standard Oil. By 1874, it had a 4-inch trunk line to Pittsburgh, 60 miles away. In 1875, the Pennsylvania Transportation Company got a charter to build a pipeline clear across the state, to the sea more than 300 miles eastward.

First, though, came pipelines to Cleveland. Then Buffalo. At last, New York, Philadelphia, Baltimore. Tide Water, though, beat the Pennsylvania Transportation Company in the race to the Atlantic, completing a 6-inch line from Bradford, Pennsylvania to the Bayonne, New Jersey refineries in 1879. By 1907, the generation following Van Syckel had built enough 6-inch and 8-inch lines to put a girdle around the world, twice.

To achieve these lengths, pipeliners figured out how far and high pumps could push oil. No single pump, or pipe, could possibly get oil across the Alleghenies alone. So they broke long routes into sections, and built storage tanks and pump stations along the way. As links make a chain, so conjoined sections made pipelines. And conjoining sections got easier as pipe manufacturers learned to consistently make good screw-threads.

Laying these 19th-century trunk lines required a big frame and a strong back. The pipe, in 18- or 20-foot sections, was hauled into the woods by horse or ox, on a wagon or sled. The pipe was heavy, as were the tools used to manipulate it. To assemble screw-coupled wrought iron pipe, a foreman banged on the end of the pipe, then another man, bucking it up, rotated it a hair with a huge wrench, called Klein tongs. The tongs

were the length of a man, and just as heavy. A bang, a turn—one, then the other. Through the woods, pipeliners buried the line in a ditch. Through wetlands, they encased it in concrete. Long days, and longer weeks, proceeded as such. Neil McElwee, the author of a small history, *The National Transit Co., Standard Oil's Great Pipeline Company*, said it was like being in the army. “Most pipeline men had an edge, a swagger, an attitude,” McElwee writes. “Pipeline men were hardworking, hard drinking rascals on their better days. Farmers liked them but sent their daughters to live with aunts in the city when the pipelines came through.” Another historian, P.C. Boyle, wrote that men accomplished “by sheer force results that now appear astonishing, and at a cost that is little short of appalling.”

After the line was assembled, buried, and filled with oil, linewalkers went out to check for leaks. In long leather coats, and high leather boots—to protect against bites from copperheads and rattlesnakes, which were “as plenty as fleas on a mangy dog”—they hunted for puddles. Discovering one, a linewalker would tap into the parallel telegraph line with a pocket relay, and notify the foreman’s office. Men and tools were requisitioned, and the pipe was dug up and fixed.



The shooter, though, had the most dangerous job. Once the torpedo had been filled, and lowered into the bottom of the well, it was his job to make it explode.

Hermit-like, linewalkers stayed in sheds along the pipeline. In the spring, many discovered that their pipelines, laid in rivers, had been taken out by floods and ice. They telegraphed for more supplies and men, who waded into frigid water and fixed the pipe. On they went, crossing rivers in rowboats that they tied to shore. In their coat pockets, they carried canned beef, hash, soup. Though they carried walking sticks, and wore hats, their job was not relaxing: If it was determined that a linewalker hadn't done his job, he could be responsible for the cost of any oil lost.

The linewalkers were not alone. Carrying brass tools, so as not to make sparks, other men kept rights-of-way clear. Carrying calibrated sticks, gaugers measured and recorded the volume of the oil in storage tanks along the line. Moving oil across the state required volumetric choreography. They checked for water in the oil, and checked the temperature of the oil, adjusting their calculations if necessary. Since these tanks were often hit by lightning, they spent much of their time putting out fires. This they did with wet carpets or sod. If that failed, they used cannon balls, aimed at the bottoms of the tanks. Once drained, a tank could easily be extinguished and repaired.

Every mile or two, inside pump stations, other men conducted the work necessary to keep oil flowing through pipelines. Firemen shoveled coal into the Woodbury & Booth 50-horsepower boilers that ran the pumps. Operators kept the boilers full of water, running at the proper pressure. Laborers maintained and repaired "Long John" engines. Station engineers, trained in hydraulics, supervised. Telegraphers sent

messages to district foremen, who sent messages to the main pipeline office. This changed the gathering of news. No longer did the reporter for the Oil City Derrick need to ride his horse from well to well, talking to pumpers and drillers. He could just visit the pipeline office, and wait for the telegraphs to come in.

Because Pennsylvania oil was light (not much wax) and sweet (not much corrosive sulfur), early pipeline operators were not especially troubled by it, at least in a maintenance sense. If necessary, they cleaned their pipelines by pumping canvas rags through them. Though well-intentioned, the efforts worked poorly. By the 1870s, a pipeline scraper—a round squeegee—was devised. Early models had leather cups; by the 1930s the cups were rubber. Pipeliners took to calling these things pigs; before that, they called them go-devils.

The origin of the term relates to another apparatus of the early oil industry. To increase production, men detonated explosives in the bottoms of their wells. The explosive of choice was nitroglycerine, in a container called a torpedo. Colonel E.A.L. Roberts, who patented the process in 1862, torpedoed a "dry hole" in 1866, and got 20 barrels a day. He did it again, and quadrupled his output. More boom meant more oil, or so the thinking went, so where he began with only four quarts of nitroglycerine in narrow tin canisters a foot long, those canisters soon grew beyond 10 feet, capable of holding more than 200 quarts.

The nitroglycerine was delivered to the well in a special wagon, skillfully driven. One man, driving a nitroglycerine wagon over a bump a few inches high, disappeared. His fragments, one writer later suggested,

would have fit in a cigar box. The shooter, though, had the most dangerous job. Once the torpedo had been filled, and lowered into the bottom of the well, it was his job to make it explode, by dropping a 10-pound cast-iron projectile onto it. The projectile was a go-devil. Well shooting, oil men wrote, sent shivers from one end of oil country to the other, and nearly blew Bradford, Pennsylvania into Cataraugus County, New York. Hence go-devil: You had to go like the devil when you dropped it.

But for the nitroglycerine, modern pipelines are not so different from the first pipelines schemed up in Pennsylvania. Most are steel, welded together, but iron pipes abound. So do pump stations and storage tanks. Dozens of companies make pipeline pigs, and now they don't just scrape pipes clean, but (using ultrasonics or magnetic flux) inspect pipes for corrosion damage, too. Through computerized systems, modern operators monitor flow rates and pressure—but the combination of man and machine leaves plenty of room for the same leaks that plagued Hutchinson. That's why linewalkers continue their work today, some in cars, but many still on foot and horseback.

Now, as then, it's one thing to build something, and quite another to maintain it. ☺

JONATHAN WALDMAN, a 2017 Alicia Patterson fellow, is working on his second book, *Sam*, about the development of an unusual robot. His first book, *Rust*, was a finalist for the Los Angeles Times Book Prize.

The Strange Similarity of Neuron and Galaxy Networks

Your life's memories could, in principle, be stored in the universe's structure

BY FRANCO VAZZA & ALBERTO FELETTI

CHRISTOF KOCH, a leading researcher on consciousness and the human brain, has famously called the brain “the most complex object in the known universe.” It’s not hard to see why this might be true. With a hundred billion neurons and a hundred trillion connections, the brain is a dizzyingly complex object.

But there are plenty of other complicated objects in the universe. For example, galaxies can group into enormous structures (called clusters, superclusters, and filaments) that stretch for hundreds of millions of light-years. The boundary between these structures and neighboring stretches of empty space called cosmic voids can be extremely complex.¹ Gravity accelerates matter at these boundaries to speeds of thousands of kilometers per second, creating shock waves and turbulence in intergalactic gases. We have predicted that the void-filament boundary is one of the most complex volumes of the universe, as measured by the number of bits of information it takes to describe it.

This got us to thinking: Is it more complex than the brain?

So we—an astrophysicist and a neuroscientist—joined forces to quantitatively compare the complexity of galaxy networks and neuronal networks. The first results from our comparison are truly surprising: Not only are the complexities of the brain and cosmic web actually similar, but so are their structures. The universe may be self-similar across scales that differ in size by a factor of a billion billion billion.

THE TASK OF COMPARING BRAINS and clusters of galaxies is a difficult one. For one thing it requires dealing with data obtained in drastically different ways: telescopes and numerical simulations on the one hand, electron microscopy, immunohistochemistry, and functional magnetic resonance on the other.

It also requires us to consider enormously different scales: The entirety of the cosmic web—the large-scale structure traced out by all of the universe’s



galaxies—extends over at least a few tens of billions of light-years. This is 27 orders of magnitude larger than the human brain. Plus, one of these galaxies is home to billions of actual brains. If the cosmic web is at least as complex as any of its constituent parts, we might naively conclude that it must be at least as complex as the brain.

But the concept of emergence makes the comparison possible. Many natural phenomena are not equally complex at all scales. The majestic network of the cosmic web becomes evident only when the sky is surveyed over its largest extent. On smaller scales, with matter locked into stars, planets, and (probably) dark matter clouds, this structure is lost. An evolving galaxy does not care about the dance of electron orbitals within atoms, and electrons move around their nuclei without regard to the galactic system they reside in.

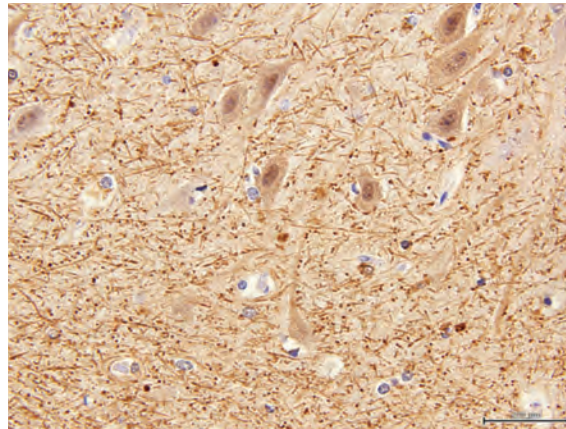
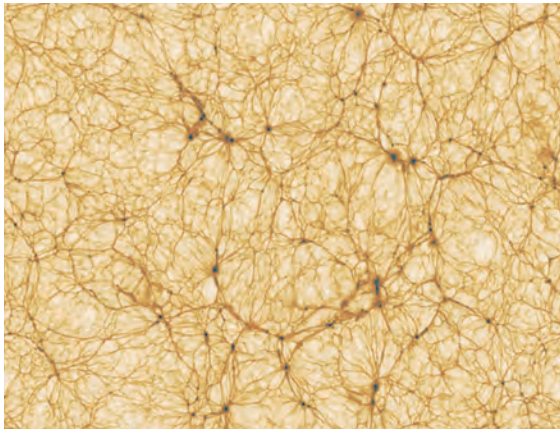
In this way, the universe contains many systems nested into systems, with little to no interaction across different scales. This scale segregation allows us to study physical phenomena as they emerge at their own natural scales.

THE BUILDING BLOCKS of the cosmic web are the self-gravitating halos of stars, gas, and dark matter (whose existence has yet to be definitively proved). In total,

the number of galaxies within the observable universe should be on the order of 100 billion. The balance between the accelerating expansion of the fabric of spacetime and the pull of self-gravity gives this network its spider-web-like pattern. Ordinary and dark matter condense into string-like filaments, and clusters of galaxies form at filament intersections, leaving most of the remaining volume basically empty. The resulting structure looks vaguely biological.

A direct estimate of the number of cells or neurons in the human brain was not available in the literature until recently. Cortical gray matter (representing over 80 percent of brain mass) contains about 6 billion neurons (19 percent of brain neurons) and nearly 9 billion non-neuronal cells. The cerebellum has about 69 billion neurons (80.2 percent of brain neurons) and about 16 billion non-neuronal cells. Interestingly enough, the total number of neurons in the human brain falls in the same ballpark of the number of galaxies in the observable universe.

The eye immediately grasps some similarity between images of the cosmic web and the brain. In Figure 1 we show a simulated distribution of cosmic matter in a slice 1 billion light-years across, along with a real image of a 4 micrometers (μm)-thick slice through the human cerebellum.



LOOKALIKES (FIGURE 1) A simulated matter distribution of the cosmic web (left) vs the observed distribution of neuronal bodies in the cerebellum (right). The neuronal bodies have been stained with clone 2F11 monoclonal antibody against neurofilaments.

The cosmic web is more similar to the human brain than it is to the interior of a galaxy.

Is the apparent similarity just the human tendency to perceive meaningful patterns in random data (apophenia)? Remarkably enough, the answer seems to be no: Statistical analysis shows these systems do indeed present quantitative similarities. Researchers regularly use a technique called power spectrum analysis to study the large-scale distribution of galaxies. The power spectrum of an image measures the strength of structural fluctuations belonging to a specific spatial scale. In other words, it tells us how many high-frequency and low-frequency notes make the peculiar spatial melody of each image.

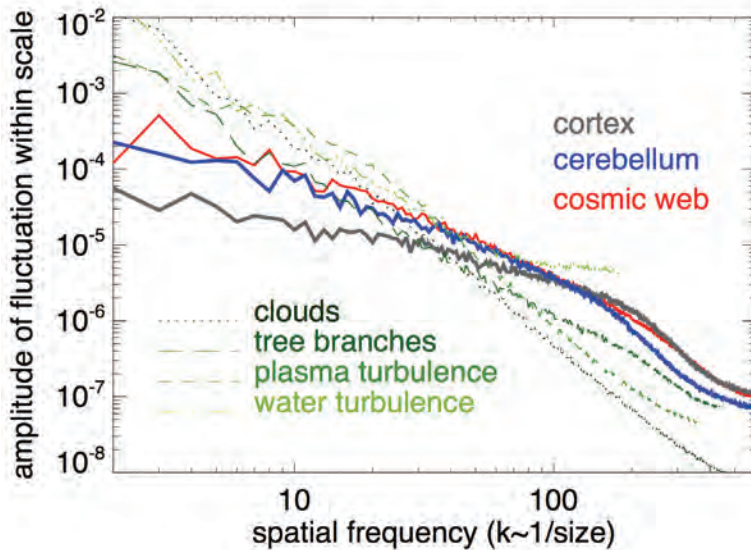
A stunning message emerges from the power spectrum graph on page 52: The relative distribution of fluctuations in the two networks is remarkably similar, over several orders of magnitude.

The distribution of fluctuations in the cerebellum at 0.1-1 mm scales is reminiscent of the galaxy distribution on hundreds of billions of light-years. At the smallest scales available to microscopic observation (about 10 μm), it is the morphology of the cortex that more

closely matches the one of galaxies, on scales of a few hundreds of thousands of light-years.

By comparison, the power spectra of other complex systems (including projected images of clouds, tree branches, and plasma and water turbulence) are quite dissimilar from that of the cosmic web. The power spectra of these other systems display a steeper dependence on scale, which may be a manifestation of their fractal nature. This is particularly striking for the distribution of branches in trees and in the pattern of clouds, both of which are well known for being fractal-like systems with self-similarity across a large variety of scales. For the complex networks of the cosmic web and of the human brain, on the other hand, the observed behavior is not fractal, which can be interpreted as evidence of the emergence of scale-dependent, self-organized structures.

As remarkable as the power spectrum comparison is, it doesn't tell us whether the two systems are equally complex. A practical way of estimating the complexity of a network is to measure how difficult it is to



FINGERPRINTS (FIGURE 2)

Distribution of fluctuations as a function of spatial scale for the same maps of Fig 1 (with the additional analysis of a thin slice through the human cortex, not shown in Fig 1). For comparison, the power spectral density of clouds, tree branches, and plasma and water turbulence are shown.

predict its behavior. This can be quantified by counting how many bits of information are necessary for building the smallest possible computer program that can perform such a prediction.

One of us has recently measured how difficult it is to predict how the cosmic network evolves, based on the digital evolution of a simulated universe.¹ This estimate suggests that about 1 to 10 petabytes of data are needed to describe the evolution of the entire observable universe at the scale where its self-organization emerges (or at least of its simulated counterpart).

Estimating the complexity of the human brain is much more difficult, because global simulations of the brain remain an unmet challenge. However, we can argue that complexity is proportional to intelligence and cognition. Based on the latest analysis of the connectivity of the brain network, independent studies have concluded that the total memory capacity of the adult human brain should be around 2.5 petabytes, not far from the 1-10 petabyte range estimated for the cosmic web!

Roughly speaking, this similarity in memory capacity means that the entire body of information that is stored in a human brain (for instance, the entire life

experience of a person) can also be encoded into the distribution of galaxies in our universe. Or, conversely, that a computing device with the memory capacity of the human brain can reproduce the complexity displayed by the universe at its largest scales.

IT IS TRULY A REMARKABLE FACT that the cosmic web is more similar to the human brain than it is to the interior of a galaxy; or that the neuronal network is more similar to the cosmic web than it is to the interior of a neuronal body. Despite extraordinary differences in substrate, physical mechanisms, and size, the human neuronal network and the cosmic web of galaxies, when considered with the tools of information theory, are strikingly similar.

Does this fact tell us something profound about the physics of emergent phenomena in the two systems? Maybe. But we must take these findings with a grain of salt. Our analysis has been limited to small samples taken with very different measurement techniques.

Also, our analysis doesn't point to a dynamical similarity among these systems. A model of how information flows across spatial scales and time in the two systems will be the crucial test. This is already feasible

for the cosmic web through numerical simulations. For the human brain we have to rely on more global estimates, usually derived from smaller portions that are then scaled upward. In the near future we aim at testing these concepts in more sophisticated numerical models of the human brain.

Programs like the Human Brain Project, designed to simulate an entire human neuronal network, and the Square Kilometer Array, the biggest enterprise ever in radio astronomy, will help us fill in some of these details and understand whether the universe is even more surprising than we thought. ☺

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We gratefully acknowledge Dr. Elena Zunarelli (Department of Anatomic Pathology, University Hospital Policlinico di Modena, Modena, Italy) for producing the slices through the cortex and cerebellum of Figure 1.

REFERENCE

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51

THERE ARE THE LIMITS that we beat fair and square. The speed of sound, which toppled about a decade after we set our sights on it. The resolution limit of an optical microscope, beaten by switching from photons to electrons.

Then there are the limits that are formally unbeatable: things like the speed of light and quantum indeterminacy. They're interesting because they describe an unexpected border between the philosophical and technological. And because we are still trying to beat them.

If an object can squeeze and stretch the spacetime around itself, it can effectively travel faster than the speed of light without doing it locally. Quantum uncertainty can be shuffled and hidden, yielding high-precision measurements without breaking any laws.

The physicist Murray Gell-Mann once repurposed a novelist's phrase to describe physics: "Everything not forbidden is compulsory." Today he might have added a corollary—everything forbidden is worth a second look.

Welcome to "Limits."

—MS

"It's the question at the heart of modern conservation: Can ecologists build a new ecosystem that will survive?"

MADELINE GRESSEL

"Reinventing Staten Island" p.74

Limits

IMAGINING THE POSSIBLE



Where the Wild Things Go

The remarkable travel itineraries of animals

BY OLIVER UBERTI

Elephants

When I sat down with Iain Douglas-Hamilton at his home in Nairobi to learn how he went from deploying the first radio collars on elephants in 1968 to deploying the first GPS collars on them in 1995, he told me about an elephant named Parsitau. “We put a prototype on him and it lasted for all of 10 days, and we thought this was absolutely the cat’s whiskers.”

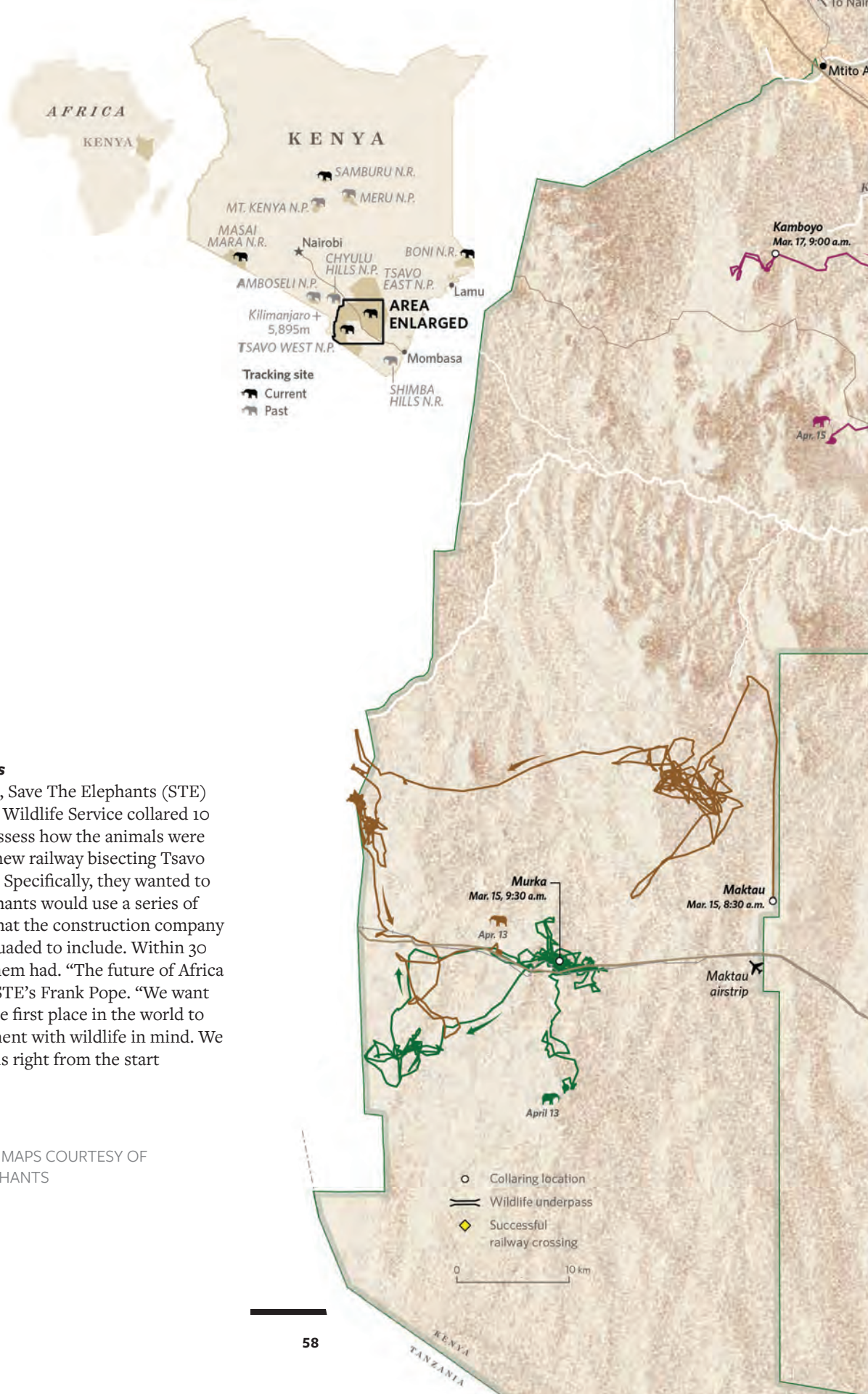
Recording four locations per day, those 40 GPS points were the first ever recorded on an animal in Africa. “It was so incredible,” Douglas-Hamilton recalled. “Here was a collar that would go across international borders, work by day, by night, inside forest, outside forest, up hills, down hills.” Plus, GPS was far more precise than radio or traditional Argos satellite tracking.

Today, the breakthroughs are still coming. Just a few years ago, Douglas-Hamilton’s research and conservation organization, Save The Elephants, partnered with Google to develop a way for GPS locations to feed

directly into Google Earth. And they have since created their own real-time tracking app for phones and tablets in partnership with Microsoft co-founder Paul Allen and his company, Vulcan.

Douglas-Hamilton was reviewing the latest collar data from Tsavo on his laptop one of the nights we met. “We haven’t had these collars on for three days,” he said, “and two of the elephants have already crossed the railway. I nearly died when I saw this! There’s Manyani. She was collared up there, streaked down, crossed, and fled to safety. And guess where safety was?” Douglas-Hamilton pointed to a building beside the road. “This is the main Kenya Wildlife Service ranger training station. Look, she’s within 500 meters of it. She’s found the human beings she likes. That’s hot stuff from the horse’s mouth.”

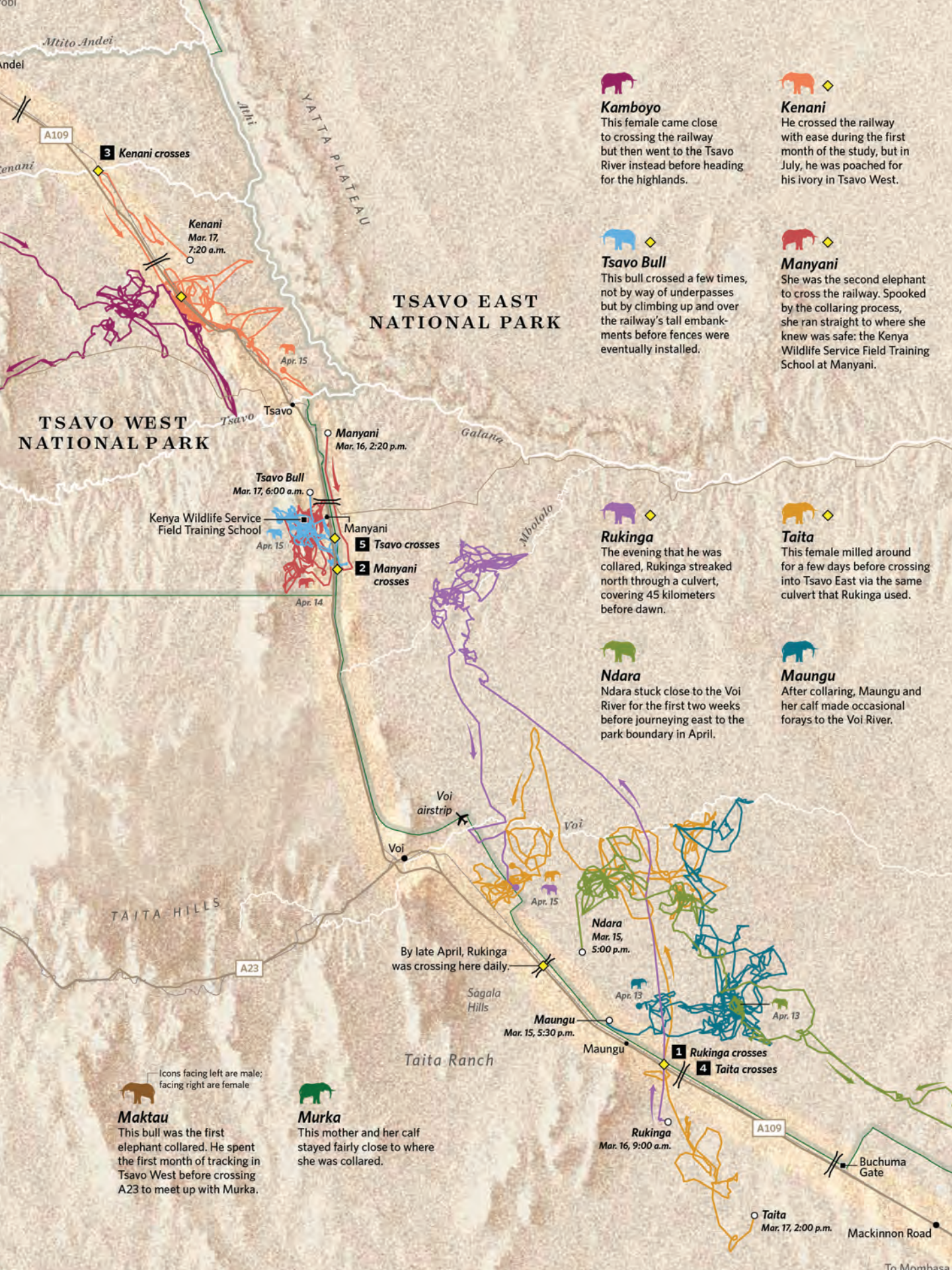
Save The Elephants currently has more than 300 active collars across eight African countries. New stories appear in the tracks every day.



Early Adopters

In March 2016, Save The Elephants (STE) and the Kenya Wildlife Service collared 10 elephants to assess how the animals were adapting to a new railway bisecting Tsavo National Park. Specifically, they wanted to see if the elephants would use a series of underpasses that the construction company had been persuaded to include. Within 30 days, half of them had. “The future of Africa is here,” says STE’s Frank Pope. “We want Kenya to be the first place in the world to plan development with wildlife in mind. We want to get this right from the start

ALL ELEPHANT MAPS COURTESY OF
SAVE THE ELEPHANTS



Kamboyo

This female came close to crossing the railway but then went to the Tsavo River instead before heading for the highlands.



Kenani

He crossed the railway with ease during the first month of the study, but in July, he was poached for his ivory in Tsavo West.



Tsavo Bull

This bull crossed a few times, not by way of underpasses but by climbing up and over the railway's tall embankments before fences were eventually installed.



Manyani

She was the second elephant to cross the railway. Spooked by the collaring process, she ran straight to where she knew was safe: the Kenya Wildlife Service Field Training School at Manyani.



Rukinga

The evening that he was collared, Rukinga streaked north through a culvert, covering 45 kilometers before dawn.



Taita

This female milled around for a few days before crossing into Tsavo East via the same culvert that Rukinga used.



Ndara

Ndara stuck close to the Voi River for the first two weeks before journeying east to the park boundary in April.



Maungu

After collaring, Maungu and her calf made occasional forays to the Voi River.



Maktau

This bull was the first elephant collared. He spent the first month of tracking in Tsavo West before crossing A23 to meet up with Murka.

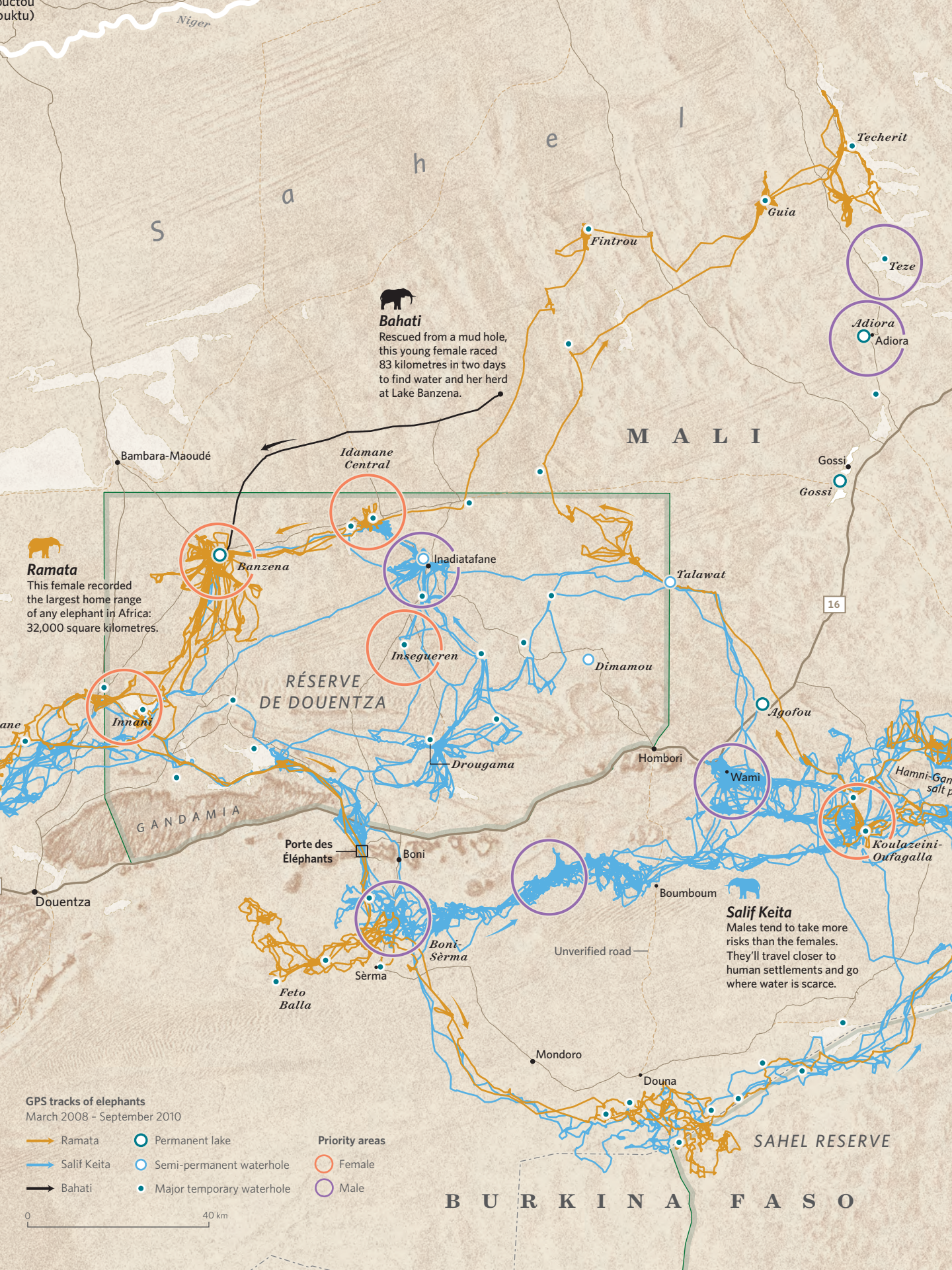


Murka

This mother and her calf stayed fairly close to where she was collared.

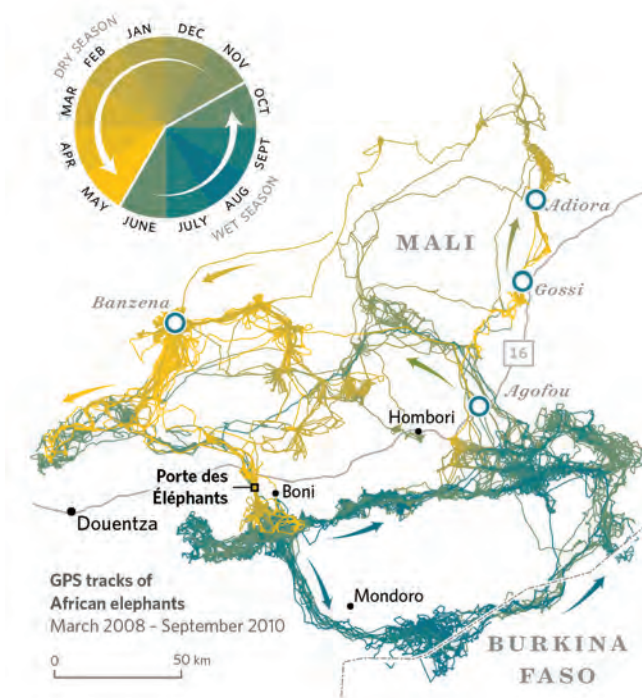
Icons facing left are male; facing right are female

By late April, Rukinga was crossing here daily



Search Technology

In 2008, STE deployed GPS collars on nine elephants in southern Mali. On the opposite page we show two individuals making their annual counter-clockwise migration in search of food and water. The researchers hope to protect 11 areas (circled) crucial to the elephants' survival.



At the end of the dry season in May, temperatures in this region can exceed 50 degrees Celsius. Shallow lakes dry up. The herds cling to Lake Banzena until the June rains permit them to move on to forage farther south.

What Is Safe?

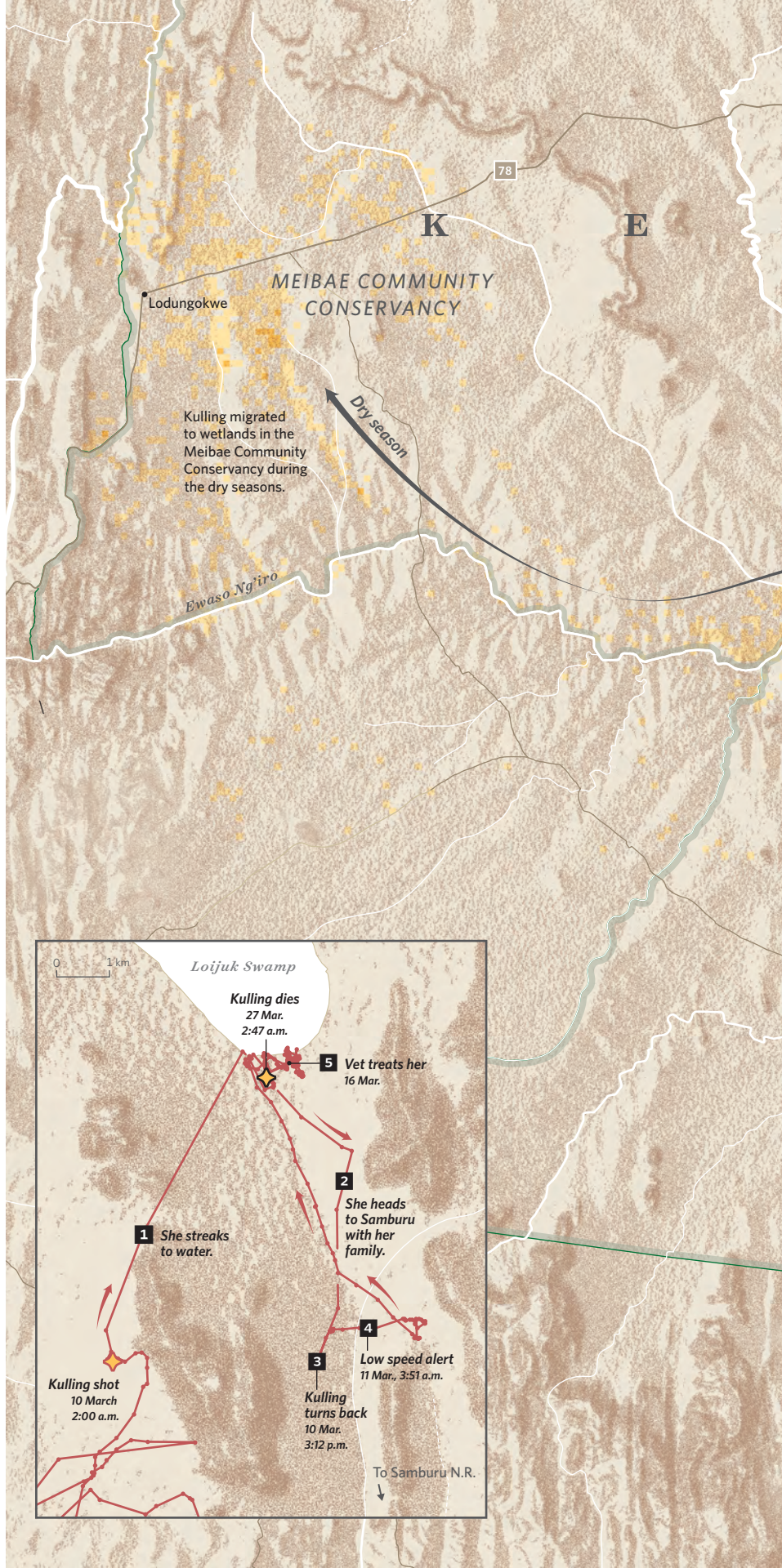
In 2011 and 2012, more than 30 elephants were poached in the regions south of Samburu in a span of three months. Kulling's family was almost certainly aware of these dangers and took evasive action to the northwest, where there was water in the dry season and relative security.

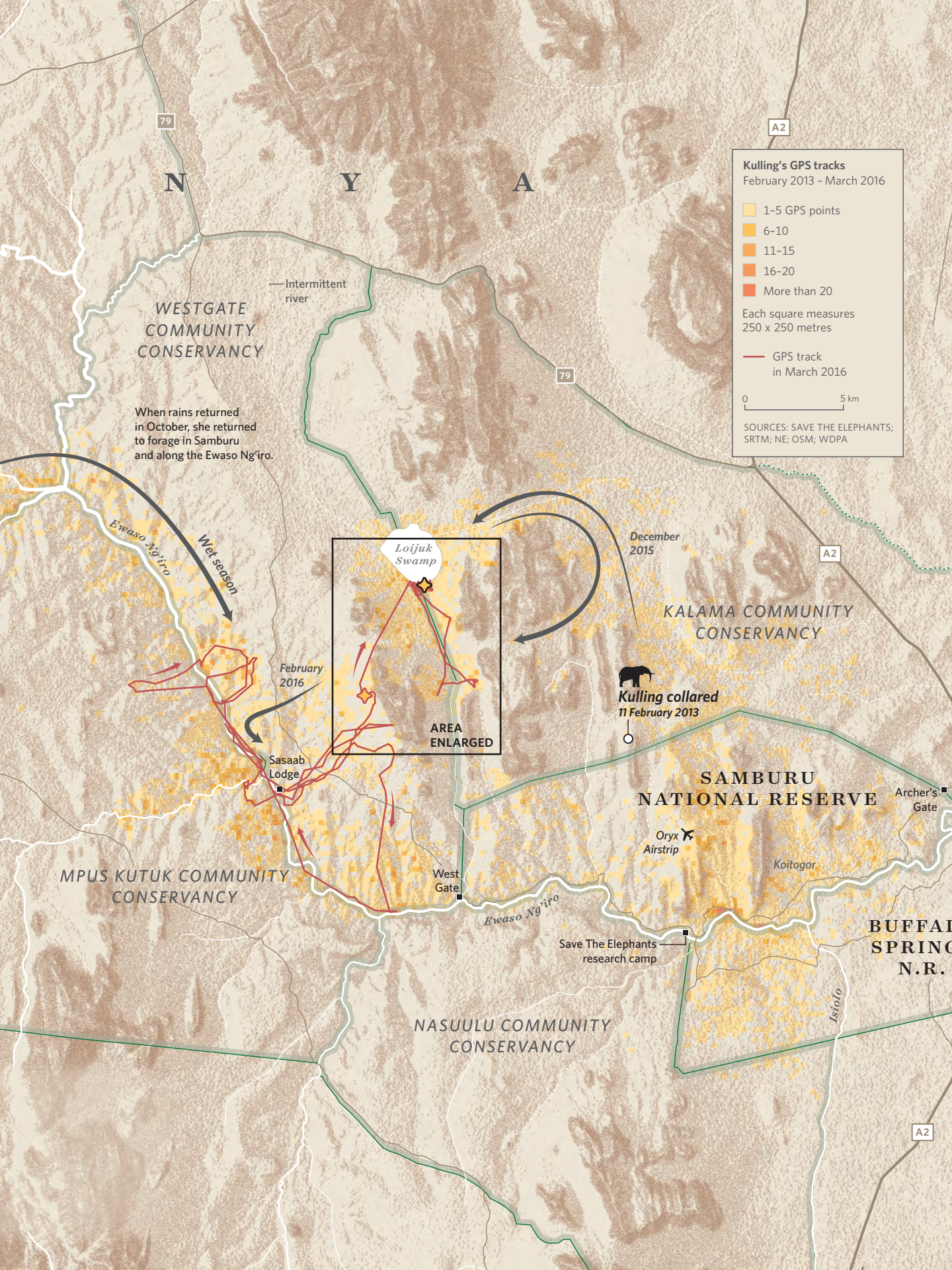
Kulling's Last Days

The elephants of Samburu spend more than half the year outside the reserve boundaries. In the box on this page, we show where an elephant named Kulling spent the last three years of her life. Some of her favorite areas included Loijuk Swamp and various spots along the Ewaso Ng'iro River.

In early 2016, Kulling was shot by nomadic herders. Loijuk Swamp had water for the first time in 10 years, drawing both wild elephants and the young herders, who had brought their livestock to drink. The elephants scared them, so they shot, hitting and killing Kulling.

STE thinks education is key to resolving human-animal conflict. A few weeks after Kulling died, STE met with herders and elders from the Loijuk community to share a meal and recall the old ways of living in peace with elephants.





Turtles

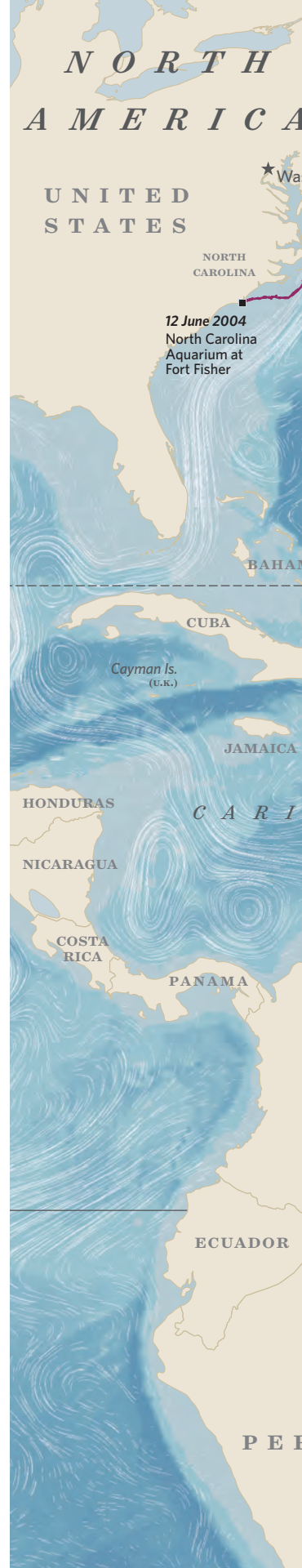
“My god, there’s a lot of turtles on here,” said Lucy Hawkes, a member of the Marine Turtle Research Group at the University of Exeter. She was scrolling through a database of their active tracking projects: “We’ve got Ascension, North Carolina, British Virgin Islands, Cape Verde, Cayman Islands, Mexico, Cyprus, Dominican Republic, Equatorial Guinea, Gabon, Israel, Kuwait, Lampedusa—that’s Italy—Mozambique, Guadalupe, Montserrat, Oman, Peru, [she takes a breath] Scotland, Turkey, Sri Lanka, and Greece.” Total number of tags deployed: 443 and counting.

One of her first traveled on a loggerhead turtle named Fisher. In 1995, biologists from the North Carolina Aquarium at Fort Fisher found him on a nearby beach. He was weak and underweight, so they brought him to the aquarium’s rehabilitation center. Eight years later, Fisher was 40 kilograms and outgrowing his adoptive home.

His caretakers loaned him to Newport Aquarium in Kentucky for an exhibit presciently titled *Turtles: Journey of Survival*. By his 10th birthday, Fisher tipped the scales at 70 kilograms. He was ready to hunt in the wild. On June 12, 2004, Hawkes stuck a tag on Fisher’s shell and released him into the Atlantic. She expected him to ride the Gulf Stream to Spain.

But Fisher had other plans. “He did a straight line to Cape Verde,” Hawkes said, “which, bizarrely, is exactly where he should be at 10 years old. It was as if he thought, ‘I’ve got to catch up with everyone.’” Imagine that. After 10 years in captivity, Fisher knew where he needed to be, at what time, and how to get there.

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North Carolina

June 2004 - June 2005

Instead of using the Gulf Stream and other currents to circle the Atlantic, Fisher cut straight across, logging 11,600 kilometres in 350 days.

U
21 Apr. 2010 -
16 Mar. 2012

P
1 Apr. - 11 July 2009

T
25 October 2009 -
22 March 2010

After this study ended, T's tag appeared on land in St. Lucia. Varo-Cruz fears T may have been hooked and eaten.

Satellite tracks of sea turtles
2004-2013

○ Nesting beach

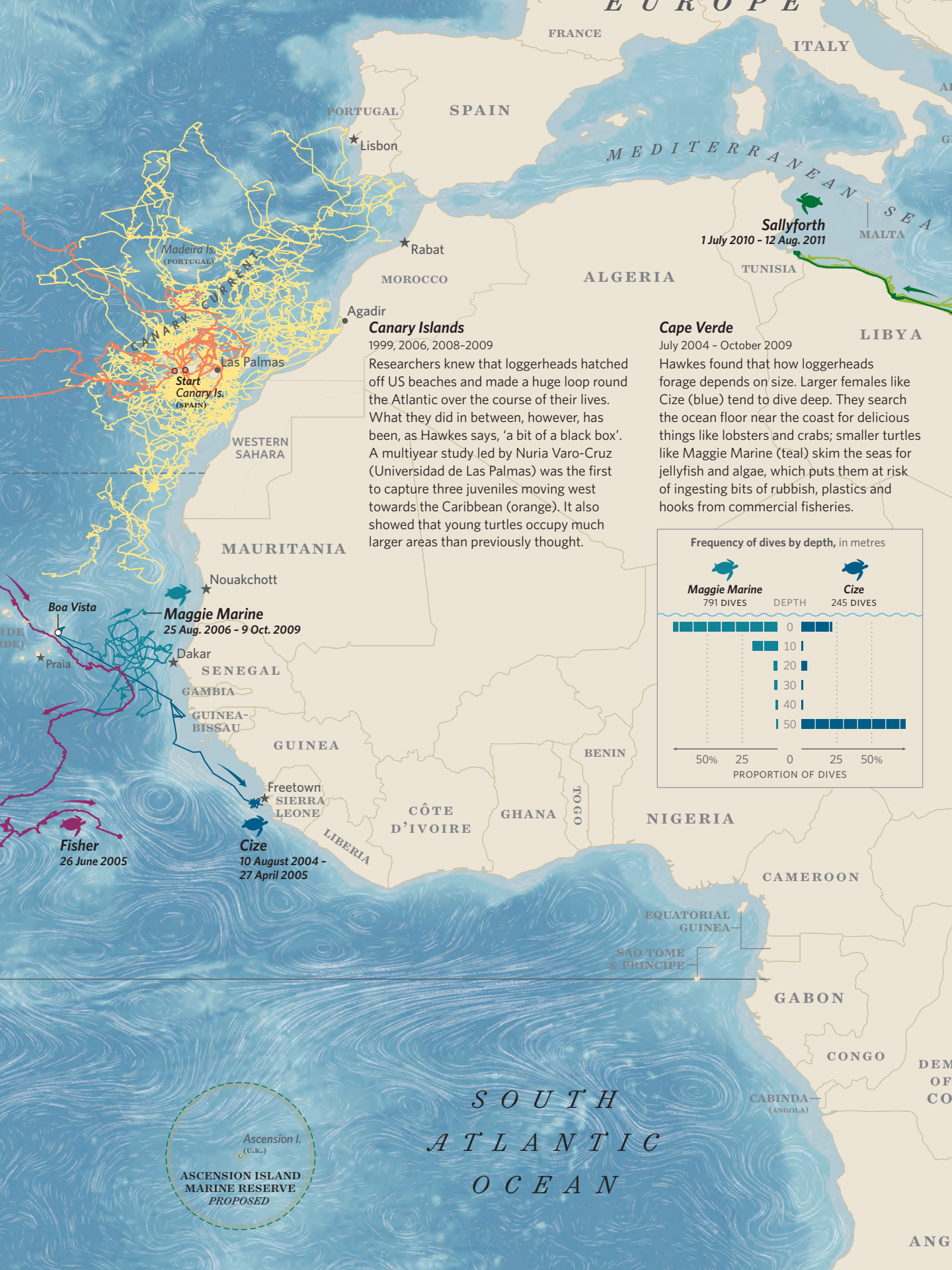
0 1,000 km
Scale at the Equator

SOURCES: LUCY HAWKES, UNIVERSITY OF EXETER; GRAEME HAYS, DEAKIN UNIVERSITY (CHAGOS); NURIA VARO-CRUZ, UNIVERSIDAD DE LAS PALMAS (CANARY ISLANDS); ANNETTE BRODERICK AND BRENDAN GODLEY, UNIVERSITY OF EXETER (CYPRUS); GEBCO; GSHHG; NE; GADM

White lines and swirls show average ocean currents for November. Researchers model their speed and direction to predict how turtles will move across the seas.

Recife

COSTA DO
ENVIRON
PROTECT



Canary Islands

1999, 2006, 2008–2009

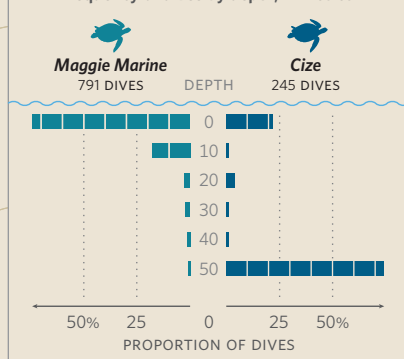
Researchers knew that loggerheads hatched off US beaches and made a huge loop round the Atlantic over the course of their lives. What they did in between, however, has been, as Hawkes says, 'a bit of a black box'. A multiyear study led by Nuria Varo-Cruz (Universidad de Las Palmas) was the first to capture three juveniles moving west towards the Caribbean (orange). It also showed that young turtles occupy much larger areas than previously thought.

Cape Verde

July 2004 – October 2009

Hawkes found that how loggerheads forage depends on size. Larger females like Cize (blue) tend to dive deep. They search the ocean floor near the coast for delicious things like lobsters and crabs; smaller turtles like Maggie Marine (teal) skim the seas for jellyfish and algae, which puts them at risk of ingesting bits of rubbish, plastics and hooks from commercial fisheries.

Frequency of dives by depth, in metres





A Sea of Parks?

Archie Carr, one of the pioneers of sea turtle tracking, defined a tenet of movement ecology: to protect animals you need to protect where they go. Using low-tech flipper tags, he proved that green turtles nesting on Ascension Island swam due west to Brazil to forage in 1962. Those two spots encompass most of their adult lives, and soon, both will be Marine Protected Areas (MPAs). Elsewhere in the world, sea turtles aren't as lucky. Six of the seven species are endangered or vulnerable. One solution: smaller but highly targeted MPAs. Another: dynamic reserves that kick in when turtles arrive in their seasonal ranges—protection that moves with the turtles.

Cyprus

July 2003 – November 2015
To monitor breeding populations, Matthew Witt (University of Exeter) and his colleagues have been tagging green turtles at their nesting grounds in Cyprus. As soon as the turtles leave the island, they swim straight for the Lebanese or Libyan coast and then head west to forage.

Chagos Archipelago

October – December 2012
At 640,000 km², Chagos is the world's largest Marine Protected Area, but it's nowhere close to big enough. When Graeme Hays and his team at Australia's Deakin University began tracking green turtles here, seven of the first eight turtles left the MPA to forage far away. Two set a new turtle record, swimming 3,900 kilometres to the Somali coast. That's like swimming from New York to Los Angeles.

#61811
13 Oct. – 19 Dec. 2012

#61813
13 Oct. – 8 Dec. 2012



Emotional Intelligence Needs a Rewrite

Think you can read people's emotions? Think again.

BY LISA FELDMAN BARRETT

YOU'VE PROBABLY MET PEOPLE who are experts at mastering their emotions and understanding the emotions of others. When all hell breaks loose, somehow these individuals remain calm. They know what to say and do when their boss is moody or their lover is upset. It's no wonder that emotional intelligence was heralded as the next big thing in business success, potentially more important than IQ, when Daniel Goleman's bestselling book, *Emotional Intelligence*, arrived in 1995. After all, whom would you rather work with—someone who can identify and respond to your feelings, or someone who has no clue? Whom would you rather date?

The traditional foundation of emotional intelligence rests on two common-sense assumptions. The first is that it's possible to detect the emotions of other people accurately. That is, the human face and body are said to broadcast happiness, sadness, anger, fear, and other emotions, and if you observe closely enough, you can read these emotions like words on a page. The

second assumption is that emotions are automatically triggered by events in the world, and you can learn to control them through rationality. This idea is one of the most cherished beliefs in Western civilization. For example, in many legal systems, there's a distinction between a crime of passion, where your emotions allegedly hijacked your good sense, and a premeditated crime that involved rational planning. In economics, nearly every popular model of investor behavior separates emotion and cognition.

These two core assumptions are strongly appealing and match our daily experiences. Nevertheless, neither one stands up to scientific scrutiny in the age of neuroscience. Copious research, from my lab and others, shows that faces and bodies alone do not communicate any specific emotion in any consistent manner. In addition, we now know that the brain doesn't have separate processes for emotion and cognition, and therefore one cannot control the other. If these statements defy your common sense, I'm right there with you. But our

PHOTO COLLAGE BY JESSICA LIN

experiences of emotion, no matter how compelling, don't reflect the biology of what's happening inside us. Our traditional understanding and practice of emotional intelligence badly needs a tuneup.

Let's begin with the assumption that you can detect emotion in another person accurately. On the surface, it seems reasonable enough. A glance at someone's face and body language reveals what the person is feeling, right? Haven't we been told that a smile tells one story whereas a scowl tells another? Raised arms and a puffed up chest supposedly display pride, while a drooping posture supposedly declares that someone is sad.

The big problem with this assumption is that in real life, faces and bodies don't move in this cartoonish fashion. People who are happy sometimes smile and sometimes don't. Sometimes they even cry when they're happy (say, at a wedding) and smile when they're sad (when missing a beloved aunt who passed away). Likewise, a scowling person might be angry or just thinking hard, or even have a case of indigestion. In fact, there isn't a single emotion that has one specific, consistent expression.

Numerous scientific studies have confirmed these observations. When we place electrodes on people's faces to record their muscle movements, we see that they move in different ways, not one consistent way, when their owners feel the same emotion. Where the body is concerned, hundreds of studies show that instances of the same emotion involve different heart rates, breathing, blood pressure, sweat, and other factors, rather than a single, consistent response. Even in the brain, we see that instances of a single emotion, such as fear, are handled by different brain patterns at different times, both in the same individual and in different people. This diversity isn't random. It's tied to the situation you're in.

In short, when it comes to detecting emotion in other people, the face and body do not speak for themselves. Instead, variation is the norm. Your brain may automatically make sense of someone's movements in context, allowing you to guess what a person is feeling, but you are always guessing, never detecting. Now, I might know my husband well enough to tell when his

When it comes to “detecting” emotion in other people, the face and body do not speak for themselves.

scowl means he's puzzling something out versus when I should head for the hills, but that's because I've had years of experience learning what his facial movements mean in different situations. People's movements in general, however, are tremendously variable. To teach emotional intelligence in a modern fashion, we need to acknowledge this variation and make sure your brain is well-equipped to make sense of it automatically.

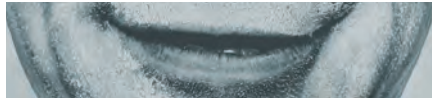
The second flawed assumption is we control emotions by rational thought. Emotions are often seen as an inner beast that needs taming by cognitive effort. This idea, however, is rooted in a bogus view of brain evolution. Books and articles on emotional intelligence claim that your brain has an inner core that you inherited from reptiles, wrapped in a wild, emotional layer that you inherited from mammals, all enrobed in—and controlled by—a logical layer that is uniquely human. This three-layer view, called the triune brain, has been popular since the 1950s but has no basis in reality. Brains did not evolve in layers. Brains are like companies—they reorganize as they grow in size. The difference between your brain and, say, a chimp or monkey brain has nothing to do with layering and everything to do with microscopic wiring. Decades of neuroscience research now show that no part of your brain is exclusively dedicated to thoughts or emotions. Both are produced by your entire brain as billions of neurons work together.

Even though the triune brain is a complete fiction, it's had an outstanding public relations campaign. Today, decades after the triune brain was dismissed by experts in brain evolution, people still use phrases



like “lizard brain,” and believe that emotions are tiny brain circuits that fire uncontrollably when faced with the right trigger, and that, at some deep, biological level, cognition and emotion are locked in battle. After all, that’s how many of us in Western cultures experience our emotional life, as if our emotional side wants to do impulsive things but our cognitive side tamps down the urges. These compelling experiences—of being emotionally out of control and rationally in control—do not reveal their underlying mechanisms in the brain. To improve our understanding of emotional intelligence, we must discard the idea of the brain as a battlefield.

A reasonable, science-backed way to define and practice emotional intelligence comes from a modern, neuroscientific view of brain function called construction: the observation that your brain creates all thoughts, emotions, and perceptions, automatically and on the fly, as needed. This process is completely unconscious. It may seem like you have reflex-like emotional reactions and effortlessly detect emotions in other people, but under the hood, your brain is doing something else entirely.



Here’s the 20,000 foot summary: Your brain’s most important job is not thinking or feeling or even seeing, but keeping your body alive and well so that you survive and thrive (and eventually reproduce). How is your brain to do this? Like a sophisticated fortune-teller, your brain constantly predicts. Its predictions ultimately become the emotions you experience and the expressions you perceive in other people.

YOUR BRAIN SPENDS its entire existence in a dark silent box, called your skull. It receives only the sensory effects of what is going on in the world—the sights, sounds, smells, touches, and tastes that come through the body’s sensors—and must guess what their causes are, because any sound or flash of light or aroma or pinch can have many different causes. To make these guesses, your brain relies on past experience: What caused these sensations before in similar contexts? What worked to keep you alive and well and might be needed again? Your brain has the amazing ability to combine bits of past experience to create the closest

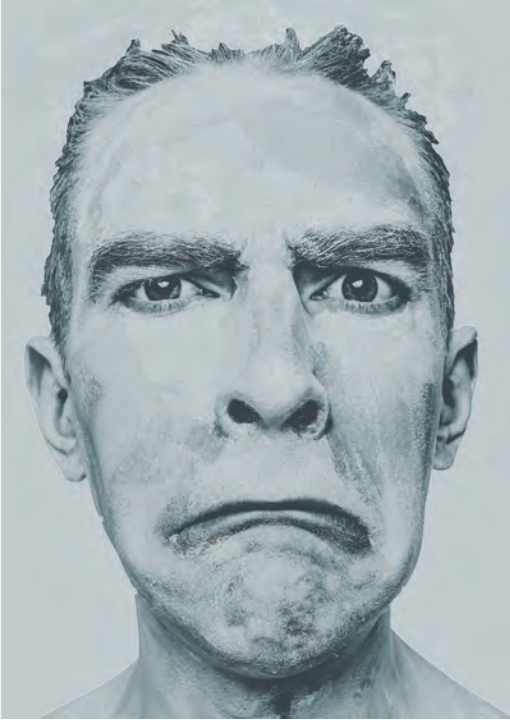
match to these sensations, given the specific situation that you are in. These past experiences are predictions. Your brain continually predicts every experience you have, and every action you take, to guess what is going on in the world and what you should do about it.

From your brain’s perspective, your body is just another source of information to make sense of—the thumping of your heart, the tug of your lungs expanding, the warmth of inflammation, and so on. These changes in your body have no objective emotional meaning. A dull ache in your stomach, for example, might be disgust, anxiety, or merely hunger. So, your brain spends most of its time issuing thousands of microscopic predictions of what your body needs (water, glucose, salt) and attempts to meet those needs before they arise. In the process, your brain also predicts the sensations that those physical changes would cause, such as feeling your heart pound in your chest, as well as what actions you should take. This constant

storm of predictions—which occur automatically and completely outside of your awareness—forms the basis for everything you think, feel, see, smell, or otherwise experience in any way. That’s how emotions, thoughts, and perceptions are made.

Emotional intelligence, therefore, requires a brain that can use prediction to manufacture a large, flexible array of different emotions. If you’re in a tricky situation that has called for emotion in the past, your brain will oblige by constructing the emotion that works best. You will be more effective if your brain has many options to choose from. If your brain can only make stereotypic instances of smiley happiness and pouty sadness, then that is all you will experience and perceive in others. But if your brain is equipped to make you scowl in anger, smile in anger, widen your eyes in anger, squint in anger, shout in anger, stew silently in anger, and even bond with others over anger, then your brain can more finely tailor your emotions and behavior to the situation. In other words, you have better tools to be emotionally intelligent.

This ability is called emotional granularity, and my students and I discovered it about 20 years ago. We asked hundreds of test subjects to record their emotions throughout the day on handheld computing



devices (in the pre-smartphone days). From the data, we found that people use the same emotion words, but not necessarily to mean the same thing. For example, some people use words like “angry,” “fearful,” and “sad” to refer to completely different experiences, while others use all three words interchangeably to mean “feeling bad.”

Emotional granularity is a bit like wine tasting. Wine experts perceive extremely subtle variations in flavor, even among different batches from the same vineyard. People with less experience might not taste these differences, but perhaps they can at least distinguish a pinot noir from a merlot or cabernet sauvignon. A wine novice is much less capable of making these distinctions—perhaps he can tell dry wine from sweet wine, or perhaps they both just taste like alcohol.

Likewise, people who exhibit high emotional granularity are emotion experts. Their brains can automatically construct emotional experiences with fine differences, like astonished, amazed, startled, dumbfounded, and shocked. For a person who exhibits more moderate emotional granularity, all of these words might belong to the same concept, “surprised.” And for someone who exhibits low emotional granularity, these words might all correspond to feeling worked up.

Emotional granularity is a key to emotional intelligence. If your brain can construct many different emotions automatically and make fine distinctions among them, it can tailor your emotions better to your situation. You’re also better equipped to anticipate and perceive emotion in others in the blink of an eye. The more emotions that you know, the more finely your brain can construct emotional meaning automatically from other people’s actions. Even though your brain is always guessing, when it has more options to guess with, the odds are better it will guess appropriately.

HOW DO YOU ENABLE your brain to create a wider variety of emotions and improve your emotional intelligence? One approach is to learn new emotion words. Each new word seeds your brain with the capacity to make new emotion predictions, which your brain can employ as a tool to construct your future experiences and perceptions, and to direct your actions. Instead of perceiving someone as generically “glad,” learn to distinguish more specifics. Are they

“overjoyed” or “contented” or “grateful?” Are they “angry” or “indignant” or “resentful” or “bitter?” More fine-grained emotions allow your brain to prepare for an array of different actions, whereas more generic emotions (angry, glad) confer less information and restrict your flexibility.

The idea that you can increase your emotional intelligence by broadening your emotion vocabulary is solid

When you learn new words, you sculpt your brain’s microwiring, giving it the means to construct new emotional experiences.

neuroscience. Your brain is not static; it rewires itself with experience. When you force yourself to learn new words—emotion-related or otherwise—you sculpt your brain’s microwiring, giving it the means to construct those emotional experiences, as well as your perceptions of others’ emotions, more effortlessly in the future. In short, every emotion word you learn is a new tool for future emotional intelligence.

People who can construct finely grained emotional experiences have advantages beyond the expected social ones. Children who broaden their knowledge of emotion words improve their academic performance as well as their social behavior, according to studies by the Yale Center for Emotional Intelligence. Adults who exhibit higher emotional granularity tend to be healthier with fewer doctor visits, less medication, and shorter stays in the hospital.

Foreign languages are a great source of new emotion words for increasing your brain’s emotional repertoire. You might already know *schadenfreude*, a transplant from German that means “taking pleasure in another person’s misfortune.” Other languages are filled with emotion words that have no direct equivalent in English. Examples are the Filipino *gigil*, an urge to squeeze

something that’s unbearably adorable, and *iktsuarpok*, an Inuit feeling of anticipation and impatience while waiting for someone to arrive. As you learn these foreign terms and the concepts behind them, you may become able to perceive these emotions in others and even experience them yourself.

Ironically, emotional intelligence is also knowing when *not* to construct an emotion. When you’re feeling overwhelmed, take a moment and consider non-emotional explanations for how you feel. Perhaps that jittery feeling in your stomach isn’t anxiety, but determination. Maybe that bitchy coworker is simply hungry. A feeling of distress when talking to your mother isn’t evidence that she said something wrong. Remember that your brain is always guessing, and sometimes its guesses are wrong.

Two decades ago, when *Emotional Intelligence* hit the bestseller list, scientists didn’t know about the predicting brain, or that the words you hear affect how your brain is wired, and emotional granularity was only newly discovered. Science, after all, is merely our best understanding of how things work, given the evidence at hand. In the face of new discoveries, explanations change, sometimes significantly. That is how science works. Many factors that were traditionally placed outside the realm of emotion, such as your vocabulary, have a profound impact on how you feel, what you see, and what you do. To bring emotional intelligence into the modern age, we must learn what these factors are—even if they challenge common sense—and use them judiciously to understand one another and ourselves. ☺

LISA FELDMAN BARRETT (@LFeldmanBarrett), a professor of psychology at Northeastern University, is the author of *How Emotions Are Made: The Secret Life of the Brain*.



Reinventing Staten Island

The ecological philosophy of turning a garbage dump into a park

BY MADELINE GRESSEL

A SITE TO BEHOLD The Manhattan skyline looms on the horizon of Freshkills Park, once the site of the largest garbage dump in the world, and now a grand experiment in restoration ecology.

PHOTO BY JO CAVALLO

WHEN THE DUTCH ARRIVED in New York Harbor in 1609, Staten Island—or Staat-en Eylandt, as they named it—was a wild wonderland, woodland in the middle and tidal salt marsh on the edges, populated by the local Lenape tribe, plus an embarrassment of natural riches: eels, bluefish, bitterns, herons, muskrats, ducks, clams, crabs, wild turkeys, porpoises, and more. Jutting mid-way into the island from the west coast, like a hook in the island’s side, was the Fresh Kills estuary, a tidal wetland thriving with plants and critters, created by the retreat of the Wisconsin Ice Sheet some 17,000 years ago.

After World War II, the bursting city of New York found itself with a trash problem. In 1948, the city started officially dumping its trash into the marshes and waters of Fresh Kills. What became America’s first landfill was meant to be temporary, but it stuck. By 1955, it was the biggest landfill in the world—indeed, at 2,700 acres, it was the biggest human-made structure in the world. By 1991, the landfill contained 150 million tons of tightly packed garbage in more volume than could fill the Great Wall of China. Fresh Kills was wetland no more.

The landfill serviced New York City for 53 years, until Staten Island residents, sick of the stench, sued the city to close it. “The Dump,” as it was un-fondly known, was finally closed in 2001 (New York’s garbage is now processed and shipped to neighboring states)—but not until 1.2 million more tons of trash were added: the charred remains of the World Trade Center.

During its closure, the Municipal Arts Society, a civic group led by a mix of urban planners and preservationists, spotted an opportunity for building something rare in New York City, where nearly every last square inch is developed—the creation of an expansive new park, 2,200 acres to be exact, three times larger than Central Park. In 2003, Freshkills (now one word) Park was born.

Transforming a mountain of garbage into a “lifescape,” as a 2006 master draft plan describes the park, is no simple task. The park will be another 20 years in the making; the Parks Department hopes to open

the first phases in 2019. But it’s also an extraordinary ecological project that poses a question at the heart of modern conservation: Can ecologists build a new ecosystem that will survive? What should their scientific North Star be?

On an unseasonably bright and balmy day in February, Cait Field, Freshkills Park Manager for Science and Research Development, drove into the park past a Coca-Cola bottling plant, an enormous dump station, and innumerable rusty fences. The landscape was dominated by four rolling hills created from trash mounds, sealed with an impermeable geotextile and covered with dirt and grass to prevent erosion. A network of creeks and tidal straits ran between the hills, punctuated by small pockets of woodland. Gold and green grass rippled across the site. In the hazy distance was the silver skyline of Manhattan.

“This is not the native ecosystem,” said Field, a laconic and thoughtful 34-year-old with a Ph.D. in biopsychology and behavioral neuroscience. “There’s million of tons of waste in there, so it’s never going to be tidal marsh. We’re past that. We’ve plopped down this non-native ecosystem, right in the middle of New York City. It’s completely manufactured. Completely manufactured to start, anyway.”

Two winsome white-tailed deer sprang by. To Field the deer are a pest, which, like the *Phragmites australis*, a tall, feathery reed, have proliferated with abandon across the East Coast, dominating ecosystems and flattening diversity. “Over the past couple hundred years, humans have taken out any predators for the deer,” she said. “And we’ve ended up with an ecosystem that’s off balance.”

A few minutes later, she corrected herself. “I don’t know if it’s balance. We’re not restoring to something that was balanced, nor can we, because this is a completely different set of conditions than it used to be.”

SINCE THE BIRTH OF ECOLOGY 100 years ago, the idea of a balance of nature dominated the field. Ecologists long believed ecosystems maintained an intrinsic equilibrium, to which they could return even after a great disturbance. The idea of a balance in nature is,

after all, deeply intuitive. Our Earth seems to be balanced on the most precarious of tightropes: just the right distance from the sun, not too hot and not too cold, tilted on its axis just so. Inside Earth's membrane, life self-regulates: Birth turns to death and back to birth, carbon dioxide becomes oxygen and vice versa.

Long before humans understood these cycles, the ancients, both Eastern and Western, conceived of nature as being in balance. In Taoism, the yin/yang dichotomy encompassed a whole range of balanced dualities in nature: darkness and light, heaven and earth, death and life. In the West, Herodotus was the first to articulate a theory of balance-in-nature, when he asked in his *Histories* how preyed-upon animals manage to avoid extinction. He deduced that the prey reproduced more prolifically, and thus balanced the scales: "For timid animals which are a prey to others are all made to produce young abundantly, that so the

species may not be entirely eaten up and lost; while savage and noxious creatures are made very unfruitful."

Herodotus attributed this fortunate balance to the benevolence of the gods—as would Plato, in his own, more elaborate theory of cosmic harmony articulated in the *Dialogues*. Five centuries later, Cicero summed it up nicely: "Everything in the world is marvelously ordered by divine providence and wisdom for the safety and protection of us all ... Who cannot wonder at this harmony of things, at this symphony of nature which seems to will the well-being of the world?"

By the 19th century, although Galileo had long since knocked Earth from the center of the universe, the idea of God's self-regulating clockwork planet was king. Scientists took as their baseline assumption that nature was in balance, even when appearances proved otherwise. In 1864, George Perkins Marsh, considered by many the founding father of American

BORN AGAIN A stream cuts through Freshkills Park, reborn as a grasslands ecosystem. Before the Dutch arrived in the 1600s, Staten Island was a thriving tidal wetland, populated by a diversity of plants and animals, including heron, turkeys, bluefish, and crabs.



conservationism, wrote that “animal and vegetable life, are subject to change only from geological influences so slow in their operation that the geographical conditions may be regarded as constant and immutable.”

As the industrial revolution left the creator god behind, scientists found a new, robust model for the balance of nature: the finely tuned machine, with its inputs and outputs and replaceable parts. The metaphor changed, but the paradigm remained. In his 1887 essay, “The Lake as Microcosm,” Stephen A. Forbes, a prominent American ecologist, echoed Herodotus when he wrote that “no phenomenon of life ... is more remarkable than the steady balance of organic nature, which holds each species within the limits of a uniform average number, year after year, although each one is always doing its best to break across boundaries on every side.” The balance of nature was an equation waiting to be solved.

THE NATURAL NEXT STEP was to define this equation. In the early 1920s, two scientists separately and simultaneously came up with one part of it, now known as the Lotka-Volterra equations, to approximate and explain the continuous interplay of predator and prey populations. The idea was simple: When prey boom, there is more food for the predators, which in turn boom with the bounty, and eat more of the prey, which shrink, and the predators go hungry. And so on, forever. Populations oscillate in elegant and opposing waves.

Around the same time, some ecologists in the field began to grumble against the too-comfortable theory of balance. In 1921, a 21-year-old zoology student at Oxford University named Charles Sutherland Elton was offered a place on the university’s first arctic

expedition, to the forlorn island of Spitsbergen (in modern Svalbard), an icy haven for polar bears halfway between the top of Norway and the North Pole. What Elton witnessed there over the course of three summers—namely, the intricate interconnectedness between birds, plants, predators, and the island itself—overturned his preconceived notions of ecology, and inspired his seminal text, *Animal Ecology* (he would also go on to coin the phrase “food chain”).

In *The Pattern of Animal Communities*, Elton wrote that, in the complex natural commerce of Spitsbergen, he saw a “very untidy, dynamic, mobile, changing picture of nature rather than a neat physiological arrangement; a world of rather unstable populations in an unstable environment, not a static arrangement of animals limited to habitat created by plants and vegetation with its special microclimates.” In short, instead of a beautifully balanced system of exchange, Elton saw an economy of chance and risk. “The ‘balance of nature’ does not exist, and perhaps never has existed,” he later wrote.

Slowly, the balance-of-nature paradigm fell out of favor. Ecologists realized, after concentrated observation, that many species not only tolerated disturbance in the ecosystem, but thrived upon it—for example, certain tree species needed periodic forest fires to survive. These populations did not fit the Lotka-Volterra equations. Nature was intractably messy.

The vanguard against balance-in-nature was led, in part, by an ecologist named Daniel Botkin. As a young man in the 1960s, Botkin had traveled to Isle Royale, a 210-square-mile island in Lake Superior between Ontario and Michigan, to study wolves and moose. The moose had walked to the island over thick ice around

We’ve plopped down this non-native ecosystem right in the middle of New York City.



THE STEWARD Cait Field, Freshkills Park Manager for Science and Research Development, gathers a water sample. To compete with nature and build a “maximally productive” ecosystem, she says, “it’s gonna take work, it’s gonna take care, and it’s gonna take stewardship.”

1900. They had no predators on the island, and so, predictably, they multiplied, decimated the foliage, and began to starve. In 1946, wolves were brought in to regulate their numbers, in an attempt to save the moose.

Like any good ecologist of the day, Botkin tried to fit what he saw on Isle Royale into Lotka-Volterra oscillations. But where he sought pattern he found only variation. The populations were indefatigably stochastic. The foremost problem with the Lotka-Volterra equations, Botkin realized, was that they took no account of life’s many vicissitudes and vagaries. The equations made all moose and wolves alike. There were no wounded moose, no senile wolves, no winter storms, no sweeping plagues. As Botkin wrote, “A logistic moose has no fat.”

The island’s ostensibly native plant species seemed no more permanent. Following the last ice age, which ended about 12,000 years ago, the region underwent a series of changes in landscape. First, it was covered in small brush and shrubs, then spruce, then pine, then birch and alder, and then back to pine. All told, the vegetation changed every 1,000 years. Ecologists had long believed that forests evolved from brush and scrub to trees, ending in a permanent “climax” phase, wherein

every species, from the redwood to the lichen, had its niche. This no longer seemed to be the case.

Years later, in his book *Discordant Harmonies*, Botkin wrote, “Wherever we seek to find constancy, we discover change ... We find that nature undisturbed is not constant in form, structure, or proportion, but changes at every scale of time and space. The old idea of a static landscape, like a single musical chord sounded forever, must be abandoned, for such a landscape never existed except in our imagination.”

The idea of balance was not just intuitive, it was convenient. Assuming that nature achieves a consistent, stable state without disruption made a return to this state a reasonable ecological goal. Conservationists had something specific to aim for. Now the target was not so clear.

Evidence against the constancy of nature, and for its fickleness, accumulated every year. Even absent human intervention, it seemed, ecosystems did not remain in a stable state for very long—a few thousand years at most. But it was still clear that some ecosystems were more robust, diverse, or stable than others. What were the mechanisms or relationships that distinguished them?





The park is built on
more garbage than
could fill the Great
Wall of China.

AROUND THE TIME that Botkin was tracking wolves on Isle Royale, ecologists formulated a new insight into a natural equilibrium. Ecosystems had been thought to regulate themselves from the bottom up—the plants, which made their own food, regulated the creatures that fed on them, and each predatory layer built on the foundation of its prey. In a now seminal 1960 paper, Nelson Hairston Sr., Lawrence Slobodkin, and Fred Smith argued that ecosystems could be built from the top down. They reasoned that if herbivores, like deer or insects, did not eat the world’s green down to nothingness, something must be keeping them in check. This became known as the green world hypothesis or, colloquially, HSS, after its three founders.

A series of experiments backed up the hypothesis. In 1963, a young ecologist named Robert Paine tossed Pisaster starfish out of their cozy tide-pools to see how their absence might change the local ecology.

The Pisaster starfish were the dominant predator in the tidepools. When Paine removed them, their prey, mostly *Mytilus californianus*, the California mussel, proliferated unchecked and began to crowd out other species on the block—chitons, limpets, and barnacles. A few months after Paine began tossing starfish, seven of the 15 species originally at home in the tidepool were gone. The Pisasters, merely by hanging around and eating the mussels, had bolstered the diversity of the entire ecosystem. The experiment quickly became one of the most famous in modern ecology. He called these high-impact top predators “keystone species.”

Everywhere ecologists looked, they found keystone species. In the Aleutian Islands of Alaska, Jim Estes discovered that sea otters allowed kelp forests to flourish by eating the kelp-eating sea urchins, which in turn nurtured the survival of a whole host of local species, from fish to eels to cormorants to bald eagles.

BALANCING ACT Planting grasslands and wildflowers in Freshkills Park should have a cascading effect, says Steven Handel, a Princeton ecologist. “We figure if we put in 50 species, there’s a chance the wind and birds will carry those seeds elsewhere and enrich the surrounding area.”



Perhaps there is a kind of balance to be found—but not forever.

Paine—who had a knack for pithy neologisms—called these systems “trophic cascades.”

The trophic cascade theory gave conservationists a guide for renewal. Easily the most famous example is the 1995 restoration of the wolf to Yellowstone National Park in the Rocky Mountains. Many ecologists argue the return of the keystone wolf has been a success, helping revive a host of plants and animals in the area, including wildflowers and willow trees, bison and beavers.

Trophic cascade theory suggested ecological order could be disrupted—and potentially restored. But the operation of a healthy ecosystem, resting on a single species, made the idea of permanent balance appear more complex than ever. Over a long timescale, who could say how equilibria might be sustained? In a melancholy 2009 editorial in *Science*, the restoration ecologist Richard Hobbs wondered, “If natural states are elusive, if environments are always changing, and ecosystems are always coming and going, then the premises underlying ecological restoration ... come under question. Does ecological history render ecological reconstruction ‘quaint’?”

THE MODERN ECOLOGIST sees nature as a vast web with cause and effect running in every which direction. In 1998, conservation ecologist E.O. Wilson put it this way: “The greatest challenge today, not just in ecology but in all of science, is the accurate and complete description of complex systems.”

Today, many ecologists are trying to unravel those systems. “What we’re trying to understand by modeling the population dynamics of complex networks of

interacting species is, under what conditions do you expect to see species persisting and coexisting?” says Jennifer Dunne, the vice president for science at the Santa Fe Institute. “Some may hit some steady state, where they increase to a certain point and then are relatively unchanging over time. Some may immediately drop out—their populations go too low. Disturbances and perturbations are occurring at all scales and altering the course of population dynamics—from someone stepping on a patch of soil all the way up to global climate change.”

Keystone species are not the only ones who can wield an outsized effect. Dunne has shown how including parasites in food webs affects their organization and structure. Meanwhile, her colleague Kevin Lafferty, a marine biologist for the United States Geological Survey, has shown that parasites and infectious diseases may profoundly affect an ecosystem’s stability and robustness—a factor ecologists have largely overlooked for decades.

To the extent that these systems are more or less stable, perhaps there is a kind of balance to be found—but not forever. “Nature does not intrinsically trend toward, and doesn’t long maintain, any kind of ‘tight’ equilibrium, but dynamic, quasi-equilibrial, ‘balances’ are ubiquitous, and although they are not forever, they can last quite a while,” Robert Pringle, a professor of ecology and evolutionary biology at Princeton University, explains in an email. “Whether one sees ‘balance’ in nature is in large measure a function of the temporal scale of one’s outlook.”

How much of these complex models can be successfully translated into real-time conservation policy

remains an open question. Alan Hastings, a theoretical ecologist at the University of California, Davis, sees a path forward. “I see a great deal of progression and understanding from a basic scientific level of what can maintain distributions and abundances of species,” Hastings says. “In thinking about conservation, we can use these ideas to manage based on feedbacks, and take actions in response to observations.”

The mathematical models are best at predicting a range of contingent scenarios that may come to pass, depending on different environmental factors. For instance, if more whales hung around the Bering Sea than usual, how would that affect the population of Alaskan pollack? Or, if sea ice in the Arctic declines as projected, how badly will that impact polar bear populations? (Very badly.) In short, the models are predictive, not prescriptive.

In certain cases, these predictions have helped guide conservation policy. The polar bear model was instrumental in convincing the U.S. Fish and Wildlife Service to classify the polar bear as an endangered species, under the Endangered Species Act, in 2008. Complex computer simulations of marine ecosystems (called EcoSim and EcoPath) have been increasingly adopted (most notably by the Australian government) as official guides in fisheries management. Pringle and his team are combining field experiments, wildlife tracking, molecular diet analysis, and mathematical modeling to understand whether the booming antelope populations in Mozambique’s Gorongosa National Park are creating an ecosystem vulnerable to collapse due to overgrazing and disease. “The picture emerging from this research suggests that missing large carnivores

such as leopards, hyenas, and wild dogs need to be brought back, and soon,” Pringle says.

While the models are myriad and sophisticated, their application is murkier. In almost all of these cases, concrete results have yet to be seen. In part, this is a matter of politics—conflicting priorities, bureaucratic drag, limited jurisdiction. But there’s also the fact that complex models don’t yield simple solutions; because these models aren’t prescriptive, they can’t, well, prescribe a cure. As a research paper in *Frontiers in Ecology and the Environment* put it, “Ultimately, the value of [these] models lies not in prescribing solutions, but in informing and guiding the planning and decision-making process.”

FOR FIELD AND HER COLLEAGUES, progress at Freshkills Park is based on data, trial, and error. Which trees attract which birds? What seeds do those birds disperse, adding new layers of vegetation? What do bats or turtles need to thrive? Which species encourage diversity around them, and which flatten it?

Through this all, there is no pretense of rebuilding some original landscape. Steven Handel, an ecologist at Rutgers University and a faculty member at Harvard University’s Graduate School of Design, who has been involved in the Freshkills project since its inception, explained, “We’re not going to make a garden. We’re going to try to rebuild these links of ecological processes to try to bring back native plants.”

For one thing, instead of its original wetlands, Freshkills Park will be mostly grasslands. The choice was utilitarian. Grasslands will help prevent erosion and allow the National Grid power company continued

The balance of nature was an equation waiting to be solved.

access to the methane coming off the capped landfill. But grasslands will also court a wide range of bird species in the region, and act as a flyway for long-distance migrating birds. The hope is these grasses and birds will set off a cascade effect, bringing in more trees, shrubs, and mammals.

The team began with a mix of local grasses sown to keep the soil in place over the landfill. In 2011, Ed Toth, the director of the Staten Island Greenbelt Native Plant Center, which has provided Freshkills with most of its seeds, designed what he called a “hurry-up mix” of 13 local grass and wildflower seeds (beautiful species like indiangrass, little bluestem, aster, and goldenrod), which have sprouted across the mounds, transforming them into meadows. The U.S. Forest Service then added trees—mostly poplars and willows—as a welcome invitation to the region’s birds, who in turn planted new seed species with their droppings. The hope is that this rich native mix, helped along by human hands, will be well-equipped to combat bully species, like the phragmites. (“The phrag,” Handel says, might have to be conquered by chemical means.) In other words, the ecological tapestry created by the park team will be robust and tightly woven.

Life is now creeping back. As Field was walking through the park, muskrats scuttled through the brush. The endangered grasshopper sparrow has been spotted flitting through the grasses. Ospreys nested on tall wooden poles, and bald eagles soared overhead. Painted turtles have taken up residence in rainwater collection ponds created by the park’s managers. Egrets, cormorants, and heron plucked their way through the creek’s shallows. New York City’s only beavers live right outside the park.

Only time will tell whether the project will succeed. “Our overall goal, from a park perspective, is productive habitat and biodiversity,” Field said. “But it’s also to study the ecological changes that take place during this transformation on a long-term basis. That’s rarely available in any kind of restoration ecology. It gives us an opportunity to see—how does this ecosystem change? And maybe get something that looks a little bit like balance, anyway.” 🌀

MADELINE GRESSEL is an assistant editor at *Nautilus*.

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Issue Index

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Science Connected.



JULY/AUG 2017 | 21

50 EMERGENCE
51 LIMITS



MAY/JUNE 2017 | 20

48 CHAOS
49 THE ABSURD



MAR/APR 2017 | 19

46 BALANCE
47 CONSCIOUSNESS



JAN/FEB 2017 | 18

44 LUCK
45 POWER



NOV/DEC 2016 | 17

42 FAKES
43 HEROES



SEP/OCT 2016 | 16

40 LEARNING
41 SELECTION



JULY/AUG 2016 | 15

38 NOISE
39 SPORT



MAY/JUNE 2016 | 14

36 AGING
37 CURRENTS



MAR/APR 2016 | 13

34 ADAPTATION
35 BOUNDARIES



JAN/FEB 2016 | 12

32 SPACE
33 ATTRACTION



NOV/DEC 2015 | 11

30 IDENTITY
31 STRESS



SEP/OCT 2015 | 10

28 2050
29 SCALING



JULY/AUG 2015 | 09

25 WATER
26 COLOR
27 DARK MATTER



MAY/JUNE 2015 | 08

22 SLOW
23 DOMINOS
24 ERROR



MAR/APR 2015 | 07

19 ILLUSIONS
20 CREATIVITY
21 INFORMATION



WINTER 2015 | 06

16 NOTHINGNESS
17 BIG BANGS
18 GENIUS



FALL 2014 | 05

13 SYMMETRY
14 MUTATION
15 TURBULENCE



SUMMER 2014 | 04

10 MERGERS & ACQUISITIONS
11 LIGHT
12 FEEDBACK



SPRING 2014 | 03

07 WASTE
08 HOME
09 TIME



WINTER 2014 | 02

04 THE UNLIKELY
05 FAME
06 SECRET CODES



FALL 2013 | 01

01 HUMAN UNIQUENESS
02 UNCERTAINTY
03 IN TRANSIT

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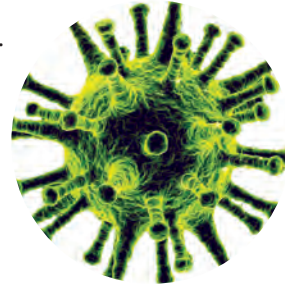
Jack Gilbert

*The faculty director of the Microbiome Center and coauthor of **Dirt Is Good** reflects on the themes in **Nautilus***

INTERVIEW BY REGAN PENALUNA

EMERGENCE

What is a microbiome? It is the microbial ecosystem of your guts. Think of a forest. It's an ecosystem that functions in equilibrium with its environment. The trees, the animals, the birds—everything is tickety-boo, there's not one thing taking over. In a healthy microbiome you have a diverse ecosystem, a community of organisms interacting and functioning with the body to produce a healthy human being. Health is an emergent property of that equilibrium. But if you have a disrupted forest, and everything else dies off and one thing takes over, that's similar to a disrupted microbiome. You can have one pathogenic organism, one dangerous bacteria, or one dangerous virus that takes over, and everything else starts to die out.



LIMITS

Our bodies are used to seeing more bacteria, more viruses, and more fungi than they are now. They're not used to coping with such a low level of microbial exposure. What does that mean for hygiene?

I still wash my hands regularly. But I also let my kids play outside in the soil. And we have dogs in the house. When kids who are less than one year old interact with a dog they are more likely to have a reduction in the development of asthma and skin disorders. But there are limits. Some pathogenic organisms circulating in the environment can cause disease. If I go into a toilet in a Bangladesh slum, drop my ice cream on the floor, would I pick it up and lick it? No. Because there are endemic diseases there for which I have no tolerance, and which cause diarrheal disease. Would I do that in my own bathroom? Yeah. Because there's nobody in my house right now, or in the last two months, who has diarrheal disease. The likelihood that there is something coming out of any of our rear ends that will cause infection is extremely small. I could eat the poop from my kids and it would not make me sick. ☺

Would I lick ice cream that I dropped in a toilet?



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