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THE INSIDE STORY OF GPS

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CAN BIO-BASED MEMORY COPE WITH THE DATA DELUGE? P. 40

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On the cover **Illustration for *IEEE Spectrum* by James Archer/Anatomy Blue**

PHOTOGRAPH BY Gregg Segal

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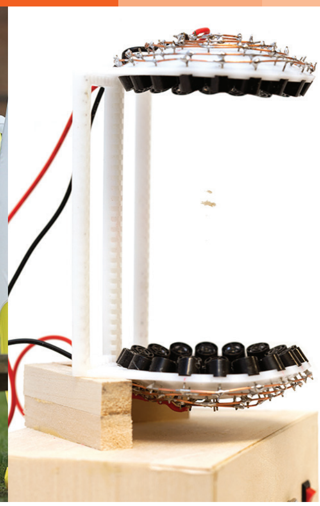

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- **COLLISION OF ART AND TECH** Historian Megan Prelinger talks about her book *Inside the Machine: Art and Invention in the Electronic Age*, which received the IEEE William and Joyce Middleton Electrical Engineering History Award.

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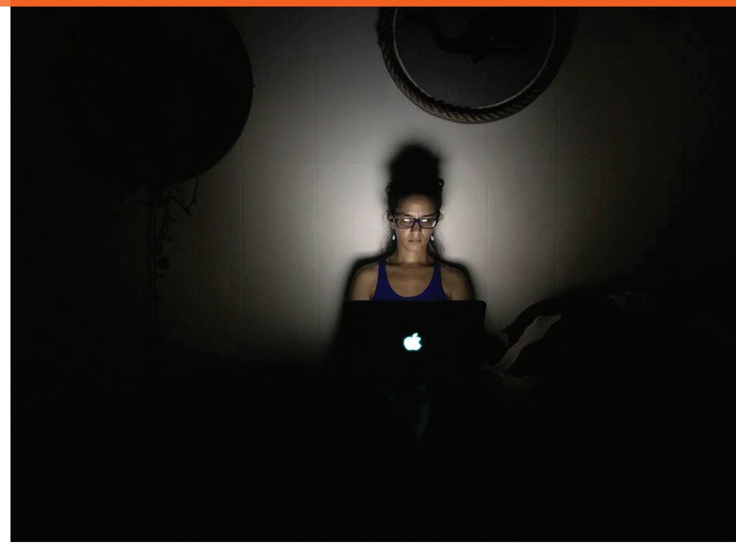

EYE OF THE STORM

GROWING UP IN SAN JUAN, Puerto Rico, the photographer Erika P. Rodríguez saw her fair share of hurricanes and tropical storms. But nothing prepared her for Hurricane Maria, which struck on 20 September and brought down the island's power grid.

At the time, she was on assignment for *The New York Times*, working from the offices of a local newspaper. "They have a generator, and there was electricity and Internet access," Rodríguez recalls. "So we were seeing photos and videos of the hurricane on social media and on the news from outside Puerto Rico." Still, when she finally stepped outside later that day, she was shocked: "The scope of the disaster was much greater than any of us expected."

By the time Rodríguez started the assignment for *IEEE Spectrum*, in mid-December, she had traveled all over the island and had seen the true extent of the damage. "I was working nonstop, and I saw so much suffering and need. I saw too much, honestly," she says. It came as a welcome reprieve to focus on the restoration of Puerto Rico's power grid and to photograph the engineers who are tackling this huge problem [see "Rebuilding Puerto Rico's Grid," in this issue]. "It was nice to shift the conversation, from 'What are the problems?' to 'What are the solutions?' "

The assignment also drove home the resilience of Puerto Ricans. "We call it *autogestión*–it's communities taking matters into their own hands, helping each other," Rodríguez explains. She mentions visiting the home of a mother and her asthmatic son, to document how an engineer had installed an emergency solar-powered charger to operate the boy's medical equipment.

"That's resilience," she says. "That's life. That's people saying, 'We're here and we're going to fight it, with whatever resources we can get.' " ■

ELLIS OMAR WILLIAMS

CONTRIBUTORS_

Maria Gallucci

Gallucci, a freelance science writer, is the 2017–2018 Energy Journalism Fellow at the University of Texas at Austin. In this issue, she writes about efforts to rebuild Puerto Rico's power grid [p. 30]. Her final day of reporting in San Juan captured the many players and perspectives involved. "I spent the morning inside the utility's gated operations center with exhausted engineers and the evening outside with frustrated residents protesting at the gates," Gallucci says.

Jeremy Hsu

Hsu, a New York City–based journalist, writes in this issue about the impact that the European Union's new General Data Protection Regulation (GDPR) will have on independent coders and developers [p. 21]. "Law firms and consultants have overwhelmingly focused on how big companies can become GDPR compliant. But there is much less advice for individual developers or small business owners, who have just as many questions and fewer resources," says Hsu.

Matt Knapp

Knapp, the founder of Zunum Aero, started building model rockets and airplanes at age 5 and went on to earn a B.S. and an M.S. in aerospace engineering at MIT. "For as long as I can remember, I've thought that people should fly more," he says. "It's fantastic to be working on the technology to make this happen." In this issue, he and Waleed Said, Zunum's chief technology officer of power, describe the company's work on hybrid-electric airplanes [p. 26].

Olgica Milenkovic

Milenkovic, a professor at the University of Illinois at Urbana-Champaign, has spent her career hearing about exciting new data storage systems that quickly became obsolete. In "Exabytes in a Test Tube" [p. 40], Milenkovic, Ryan Gabrys, Han Mao Kiah, and S.M. Hossein Tabatabaei Yazdi explain why using DNA, once a radical proposal, might survive the hype and become a viable option for the long-term storage of massive amounts of scientific data.

Gregg Segal

When Segal made plans to photograph Bradford W. Parkinson, the 2018 recipient of the IEEE Medal of Honor [p. 46], Parkinson emailed him detailed turn-by-turn directions along with a scanned map of the route to his house—ironic, given that Parkinson led the development of the GPS navigation system. Segal reports that GPS got him to his destination just fine. "I can barely remember how I got around before GPS," he says.

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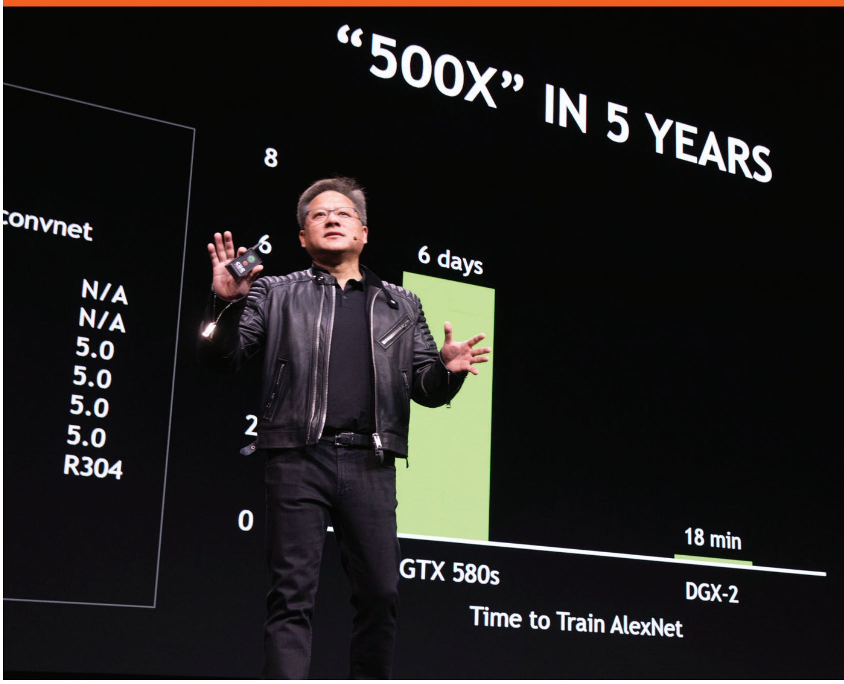


NVIDIA CEO JENSEN HUANG expands on new metrics for measuring the increasing power of GPUs.

Move Over, Moore's Law. Make Way for Huang's Law

Graphics processors are on a supercharged development path that eclipses Moore's Law, says Nvidia's Jensen Huang

Earlier this spring, Nvidia hosted its 10th annual GPU Technology Conference (GTC) in San Jose, Calif. Attendees lined up early, some of the 8,300 people reportedly camping overnight to get into CEO Jensen Huang's overflowing keynote address. With many of the breakout sessions also standing room only, it's just a matter of time before this conference bursts out of the San Jose Convention Center. ¶ Huang, in his trademark leather jacket, seemed to be everywhere. He popped up unannounced at a press lunch shortly after his nearly 3-hour keynote to field some tough questions about the recent Uber tragedy, and later joined Nvidia cofounder Chris Malachowsky to reminisce and hand out a million dollars, divided among three new startups. ¶ During his keynote, Huang suggested that Moore's Law has been blown out of the water by graphics processors. These follow a new "supercharged" law, although by *supercharged* he could have been referring equally to his own supersize personality. He repeatedly made the point that because of extreme advances in technology, graphics processing units (GPUs) are governed by a law of their own. ¶ Huang never called it Huang's Law, and I'm guessing he'll leave that to others. After all, Gordon Moore wasn't the one who gave Moore's Law its now-famous moniker. (Moore's Law—Moore himself called it an observation—refers to the regular doubling of the number of components per integrated circuit that drove a dramatic reduction in the cost of computing power.)

But Huang did make sure no one attending GTC missed the memo.

Just how fast does GPU technology advance? In his address, Huang pointed out that Nvidia's GPUs today are 25 times as fast as they were five years ago. If they were advancing according to Moore's Law, he said, they would have increased in speed by only a factor of 10.

Huang later considered the increasing power of GPUs in terms of another benchmark: the time to train the convolutional neural network AlexNet on 15 million images. He said that five years ago, it took AlexNet six days on two of Nvidia's GTX 580s to go through the training process; with one DGX-2, the company's latest hardware, it takes 18 minutes—a factor of 500.

During his speech, Huang threw out a lot of numbers, so it seems he's still working out the exact very large multiple he'll settle on. But he was clear about the reasons that GPUs need a law of their own. They benefit from simultaneous advances on multiple fronts: architecture, interconnects, memory technology, algorithms, and more. —TEKLA S. PERRY

A version of this article appears in our View From the Valley blog.

A HELPING HAND FOR PUERTO RICO

This issue features Maria Gallucci's report on rebuilding Puerto Rico's electrical grid in the aftermath of Hurricane Maria, with photographs by Erika P. Rodríguez. Since the storm careened across the island last September, IEEE members in Puerto Rico have been distributing solar lanterns and installing off-grid solar-powered charging stations in rural communities where, even now, at the time of this writing, power has not yet been restored. Each 4-kilowatt-hour system includes ports for charging cellphones and other electronic devices and a small refrigerator for storing medications and other perishables. To support the IEEE Foundation's IEEE Juntos Podemos–Together We Can Fund, visit **http://www.ieeefoundation.org/puertorico.**

NVIDIA

NEWS

20 MINUTES: THE TIME IT TAKES FOR THE FIRST SYMPTOMS TO APPEAR AFTER EXPOSURE TO A NERVE AGENT

SPYING DEADLY CHEMICALS FROM 30 METERS

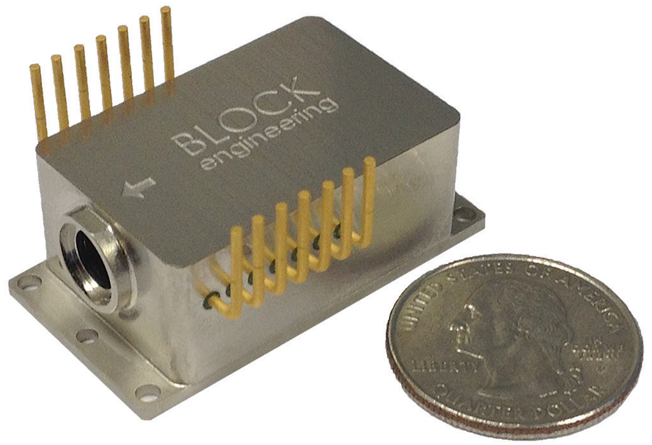
U.S. intelligence agencies seek tech to spot bombs, nerve gases, and other threats

CAREFUL WORK: Investigators examine a bench in England for chemical traces of a nerve agent after two victims were found there.

Sergei Skripal, a former Russian intelligence officer who became a double agent for the United Kingdom, and his daughter, Yulia, weren't the only people affected by a nerve-agent attack in Salisbury, England, in March. Nearly 40 others were sickened, including three police officers who were hospitalized, one of them for more than two weeks. A swarm of hazmat-suited chemical warfare experts inspected every place the Skripals had been recently in the hope of finding out what happened and whether there was still a danger to the public.

U.S. intelligence agencies have been on the hunt for a technology that would make such investigations faster and safer and perhaps even prevent this kind of attack altogether. The Standoff ILluminator for Measuring Absorbance and Reflectance Infrared Light Signatures (SILMARILS) program at the »

ANDREW MATTHEWS/PA/GETTY IMAGES



PORTABLE SCANNER: This quantum cascade laser built by Block MEMS is one of several approaches to standoff chemical detection being developed for SILMARILS.

BLOCK MEMS

Intelligence Advanced Research Projects Activity should conclude, by mid-2021, with a possible solution: a portable scanner that can identify a fingerprint's worth of a library of some 500 chemicals—spanning the dangerous (the explosive PETN) to the mundane (caffeine)—on surfaces like car doors from a distance of 5 to 30 meters.

Program director Kristy DeWitt explains that detecting such chemical signatures is already possible using what's called Raman spectroscopy. That technology uses a laser, made up of a single wavelength of light, that produces a minuscule fraction of photons of a variety of wavelengths when the beam scatters off the scanned material. What those wavelengths are and what their relative abundance is act as an identifying signature.

The problem is that the fraction of new photons is so small that you need a strong—potentially burn-your-eyes-out strong—laser behind it. And that's no good if you're planning to surreptitiously scan everyone who walks into an airport.

The systems that SILMARILS is exploring instead use lasers that span a wide swath of the infrared (IR) spectrum and look for spectroscopic signatures in the few photons that reflect back. Using a broad range of IR wavelengths means you can use a less-powerful light source—something no more dangerous than a grocery store scanner, DeWitt says.

The three teams in the program are developing a complete system that includes both illumination and spectroscopy, but they each have specialties. Defense contractor Leidos is relying on a pulsed supercontinuum laser. Such devices are typically optical fibers doped with chemicals and with micro- or nanostructures built into them to produce a peculiar nonlinear effect. Specifically, some light pumped into the fiber stimulates the production of a continuous spectrum of wavelengths. Using a series of differently doped fibers, Leidos and researchers at the University of Michigan recently managed to produce a supercontinuum laser with wavelengths that span from 2 micrometers all the way to 11 μm.

Block MEMS, based in Marlborough, Mass., is also using a specialized laser, although one that's less experimental. The company already provides several chemical detection products based on its quantum cascade lasers. These lasers are made of semiconductors with precisely controlled subnanometer thicknesses. Electrons see these layers as if they were a "staircase" of energy and emit a photon at each step. Block MEMS's twist on this technology is a laser that rapidly sweeps through a range of infrared wavelengths, by adjusting optical components outside of the semiconductor, explains CEO Petros Kotidis.

Honolulu-based Spectrum Photonics has leveraged its experience building compact, low-power hyperspectral imaging systems. These camera-based spectrometer systems capture a rapid series of images, each with encoded spatial and wavelength information. Spectrum Photonics president Ed Knobbe says the company is developing an imaging spectrometry system for SILMARILS that can detect light with wavelengths of 1.2 μm (short-wavelength IR) to 13.5 μm (long-wavelength IR). "Most of the primary spectral information is in long-wave infrared," explains Knobbe. "But there is a tremendous amount of complementary information in midwave and shortwave IR bands."

Much of the work now lies in interpreting the returned signal—the brains of the system rather than its beams, says DeWitt. "One of the hardest problems is dealing with the fact that the signature on a surface is not the same absolute bar code you'd get from a chemical floating in the air. When you have small quantities of chemicals on a surface, the spectrum changes considerably according to the substrate and the particle size."

If any of these teams can solve the remaining problems, the applications will extend well beyond intelligence agencies' needs. "It changes the whole idea of standoff detection," predicts Block MEMS CEO Kotidis.

For Leidos's principal investigator, Augie Ifarraguerri, it's kind of a dream come true. "There was always this sense that out there, somewhere, was the ability to make the ultimate sensor—the 'Star Trek' tricorder," he says. When he started his career in the 1990s, "it seemed very elusive." But the technology is close now, and he's finally getting to do what he'd wanted to do "for, I don't know, 30 years."
—SAMUEL K. MOORE

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CHIP HIRES/GAMMA-RAPHO/GETTY IMAGES

DRINK UP: A desalination plant in Al Khafji, Saudi Arabia, is powered by fossil fuels. A new, solar-powered desalination plant is now being built in the city.

OIL STATES TRY TO TURN SUNLIGHT INTO FRESHWATER

Saudi Arabia pushes to combine solar power with desalination

It seems like a natural fit for desert dwellers: Use the sun to scrub salt from groundwater or seawater and make it suitable to drink.

Armed with oil money, the Saudi government's Saline Water Conversion Corp. (SWCC) has already built the world's most extensive network of desalination plants. However, like many facilities in Saudi Arabia, those plants are powered mostly by fossil fuels.

Thanks to a steep drop in the cost of photovoltaics (PV), solar power is now starting to look like a tantalizing replacement. As of press time, desalination expert Thomas Altmann of ACWA Power was expected to argue that solar power is turning the industry "on its head" at a conference in Paris in April, according to a session description.

But a 2015 attempt by SWCC to commission a 15-megawatt solar PV-powered desalination plant at Al Khafji, in Saudi Arabia, is behind schedule. When it does come on line, the solar power and desalination components will likely operate separately, insiders say. Another solar desalination plant, in Morocco, has also failed to integrate the two parts.

Energy costs make up 40 to 50 percent of the cost of desalination, estimates Carlos Cosín, CEO of Almar Water Solutions, in Madrid. Industry leaders in Saudi Arabia, Abu Dhabi, and Chile are particularly interested in using solar power to run reverse-osmosis desalination, which uses electricity to pump saline water through membrane filters.

Despite the missteps, a Middle Eastern country will still be first to operate a commercial solar desalination plant, predicts Cosín, who worked on the Al Khafji site. He estimates such a plant could open in 2021 or 2022.

NEWS

The countries in the region have lots of sunlight and stand to gain from cheaper freshwater, given the dearth of local sources. Switching to solar also means they could export more oil for US $65 a barrel, instead of selling it to desalination plants for subsidized prices.

Renewable energy "actually is cost competitive" for some remote desalination plants, says engineering researcher John Lienhard, of MIT. But for others, that calculation depends on the type of solar power used and the kind of desalination that occurs there.

Concentrated solar power (CSP), which uses circles of mirrors to direct sunlight toward a solar tower filled with thermal salts, generates electricity more consistently. It can also store heat for several hours, which certain types of desalination plants can use to evaporate saltwater.

PV is less than half the price of CSP during the day, but it produces only electricity—not heat. That makes PV a better fit for reverse-osmosis desalination than for evaporation techniques.

However, the Persian Gulf and the Red Sea are so saline that desalting seawater may drive up electricity costs for reverse osmosis. In such places, evaporative desalination paired with CSP might be best because the costs of evaporation do not increase with salinity.

In fact, the Saudi government announced plans a few years ago to build 25 gigawatts of CSP capacity by 2032, and a 2015 study concluded that combining CSP with evaporative desalination could make sense in the Middle East and in the U.S. Southwest. But nobody has put any solar technology into commercial desalination practice.

The original contractor on the Al Khafji site, which was designed to perform reverse osmosis using solar PV, narrowly avoided bankruptcy. SWCC divided the project into parts, handing the solar-PV component to one contractor and the desalination part to another. In the end, the desalination plant might run on the grid instead of on solar.

The setback has not fazed the Saudi government. In March, King Abdullah Economic City, in Saudi Arabia, broke ground on its own solar PV-powered desalination plant, which will also lean on the grid. —LUCAS LAURSEN

Energy costs make up 40 to 50 percent of the cost of desalination

—Carlos Cosín, CEO of Almar Water Solutions

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THE DIGITAL FINGERPRINTS OF BRAIN DISORDERS

Computers and phones monitor your brain's health through the way you type and talk

The medical professionals tasked with caring for our minds don't have an easy job. To diagnose people with neuropsychiatric diseases, doctors can perform brain scans, but such scans are expensive and the results are sometimes inscrutable. The other options include conducting time-consuming cognitive tests, or relying on doctors' own subjective analyses.

Seeing an opportunity, a number of startups have devised quantitative methods to diagnose diseases or assess mental health while patients complete routine activities, like talking on a smartphone, typing on a keyboard, or scrolling through a website. Here are three companies that say they can lift the "fingerprints" of mental disorders from people's mundane behaviors.

MINDSTRONG HEALTH

This Silicon Valley company began by collecting reams of data from smartphone sensors and usage logs in a clinical study with help from researchers at Stanford University. Many psychiatrists have wondered if data about a patient's movements and social activity can provide a window into mental health—for example, a person who stays in one place and doesn't call anyone might feel isolated and depressed. But cofounder and CEO Paul Dagum says that such data hasn't proved predictive.

"My days are really busy," he says. "On a Saturday, when I'm not getting any calls or emails and I'm in my living room reading a book, I'm not depressed—I'm actually very happy."

Mindstrong found clearer signals in the rhythms of a person's typing and scrolling on a smartphone screen—data that can be gathered from people's everyday activities. "These human-computer

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interactions, measured in millisecond response times, are predictive of a person's cognitive and emotional state," Dagum says.

Mindstrong's technology is already being used in pharmaceutical companies' trials for drugs targeting schizophrenia and depression; changes in test subjects' metrics indicate their response to medication. The startup is also working on several clinical projects. In the Aurora study, 12 hospital trauma centers are offering patients the Mindstrong app upon discharge, so that physicians can monitor them for signs of post-traumatic stress disorder. And in an upcoming study of postpartum depression, 4,000 women will be proffered the app during visits to their obstetricians.

NEURAMETRIX

From San Francisco comes a startup focused on typing cadence—how long people hold down each key, and how long it takes them to move their fingers from one key to another. Data that can be harvested by looking at keystroke combinations provides a unique signature for an individual, says CEO Jan Samzelius. Doctors can then keep an eye out for changes that may indicate trouble.

"We don't care how fast people type, or if they hunt and peck," Samzelius says. "If you're healthy, you should be incredibly consistent over all times of day, all days of the week, because the habit is hardwired into your brain. But when the brain gets attacked by disease, that wiring starts to break."

Samzelius hopes this measure of brain health will first be used to manage care for people with Parkinson's disease, depression, and Alzheimer's disease. These disorders all change typing cadences in particular ways, he says, citing an internal study about Parkinson's that he claims distinguished patients from healthy people with 99.9 percent accuracy.

NeuraMetrix wants health-care providers to use its app to monitor patients' conditions, and it's also offering an app directly to consumers. That consumer app doesn't provide an evaluation, a feature that could have gotten the company in trouble with government regulators. "At the moment, the app just says, 'Here's your consistency score,'" Samzelius says. It also shares the typical score range for a healthy person—and lets users draw their own conclusions.

WINTERLIGHT LABS

The third startup, Toronto-based WinterLight, takes samples of a person's speech to help clinicians diagnose and monitor Alzheimer's patients. Cofounder Liam Kaufman says the company originally considered more than 400 variables that could be drawn from speech. Then it used statistics to narrow the field to the 30 or 40 variables most useful in recognizing the signature of Alzheimer's. Other variables may prove helpful for other disorders, such as depression and schizophrenia.

Kaufman says that the traditional cognitive test for Alzheimer's is a pen-and-paper test administered in the clinic by doctors. With WinterLight's technology, patients could routinely record their own speech at home, and the company's algorithms would raise a red flag if they detect worrisome changes.

The company is initially selling its app to pharmaceutical companies searching for Alzheimer's drugs; no medication yet exists to stop the disease's progression. With drug development costs in the billions, Kaufman says, "these companies are looking for new ways to monitor response to therapy that are quicker and more reliable."

Another version could be used in senior-care homes. The cognitive assessments used in these facilities today "create a lot of anxiety," Kaufman says, because many patients know when they're flunking a memory test. People being evaluated through the WinterLight system simply describe what they see in a picture. "It's less obvious that there's a right answer," he says, "so people don't get stressed out."

—ELIZA STRICKLAND

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/brainhealth0518

FORGING VOICES AND FACES

JONATHAN KNOWLES/GETTY IMAGES

In a world where software can make anyone say anything, whom can you trust?

In 1963, before he could give the speech he'd prepared for his trip to Dallas, U.S. president John F. Kennedy was assassinated. In March 2018, a company re-created the speech that Kennedy had intended to give, synthesized from fragments of his own voice.

Technology companies including Google, Baidu, and Adobe have recently funded efforts to fabricate audio or video from samples of speech or fragments of footage. Startups including Voicery and Lyrebird have developed customizable human voices (built from audio recorded by professional voice actors) that can be programmed to say anything. These companies have also released do-it-yourself software that lets you synthesize your own voice (or someone else's, with their permission) from a 1-minute recording. And open-source tools to build such programs are available on Github.

The results are now convincing enough to raise concerns that these tools could fall into the wrong hands. "It's not unreasonable to think that you could fool a large group of people with the technology in the state that it's in today," says Michael Fauscette, chief research officer at the software review site G2 Crowd.

Someone could use a synthesized voice to deceive devices trained to recognize an individual's "voiceprint," or generate a fake video to use as blackmail. Fabricating statements by world leaders, or publishing fake videos of CEOs, could create problems much faster than those clips could be debunked.

To synthesize audio or video, experts have primarily focused on two techniques, both of which rely on machine learning: text-to-speech (generating humanlike speech from annotated voice recordings), and style transfer (in which the style of a piece of content, such as the 1889 painting *The Starry Night* by Vincent van Gogh, is imposed onto photos or videos).

Mikel Rodriguez, a machine-learning researcher at the Mitre Corp., says the algorithms used to fabricate videos are a twist on techniques that have long been used to classify images. Such programs rely on convolutional neural networks, in which artificial neurons learn to use a numerical matrix, called a filter, to assign values to pixels in an image.

These programs have traditionally used those values to draw a conclusion about an image's content—to say, for example, whether a photo shows a dog or doesn't show a dog. In the new versions, Rodriguez explains, "Essentially, instead of saying, 'Give me the answer,' you're saying, 'Give me the pixel.' "

Such systems are rapidly improving. In December 2017, Google researchers published a paper describing Tacotron 2, a text-to-speech (TTS) system based on neural networks that could generate speech that sounds as natural to listeners as recordings of people would. In February, Baidu described Deep Voice 3, a TTS system that can be trained much faster than the original version of Tacotron. A month later, Google published two more papers devoted to improving Tacotron's ability to convey humanlike expressiveness—such as intonation, stress, and rhythm—to match the content of its synthesized speech.

Companies believe the tools needed to synthesize voices or videos could become valuable products. CereProc, the company that synthesized Kennedy's speech, has created more than 100 custom voices for people who have lost their own due to illness. In a statement about its beta TTS project, called VoCo, Adobe said podcast producers or advertisers could use it to make last-minute edits to a show or voice-over.

To avoid misunderstandings, creators could embed a digital watermark into any synthesized media they produce. But there's no guarantee that everyone will follow the same rules. And there's no good way to independently tell whether a video or audio recording has been falsified. "Right now, there's no tool that works all the time," Rodriguez says.

Bryce Goodman, who co-led a workshop on machine deception at the Neural Information Processing Systems conference last December, is concerned about a wider loss of trust that such programs could engender: "I think we're still at the point of people not necessarily thinking through the implications of what their research or hobby projects have in the long run." —AMY NORDRUM

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/voicesynthesis0518

PHOTOGRAPH BY Ayane Shindo

DANCE MUSIC

SUCCESS IN CERTAIN professions—say, sports and the performing arts—is often tied to the ability to turn one's body into a finely tuned instrument. Dancers, who are an example par excellence of this connection, often demonstrate their mastery of timing, rhythm, and coordination in league with musicians. But last November, at a special performance in Tokyo, world renowned dancer Kaiji Moriyama literally became a musical instrument. While he danced, a specially adapted artificial-intelligence technology picked up signals from sensors attached to his body. The AI interpreted Moriyama's whirls, leaps, and shimmies in real time, turning them into Musical Instrument Digital Interface (MIDI) data, which a Yamaha Disklavier player piano then translated into notes and chords.

RESOURCES

1893: FRANCIS GALTON INVENTS THE GALTON WHISTLE, PERHAPS THE EARLIEST DEVICE USED TO INTENTIONALLY PRODUCE ULTRASOUND.

ACOUSTIC LEVITATION

MAKING THINGS FLOAT WITH ULTRASOUND

Magicians have long made things appear to hover without any visible means of support. For some reason, engineers delight in trying to turn this particular illusion into reality, and we're no exception at *IEEE Spectrum*. Back in 2014, for example, W. Wayt Gibbs wrote for us about how to make a miniature disco ball levitate using the power of electromagnetism. But that system works only for objects that can have a magnet attached. So, when I saw a kit promising to make any kind of small object float, even drops of liquid, I knew I had to have it.

The US $70 kit is from Makerfabs and is based on the TinyLev design created by Asier Marzo, Adrian Barnes, and Bruce W. Drinkwater as published in last August's *Review of Scientific Instruments*. (Their goal was to create an inexpensive way to examine materials using techniques like spectroscopy without worrying about contamination from a container. ▸

USE THE FORCE: Momentum imparted by interfering ultrasonic waves can hold small objects aloft against the force of gravity, such as this drop of colored water.

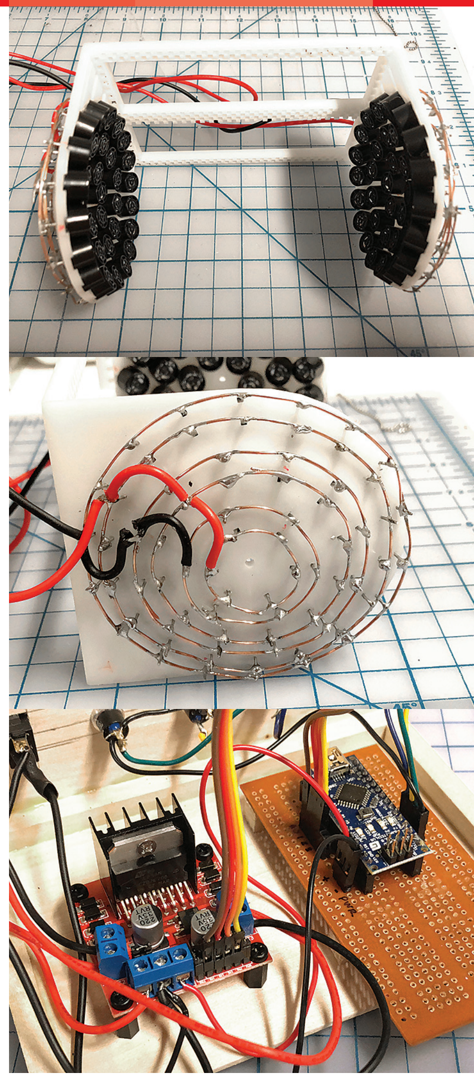
My goal is to be able to make something float while cackling, “Behold!”)

The basic operating principle is to set up an acoustic standing wave. Just as with a vibrating guitar string, such a standing wave will have nodes, which are spatially fixed points where the sound’s vibrations are at a maximum. A small object placed at one of the nodes will be held in position, thanks to the momentum imparted by vibrating air molecules.

The standing wave is formed by two opposing concave arrays of ultrasonic transducers, with 36 transducers per array. Sound waves emanating from the arrays interfere with one another to produce the standing wave.

Technically, you can create a standing wave using just two transducers pointed directly at each other, but using the arrays has two advantages. First, they deliver a lot more power, allowing for heavier objects to be held aloft and a wider separation between the opposing transducers. And second, the arrays’ curved shape focuses power toward the central axis of the levitator, providing lateral forces that keep levitating objects from drifting sideways out of the node.

The TinyLev can lift light objects with a maximum length of about 4 millimeters. The creators have even demonstrated the system with an ant. Their published paper has everything you need if you want to build the TinyLev completely from scratch, including files for 3D-printing the frame that holds the arrays, but you can save yourself a lot of trouble by buying the Makerfabs kit. In particular, the frame needs to be printed at a fairly high resolution or getting the transducers to fit into their shallow sockets may require a lot of finishing work. In addition to the transducers and the frame, the other major components are an Arduino Nano and a motor-driver breakout board. The motor driver provides the current to power the arrays. The Nano controls the driver by providing 40-kilohertz square-wave timing signals. The Nano can also be used to alter the phase difference between the two arrays, which lets you tweak the vertical position of floating samples.



STRENGTH IN NUMBERS: I mounted 72 ultrasonic transducers in a 3D-printed frame [top] and then wired them so that they are controlled in sync [middle]. The transducers are connected to a motor driver board that is controlled by an Arduino Nano [bottom].

Makerfabs’ online instructions are taken from the original scientific paper’s supplementary material and include some video. Ideally, I’d like to see Makerfabs reformulate the instructions for its website. As it is, I completely missed wiring one jumper because it was cropped out by the border of one diagram. It wasn’t until later, when I noticed the diagram could be enlarged, that I spotted the missing connection.

But the biggest mistake I made was all my own. Each transducer in an array has to emit a sound wave that is in phase with the rest. The instructions offer two different ways to determine the internal polarity of the transducers, so that they generate waves that are correctly phased when the driving signal is fed to the array. Looking at the transducers, I noted each one had a little “+” symbol by one leg and thus assumed that the transducers used in the instructions must be ones that didn’t have their polarity marked in this way. So, I wired in the transducers with regard to this symbol and hooked up the control circuitry, a straightforward if somewhat lengthy process that also entails downloading and installing control software into the Nano.

But when I turned it on, I realized that no power of levitation was present. Following the troubleshooting section of the instructions, I wired up two extra transducers to an oscilloscope. Using one transducer as a reference and the other as a probe, I measured the phase of the transducers in each array (just as a small speaker can be used as a microphone in a pinch, the transducers can convert ultrasound into a voltage). About a third of my sensors were out of phase, so I had to desolder, flip, and solder them back in.

Once that was done, I tested the array again and, with a bit of trial and error, managed to successfully float a small chip of wood. I built a wooden case to support the TinyLev’s frame and hold the control electronics.

I then tried to levitate everything in reach that was about the right size and weight. Finding the invisible nodes proved tricky. I got my best results from using clumps of sawdust loosely held with tweezers, as it’s easy to see the sawdust twitch when it’s being vibrated. Tiny amounts of sawdust can also help to mark the locations of the nodes when you are trying to levitate something more substantial.

It’s really pretty impressive to see multiple objects levitating at once, each in its own node. And once you do get something to float, the system can be surprisingly stable: I have had objects levitating for several hours, which allows me to indeed cackle, “Behold!” whenever someone comes into my office, without any embarrassing utterances of “Wait, wait, just let me try it *one* more time....” **—STEPHEN CASS**

POST YOUR COMMENTS at https://spectrum.ieee.org/levitation0518

WHAT YOU NEED TO KNOW ABOUT EUROPE'S DATA PRIVACY RULES

NEW GDPR REGULATIONS ON PERSONAL DATA WILL AFFECT EVEN INDIVIDUAL CODERS

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On 25 May, enforcement will begin of the European Union's General Data Protection Regulation (GDPR): a law covering any organization anywhere in the world that handles the personal data of EU residents. Many individual developers and small-business owners will need to make sure that their applications, services, and websites comply with the GDPR, even if they do not live in EU countries.

The GDPR aims to give Europeans a clear understanding of who has their personal data and more control over its use. This means organizations must be much more disciplined about capturing and using personal data. "You need to be able to produce, delete, and audit the data easily," says Michela Palladino, director of European policy and government relations for the nonprofit Developers Alliance.

Individual developers can get started by mapping out all the personal data in their possession. GDPR defines personal data as anything that could directly or indirectly identify a person, such as a name, a photo, an email address, bank details, posts on social networking websites, or medical information. In addition, the regulations also cover "special categories of data," says Lydia de la Torre, a privacy law fellow at Santa Clara University, in California. These special categories include racial or ethnic origin, political opinions, religious or philosophical beliefs, trade union membership, and data concerning a person's sex life or sexual orientation.

The next step for developers is to understand what they would need to change in order to comply with the GDPR, says Palladino. She recommends simply no longer collecting any personal data that is not actually needed (and deleting any such archived data), to minimize complications and risks.

For the personal data that is needed, developers must clearly specify the intended use and seek consent in each use case. "For example, if you are collecting telephone numbers from users in order to enable two-factor authentication, you cannot then use those same telephone numbers for a different purpose," de la Torre says.

Some collection and data use do not require consent under the flexible category known as "legitimate interest," says Bozhidar Bozhanov, founder and CEO of the secure auditing company LogSentinel, in Bulgaria.

For example, a website comment box that invites users to leave both a comment and email address could use that email address to notify them about follow-up comments under the legitimate interest category, Bozhanov says. But using the email address for other purposes, such as auto-registering them for another website, would require consent.

Developers and website owners probably need not panic over basic processes such as logging IP addresses. Simple access logs should not be a problem because they rotate frequently and cannot be used on their own to identify an individual person.

"If you store the IPs of users and actively try to correlate IPs with behavior, then you should ask for consent," says Bozhanov. "But if you do that, you are probably not a small-website owner."

Small-website owners, with a few hundred users, may not attract the spontaneous scrutiny of regulators but could find themselves facing individuals demanding their GDPR rights. Such individuals could also file complaints with regulators. Enforcement authorities will be holding audits to ensure compliance with the GDPR, so start keeping detailed logs and reports.

"Don't assume the data on your website doesn't matter," Bozhanov says. "On the other hand, don't be too scared of huge fines and don't rush to pay expensive consultants. But do make sure you have adequate—a word used too often in the regulation—protection of users' data." The Developers Alliance's Palladino recommends taking an in-depth look at who within the organization has access to personal data and to start limiting access where possible.

De la Torre recommends reading the *Privacy by Design* report by the European Union Agency for Network and Information Security. She also suggests that independent developers and small-business owners follow updates from the Electronic Frontier Foundation. **—JEREMY HSU**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/gdpr0518

BREAK THESE HABITS FOR A BETTER WORKPLACE

JOAN WILLIAMS CREATES PRACTICAL TOOLS TO COMBAT GENDER DISCRIMINATION

It's not news that women engineers face biases in many workplaces. However, traditional workplace-mandated diversity training doesn't make things better. Joan Williams, director of the Center for WorkLife Law at the University of California Hastings College of the Law, in San Francisco, wants to change that. Last year, Williams launched Bias Interrupters, a free set of tools for managers and organizations to correct discriminatory practices—and, hopefully, hire and retain a diverse engineering workplace. She spoke with Katherine Bourzac for *IEEE Spectrum*:

Katherine Bourzac: What kinds of bias do women engineers experience at work?

Joan Williams: In our 2016 study, women engineers reported feeling disadvantaged by virtually every workplace process. Women work more and get paid less, get less honest feedback, and were less likely than white men to report they had equal access to networking, or that their performance evaluations were fair. A narrower range of behavior is accepted from women than from men, and we've also found pretty marked differences by race.

The same behavior may be seen as admirably assertive in a man but lamentably aggressive or abrasive in a woman. Women tend to get larger loads of what we call "office housework," tasks like finding a time when everyone can meet, taking notes, and planning office parties. They get less of what we call the "glamour work," so that twice as many women as men reported pressures to let others take the lead.

K.B.: Do traditional diversity trainings help?

J.W.: No, they've been shown to be quite ineffective. Giving a one-shot bias training, having a "women's initiative"—all those things are good ideas. But if you have gender and racial bias being constantly transmitted day after day through your basic business systems, having an employee resource group is not going to solve that problem.

K.B.: What can organizations do?

J.W.: We have developed a set of evidence-based tools at Biasinterrupters.org that can be used to interrupt bias in hiring, performance evaluations, and assignments. Tools for compensation are coming.

We've tried to make it really easy. You start out with an assessment. There are tools online that tell you what exactly to measure. The second step is to interrupt the bias if you find it, which you probably will.

For example, we have an office-housework survey that an organization can use to find out who is doing the office housework in their environment and a protocol to find out who is getting the glamour work. We have tools to help managers allocate this work fairly.

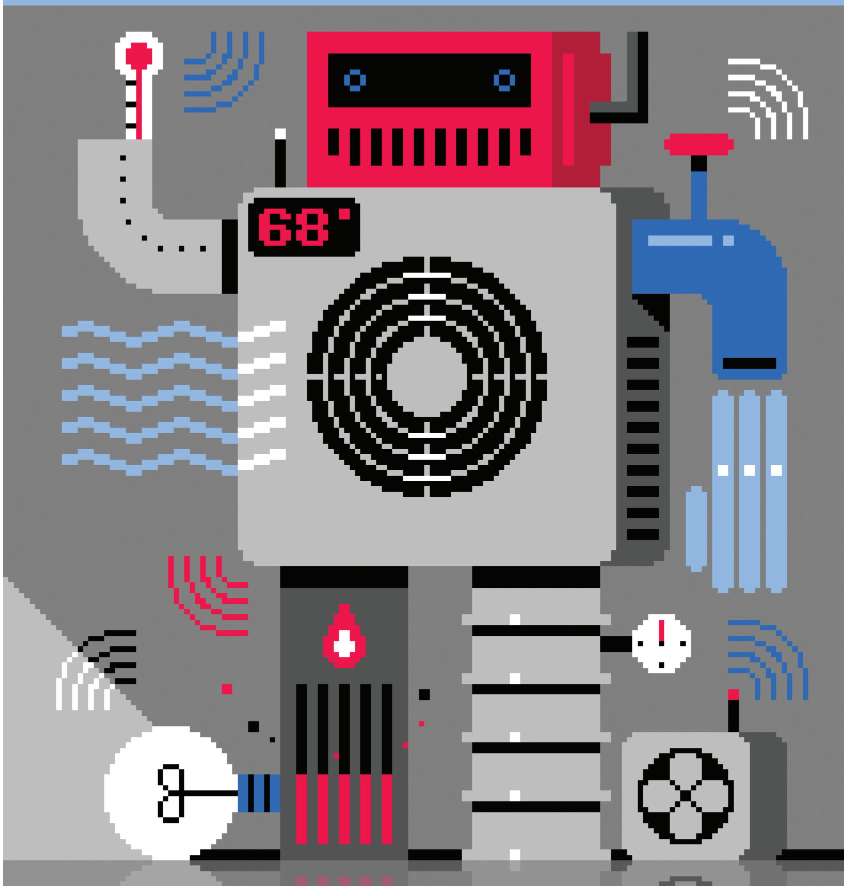
K.B.: What if the company is not on board? What can individuals do?

J.W.: We have tools that individual managers can use, for example during performance reviews. We offer a worksheet you can hand out to anyone who's required to do a self-evaluation, explaining that she needs to tell about everything awesome that she's done! Women, Asian-Americans, and professionals who are first-generation college graduates are predictably going to give a modest self-evaluation. These groups have been brought up, or sense in their environment, that a modesty mandate applies to them. That's going to systematically disadvantage them.

Workers who are experiencing bias should get my book *What Works for Women at Work* [NYU Press, 2014]. It has strategies that successful women have used to navigate subtle forms of gender bias. For example, research shows that people who engage in self-promotion get further than people who don't. Yet research also shows that women who engage in self-promotion encounter pushback because women are expected to be self-effacing and nice. How do you thread that needle? One of the strategies savvy women use is the posse. Develop an alliance with people about at your level or one notch above and celebrate and promote each other's successes. That is not only going to not hurt you, it probably will help you. It will be a way of getting your accomplishments known, and also enhance your reputation as being a good team player—which is what the "good woman" is required to be.

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/williams0518

JOSE LUIS PELAEZ/GETTY IMAGES



HOW TO IoT

IN A HOME or on a manufacturing floor, there's no point in connecting something just so it's online. You must have a reason.

Andy Rhodes, the former vice president and general manager for Dell's Internet of Things (IoT) commercial sales division, once told me that he no longer takes phone calls from companies asking for "some IoT." If the company doesn't know what it wants to do with connected devices, it isn't ready for a sales talk.

So how does a management team decide what it wants from the IoT?

There are two paths here. The first is to start small with a project that can offer a short-term return on investment (ROI). In a factory, this could mean installing cameras and sensors on a manufacturing line to replace human spot-checkers. Cities might install sensor-infused LED lighting to reduce energy costs.

The second path is a bit more visionary: Build a platform or product that can change your entire business model. For example, in 2015 Emerson Climate Technologies launched a new connected product in its HVAC business. With US $100 worth of sensors per home, the HVAC installer and Emerson could guarantee a period of time that a customer's heating or cooling system would operate before needing repairs.

The ROI on this project is still unclear. But the idea was that tracking how hard the AC unit was running, and how long it takes to cool a home, could change Emerson's business model from offering a product (HVAC units) to delivering a service.

However, Emerson's client would have to add sensors, connectivity, and a gateway. And that requires labor at every point, which means it doesn't scale in the way that traditional IT projects scale.

Upal Basu, general partner at NGP Capital, is concerned that focusing on short-term ROI leaves a lot of money on the table. He says the value in IoT deployments comes from data gathered by sensors—not from some centralized platform.

But a long-term approach is far more costly to execute. Which is why most companies will try to tweak small production lines or other minor functions within their businesses first.

Once a company has decided on a problem to solve—whether it's saving energy by turning off lights or using sensors to gather information on a factory floor—the next step is to figure out who has done a similar project and talk to them about their process.

Peter Zornio, chief technology officer at Emerson Automation Solutions, says most clients turn to his team to understand how Emerson's automated plant operations would work for other facilities.

"Unless you have a sparky operations guy who is reading about this—they may come to you with a specific example and solution—most customers come to us because we've already done this," he says.

When it comes to assessing ROI for a deployment, there are so many metrics and factors involved that it can be daunting. Even tech giants such as Microsoft and Cisco have signed partnerships within highly specialized industries like manufacturing, health care, and construction to develop the expertise they need to help clients.

Essentially, a large-scale industrial IoT project isn't something you should ever try to do alone. ■

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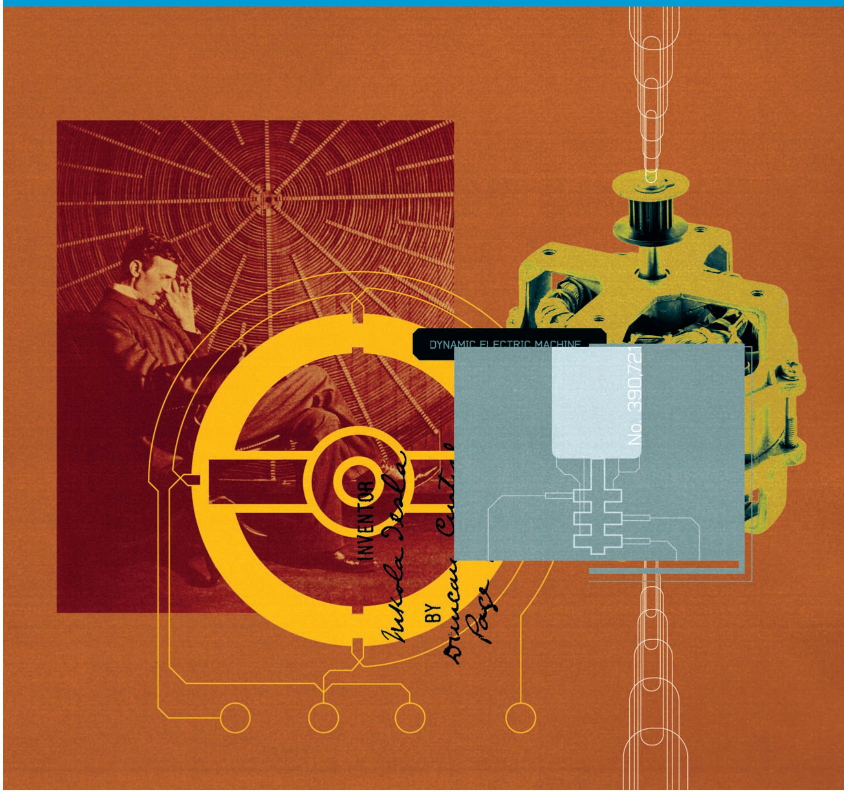
ILLUSTRATION BY Nicholas Little



MAY 1888: TESLA FILES HIS PATENTS FOR THE ELECTRIC MOTOR

ELECTRICAL DEVICES ADVANCED by leaps and bounds in the 1880s, which saw the first commercial generation in centralized power plants, the first durable lightbulbs, the first transformers, and the first (limited) urban grids. But for most of the decade, advances in electric motors lagged behind. • Rudimentary DC motors date back to the 1830s, when Thomas Davenport of Vermont used his direct-current motors to drill iron and steel and to machine hardwood, and Moritz von Jacobi of St. Petersburg used his motors to power small paddle wheels on the Neva. But those battery-powered devices couldn't compete with steam power. More than a quarter century passed before Thomas Edison finally commercialized a stencil-making electric pen, to duplicate office documents; it, too, was powered by a DC motor. As commercial electricity generation began to spread after 1882, electric motors became common, and by 1887 U.S. manufacturers were selling about 10,000 units a year, some of them operating the first electric elevators. All of them, however, ran on DC. • It fell to Edison's former employee, the Serbian-born Nikola Tesla, to set up a company of his own to develop a motor that could run on alternating current. The goals were economy, durability, ease of operation, and safety. But Tesla was not the first to go public: In March 1888, the Italian engineer Galileo Ferraris gave a lecture on AC motors to the Royal Academy of Science, in Turin, and published his findings a month later. This was a month before Tesla's corresponding lecture at the American Institute of Electrical Engineers, one of IEEE's predecessor societies. However, it was Tesla, helped with generous financing from U.S. investors, who designed not only the AC induction motors but also the requisite AC transformers and distribution system. The two basic patents for his polyphase motor were granted 130 years ago this month. He filed some three dozen more by 1891.

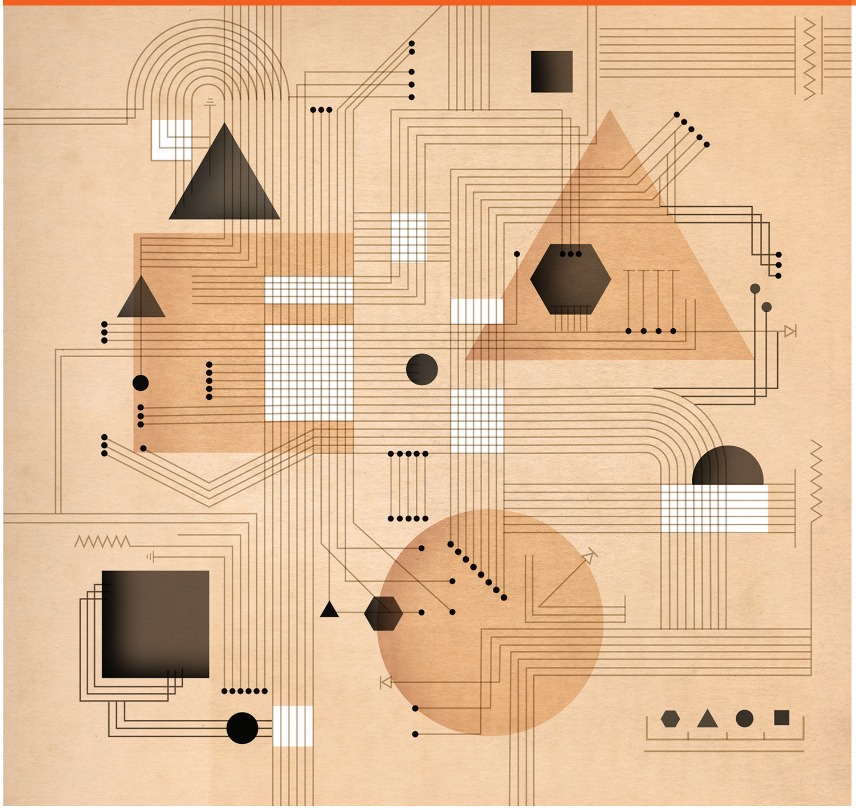
In a polyphase motor, each electromagnetic pole in the stator—the stationary housing—has multiple windings, each of which carries alternating current that's out of phase with current in the other windings. The differing phases induce a current flow that turns the rotor.

George Westinghouse acquired Tesla's AC patents in July 1888. A year later Westinghouse Co. began selling the world's first small electrical appliance, a fan powered by a 125-watt AC motor. Tesla's first patent was for a two-phase motor; modern households now rely on many small, single-phase electric motors. The larger, more efficient three-phase machines are common in industrial applications. Mikhail Osipovich Dolivo-Dobrovolsky, a Russian engineer working as the chief electrician for Germany's AEG, built the first three-phase induction motor in 1889.

Today, some 12 billion small, nonindustrial motors are sold every year, including some 2 billion tiny (as small as 4 millimeters in diameter) DC devices used for cellphone vibration alerts, whose power requirements come to only a small fraction of a watt. At the other end of the spectrum are 6.5- to 12.2-megawatt motors powering French rapid trains (TGV), while the largest stationary motors used for compressors, fans, and conveyors have capacities exceeding 60 MW. This combination of ubiquity and power range makes it clear that electric motors are truly indispensable energizers of modern civilization. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/tesla0518

PHOTO-ILLUSTRATION BY Stuart Bradford



DEEP COMPLEXITIES IN EE

FROM TIME TO TIME I HAVE SEEN Internet videos of seemingly impossible gymnastic performances. Sometimes the links to these videos have been accompanied by a comment by the poster to the effect of "I could do this if I wanted, but I choose not to." This brings a little smile to my face, but I've been thinking lately that I've been telling myself something similar when I see some of today's technical literature. • The scope of electrical engineering has been growing continuously through the years, but so too has the depth of complexity and required knowledge across this ever-larger landscape. There are many more highly trained engineers worldwide now than there were a few decades ago, so new applicable knowledge accumulates at a faster pace, while it seems that older, irrelevant knowledge leaves the field more slowly. There is more to know, and it is more demanding and complex. • I took a cursory look, for example, at the mathematics in information theory or the physics in quantum computing or in electronic and optical devices, and I said to myself, "I could do this if I wanted, but I choose not to." • I remember when engineering seemed much simpler. As I write this, I'm noticing across the room the little blinking node on my Wi-Fi mesh network. Not so long ago AM/FM radios and TVs were the ubiquitous home electronics exploiting the electromagnetic spectrum. Those were the days when radios were just simple devices whose only standardization was the frequency band and a fairly simple modulation scheme. Take a look, though, at the specification for the IEEE 802.11ac family of Wi-Fi transceivers.

There are many, many pages of complicated minutiae needed to describe the protocols, controls, signal formats, and so forth. Then, if we dig down deeper, the math for multiuser MIMO (multiple-input, multiple-output) needs to be understood. The encryption is based on elliptic curve cryptography–try checking that out. Everywhere we look at increasing depth, the complication turns to turgid complexity. That is the world we live in now.

How is it that we can survive and indeed thrive in such a world? The obvious answers are specialization to narrow the field, and the layering of knowledge to reduce complexity to only that needed for a given purpose. In this latter pursuit we are aided by software that empowers the user while hiding the underlying complexity. I think that most engineers seldom will have the need, or the privilege, to examine the complex math and physics beneath so much of what we do. I'm reminded of the perhaps apocryphal tale of Richard Feynman's advice on understanding quantum mechanics, when he said to just "shut up and calculate."

So, am I kidding myself that I could do this stuff if I chose to? I hope not, but I can't be sure. The problems are time and motivation. I have the engineer's curiosity and I want to know everything, and it bothers me when I don't truly know how something works. But there is limited time and so very, very much to know. Sadly, I have to choose, and the choices are influenced by motivation. There are things that I have to know, and things that it would be nice to know. Often, the former overwhelm the latter.

The way complexity is increasing, I imagine that in the future, computers will be writing papers for the IEEE societies' *Transactions*, but those papers will be so complex that only other computers will be able to understand them. A lot of the fun will be gone. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/reflections0518

ILLUSTRATION BY Chad Hagen

ELECTRIC BLUE SKIES

ILLUSTRATION BY Jonathan Carlson

Zunum Aero's hybrid-electric airplane aims to rejuvenate regional travel

By Matt Knapp & Waleed Said

In the century that's elapsed since the dawn of commercial aviation, air transportation has become pretty well refined. Yet paradoxically, it's easier to fly halfway around the world than to travel to a nearby city. As a result, many people shun air travel when taking short trips.

Consider the process: From an origin point, you must first travel via car or rail to an often-distant metropolitan hub airport. Then, you wait in line to pass through security. You wait some more to board at the gate. You and your fellow passengers wait still more to taxi to the runway before your plane finally takes off. Then you repeat most of the ordeal in reverse on the other end, having spent approximately 70 percent of your travel time on the ground. It's little wonder that in the United States, 10 percent of round-trips between 800 and 1,600 kilometers (500 to 1,000 miles) and less than half a percent of those under 800 km are undertaken by air.

Putting up with the delays and inconvenience would be easier if short-haul air travel were less expensive than surface transport. It's not, though, largely because takeoffs and landings with small jet engines burn large amounts of costly fuel.

In contrast, cruising for long distances, especially with today's larger engines, efficiently sips rather than guzzles. These economies of scale and range have driven even regional operators to offer longer flights on larger planes. Today, regional planes average 80 seats, up from 20 seats in the early 1980s.

Back then, airline operators in the United States made greater use of the airports spread throughout the country–now there are 13,500 of them, the most of any nation in the world. Just 1 percent of this vast number of airports carries over 96 percent of air traffic. Unsurprisingly, regional door-to-door times are worse today than they were 50 years ago. And it is not just individual airline passengers who suffer from having to waste half the day schlepping to and then waiting around at large airports. In the globalized economy, communities without good air service struggle to attract investment and create jobs.

To undo the damage, we and others are looking to hybrid-electric aircraft propulsion, a system made possible by the convergence of technological trends in battery development, high-power motors, and power electronics. When we began in 2013, no one in commercial aviation was thinking in these terms. At the time, electric propulsion was not considered remotely feasible, except perhaps for a very light trainer. But as we looked at development trends for batteries, motors, power electronics, and almost as important, the regulations that support the industry, it became clear that the technology would come of age in the early 2020s.

Aircraft development typically takes five years or longer, which is why our company, Zunum Aero, embarked on its mission right away rather than waiting for the technology to mature. This decision has paid off, and we have brought these technologies together in Zunum Aero's recently unveiled design for a 12-passenger hybrid-electric airplane, which we're building now. We plan to conduct our first flight tests in 2019. Beginning in 2022, we plan to sell these planes to airlines, perhaps including JetBlue, which together with Boeing is backing our efforts. Other players have more recently entered the fray, and we welcome them: Their decision validates our concept.

We expect our plane to offer 40 to 80 percent lower operating costs than those of regional aircraft today, which would save passengers money and greatly reduce the noise heard in the cabin and down below on the ground. As hybrid-electric short-haul flight spreads, it will reinvigorate thousands of underused regional airports, slashing door-to-door times for travelers. What's more, the new propulsion system will lower carbon emissions from aircraft by up to 80 percent, rising to 100 percent when short-haul planes become fully electric in the 2030s.

Sure, there's a lot of work to be done to get there. But we're not starting from square one. Zunum is adapting for aviation many discoveries already made in the development of hybrid-electric automobiles, buses, and ferries. The substantial investment and rapid innovation in vehicle-drive technologies, helped along by the breakneck pace of growth in consumer electronics, has provided an opportunity for hybrid-electric propulsion to revamp aviation as well.

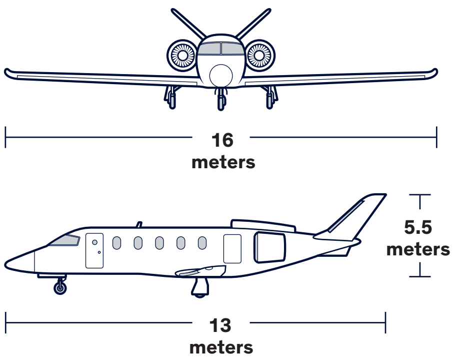
We plan to conduct our first flight tests in 2019. Beginning in 2022, we plan to sell these planes to airlines

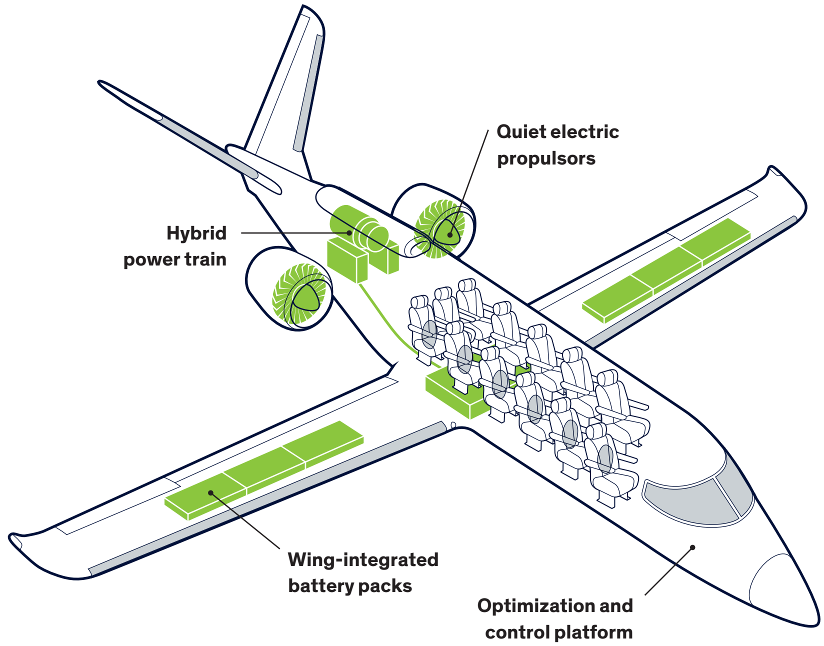
T**he hybrid-vehicle market** has come a long way since the advent of the Toyota Prius in the late 1990s. Just a few thousand of these pioneering vehicles were sold stateside in the year 2000. In 2017, nearly 400,000 hybrid-electric vehicles left U.S. dealers' lots, offered in about 60 different models from more than a dozen manufacturers, according to data compiled by HybridCars.com. That sales figure actually fell from a peak in 2013, when about half a million hybrid-to-electric cars sold domestically before lower gasoline prices temporarily chipped away at their appeal. The effect was to spur technological development of hybrid-electric drivetrains and components, many of which can be either used directly or mimicked in electric flight.

Meanwhile, widespread adoption of hybrid diesel-electrics for municipal bus services has led to key advances in onboard energy management. This process involves computer-driven switching between batteries and conventional fuel, to save money on energy and to ensure that the bus has the range to cover its route before it needs to recharge and refuel. The same concept will, of course, apply to the efficient, cost-effective, and safe operation of hybrid-electric aircraft.

The maturation of these technologies on terra firma has even started to translate to water transport. Hybrid ferries using a variety of energy-reaping methods–including solar and wind–to charge batteries alongside traditional diesel engines are now operating in some cities, including New York and San Francisco. Norway launched the first all-electric car ferry and commercial fishing boat, which entered service three years ago. And a recent report shows that 70 percent of that country's fleet of 180 ferries could readily change over to hybrid- or battery-based propulsion.

BATTERIES ARE INCLUDED: Zunum Aero's regional hybrid-electric plane stores lithium-ion batteries in the wings for supplemental power, particularly on takeoff. Cruising power is generated by a gas turbine linked to a generator, in the back.





A common denominator in these efforts is better batteries, above all lithium-ion batteries, which continue to pack ever more energy into lighter cells. Such energy density is especially critical for aviation. Since 2010, battery pack costs have fallen from US $1,000 per kilowatt-hour to less than $250/kWh today, with a concomitant increase in energy density. Other critical technologies, such as supercapacitors and power converters, have likewise improved by leaps and bounds.

Our aircraft is powered by a pair of low-pressure ducted fans, each driven by an integrated 500-kilowatt permanent-magnet motor. The fans provide high static thrust for takeoff, high efficiency for cruising, and—in part because of the ducting—significant reductions in noise. Indeed, this design produces between a third and a fifth less noise than do traditional jet engines and turboprops, allowing our design to serve airports near towns without bothering the residents so much. We call these ducted fans "quiet electric propulsors" (QEPs).

The QEPs draw electricity from batteries, supplemented by a 500-kW generator driven by a small, highly efficient gas turbine. The gas turbine doesn't produce thrust, just electric power to drive the QEPs. It shuts down when it isn't needed, saving fuel. The combination forms a series hybrid-electric power train, which is managed by a control system that minimizes the pilot's workload while maximizing system efficiency.

We stow the batteries in the wings, where fuel tanks would normally reside. These batteries are designed for quick swap-outs at airports should there be too little time for an adequate recharge. Their cells have a minimum power density of 350 watt-hours per kilogram—a level now becoming readily attainable and enough to meet the aircraft's power needs. Advanced lithium-ion cells currently provide this energy, but we are intentionally designing our planes to be flexible about the battery chemistry used, given the incredible pace of innovation in this sphere. In this way, the aircraft will be future-proofed and ready to accept the latest chemistries and form factors that the battery industry provides.

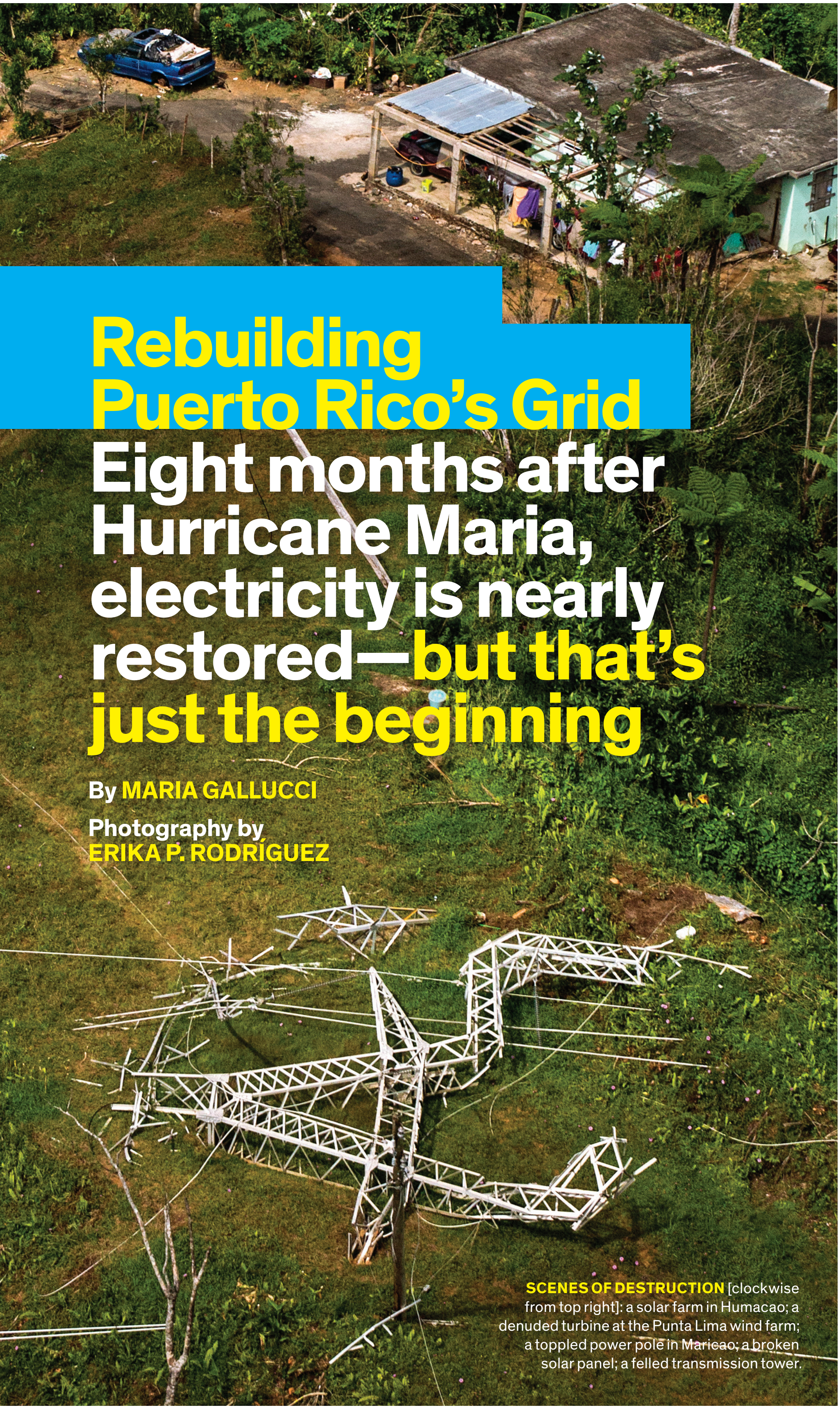
We have developed proprietary algorithms specific to aircraft to optimize performance and range. The system first develops a minimum-energy plan for the route and then monitors and updates the plan in flight based on sensor readings from the onboard motors, batteries, and fuel tanks, as well as from real-time flight data and weather reports.

Such methods have already eased the job of pilots in steering airplanes using what are known as "fly by wire" systems. Here it is a power-by-wire experience, with the power-optimizing control system seamlessly managing the loads and sources to achieve the thrust and range needed for each phase of the flight. Built-in fail-safe conditions, such as redundant power and cooling paths for critical power-train equipment, will further ensure successfully getting from point A to point B.

Our primary concern for the fan and power train is total propulsive efficiency at minimum weight, because even subtle changes in design details can have a big impact on the power required, and hence on aircraft performance.

Because we plan to deliver a Zunum plane to our first customer in 2022, we have established precise testing milestones for the coming 18 months. These include producing a "copper bird"—a model of the electrical systems—at a testing facility in Illinois. At the same time, we will | CONTINUED ON PAGE 52

ILLUSTRATION BY James Provost



Rebuilding Puerto Rico's Grid

Eight months after Hurricane Maria, electricity is nearly restored—but that's just the beginning

By MARIA GALLUCCI

Photography by
ERIKA P. RODRÍGUEZ

SCENES OF DESTRUCTION [clockwise from top right]: a solar farm in Humacao; a denuded turbine at the Punta Lima wind farm; a toppled power pole in Maricao; a broken solar panel; a felled transmission tower.

As Hurricane Maria churned menacingly toward Puerto Rico on 19 September,

Gary Soto was hunkering down on the outskirts of San Juan. Soto, the operations manager of Puerto Rico's state-run utility, faced a daunting task: to keep the grid running and minimize damage from the storm.

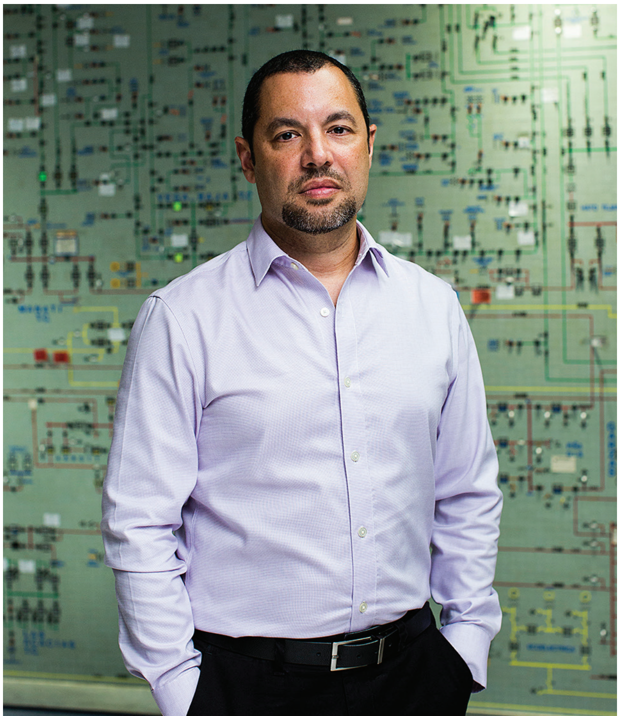
In the windowless, wood-paneled control center at the Puerto Rico Electric Power Authority (PREPA), Soto and a dozen other engineers and supervisors worked at U-shaped desks littered with paper coffee cups, staring at computer monitors that displayed real-time conditions on the grid. One after another, transmission lines were failing, and the team hastily debated their course of action. In this fragile state, the network wouldn't be able to absorb an oversupply of power, excess voltages, or swings in frequency. They could inject test currents into the downed lines, to see which ones could be restored, or else reduce the level of electricity being put on the grid, to protect the remaining transmission system. Hour after hour, the team's chatter filled the room with rising urgency.

By nightfall on the 19th, the PREPA crew knew their efforts were futile. Outside, winds topping 280 kilometers per hour had begun toppling transmission towers, snapping power poles, entangling lines, and battering power plants. The PREPA engineers watched in dismay as small outages spread and bloomed like a virus. Finally, at 2 a.m. on 20 September, Soto says, "We went into total blackout."

All of Puerto Rico was now in the dark.

Four hours later, Maria barreled into the island, the strongest hurricane to hit Puerto Rico since 1928. The storm tore a diagonal 160-km-long path from the island's southeast to its northwest, demolishing tens of thousands of homes, washing away roads and bridges, stripping the limbs from lush green palms, and leaving in its wake a jarringly lifeless landscape. Unofficial tallies after the storm suggest that about 1,000 people lost their lives.

In the months to come, Puerto Ricans—who are, after all, citizens of the United States, a country of unquestioned technological preeminence—would discover how breakable their modern society actually was. Water treatment facilities couldn't provide drinking water, markets and restaurants couldn't refrigerate food, banks couldn't operate ATMs or conduct transactions. Cellular and Internet access was gone. Streetlights and traffic lights stopped working. Schools, hospitals, and stores closed indefinitely. Factories shut down; tourism ground to a halt. After the storm, 200,000 Puerto Ricans decamped for the mainland United States in search of jobs, medical care, or just modern comforts. At press time, seven months after the storm, 94 percent of PREPA's nearly



PICKING UP THE PIECES [clockwise from left]: Blue tarps serve as temporary roofs; Col. John Lloyd of the U.S. Army Corps of Engineers; a new power pole goes up in Guaynabo; Eric Silagy of Florida Power & Light; Gary Soto of the Puerto Rico Electric Power Authority (PREPA).

1.5 million customers had power. But occasional blackouts were still occurring, and U.S. officials were saying that remote areas in "challenging terrains" would not get service until the end of May.

The restoration of Puerto Rico's power grid is an object lesson on the vulnerabilities of electrical networks and on the emerging options for minimizing those vulnerabilities. Power experts are now not just repairing the grid but doing so with an eye toward a future that portends storms of increasing intensity and frequency. Grid operators around the world are considering the merits of microgrids, utility-scale energy storage, and distributed and renewable generation. But for Puerto Rico, these possibilities are of more than abstract interest.

This past December, I traveled to Puerto Rico to report on this massive undertaking. I found contradictions everywhere I went. I saw utility workers fanned out across the island, yet progress remained excruciatingly slow. I met rank-and-file PREPA employees working flat out to restore power, yet each day brought a new report of fumbles at the utility's top levels. And I heard many smart and exciting ideas for how to build a modern, resilient grid in Puerto Rico, even as the urgent need to restore power meant resurrecting the vulnerable existing system.

AS SOON AS THE STORM CLEARED, recovery efforts at the PREPA control center began. Step one was to figure out what exactly had happened, all over the island. The control center was running on a diesel generator, but island-wide communications were down. That meant the usual way of gauging conditions on the grid—using automated remote terminal units at substations to collect and send data to the central SCADA (supervisory control and data acquisition) system—didn't work. PREPA's grid reaches nearly every home, business, school, and hospital on the main island, as well as on the smaller islands of Vieques and Culebra. For months, the utility was unable to say just which customers were still in the dark.

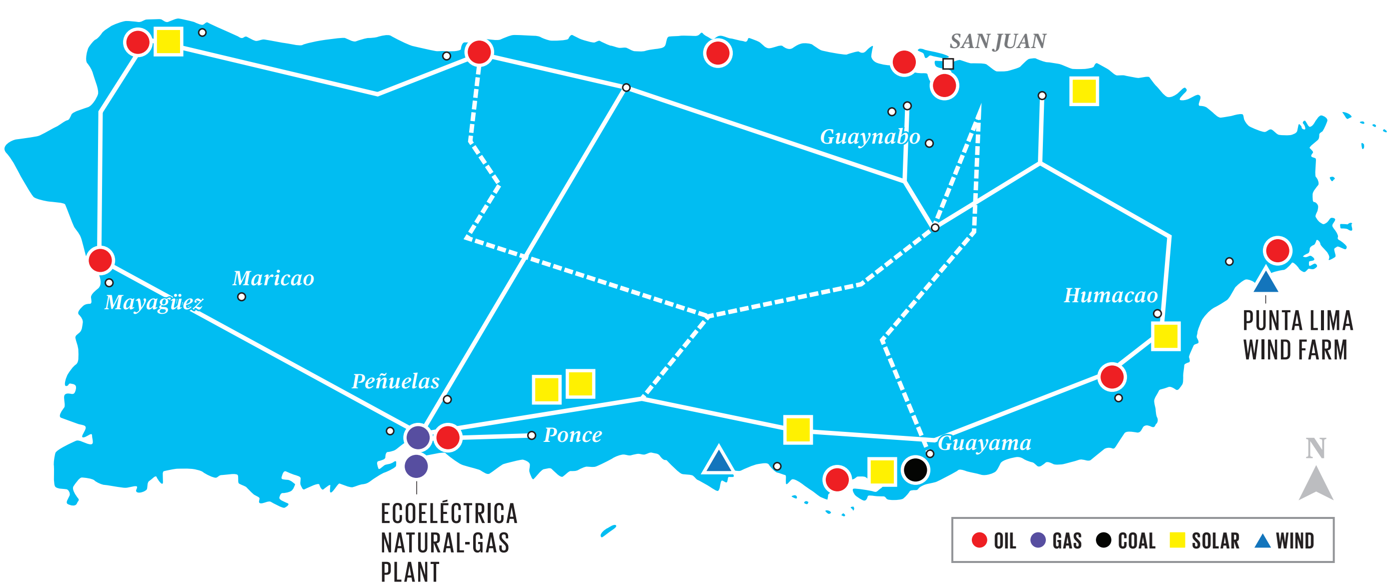
Under normal conditions, Puerto Rico's generating capacity exceeds 5,800 megawatts, but peak demand is only around 3,000 MW. About half of the electricity comes from PREPA's 10 oil-fired power plants. Much of the rest is produced by a pair of natural-gas power plants and a coal plant. Renewables—including seven solar farms, two wind farms, and seven small hydropower sites—supply just 2.4 percent of generation.

Seventy percent of Puerto Rico's power generation is in the south, while 70 percent of power demand is in the north. This disparity reflects decades-old decisions to build up the island's manufacturing base. Back in the 1970s, mainland U.S. companies were lured to Puerto Rico by a generous tax incentive, and many sited their factories in the south. Accordingly, PREPA expanded its power generation and transmission infrastructure to service those facilities. But in 1996, the U.S. government began phasing out the tax break, and manufacturers moved overseas. Now PREPA's biggest customer base is on the other side of the island, centered around San Juan.

Soto calls the south-to-north transmission lines that bisect the island "one of the biggest problems of how PREPA is configured." Hurricane Maria sliced straight through these vital connections, only 15 percent of which were designed to withstand a Category 4 hurricane.

From the control center, Soto and I drive to a grassy clearing and climb aboard a PREPA helicopter. We rise up into the air, and buildings in San Juan's outskirts soon give way to undulating green mountains and plunging valleys, the bright blue Atlantic Ocean glimmering in the distance.

As the helicopter veers southeast, scenes of unsparing destruction emerge. Steel lattice transmission towers lie in broken piles. High-voltage wires wrap around treetops. At the Punta Lima wind farm, the masts of turbines, their blades shorn



LOPSIDED GRID: The solid and dotted lines show parts of Puerto Rico's 230-kilovolt and 115-kV transmission networks, including the north-south corridors that were severed by Hurricane Maria. Restoring those lines is crucial, as most of the power generation lies in the south, while most of the population lives in the north. The island still leans heavily on fossil fuels for its electricity, with renewables supplying just 2.4 percent of generation.

HELPING HAND: Ivette Vizcarrondo [far right] needed a way to charge her son's nebulizer. Solar engineer Gabriel Rivera [above] installed an emergency solar charging system on the roof. A yellow power cord leads to the Vizcarrondos' apartment [right].

off, stick up like fat white flagpoles. Near the beach town of Humacao, a solar farm has been reduced to fields of shattered glass and twisted metal. Blue tarps dot the landscape; these temporary roofs are all that shield the buildings' occupants from the elements.

The storm damaged, destroyed, or otherwise compromised 80 percent of the island's grid, according to the U.S. Army Corps of Engineers, which is in charge of its reconstruction. Of 334 substations, nearly 40 percent suffered major harm. Some power plants were hardly touched, while others were devastated. The largest facilities were operational within weeks but couldn't export their power to the grid until the network was repaired.

A storm the size of Maria would have wreaked havoc on any electric system in its path. But Puerto Rico's grid was especially vulnerable to extreme weather. Decades of mismanagement and questionable practices left PREPA US $9 billion in debt. Puerto Rico's decade-long recession, shrinking population, and declining manufacturing sector further eroded revenues. To stem costs, PREPA halved its workforce, leaving the remaining 5,000 employees, like Soto, to juggle multiple roles. Routine maintenance, like clearing brush impinging on power lines, got deferred, and aging equipment wasn't replaced. Last July, PREPA filed for bankruptcy.

Traveling around the island, I see signs of PREPA's decline everywhere. Along a small creek, houses have been built directly on an access road leading to transmission lines. Repair crews have had to either airlift in replacement parts or haul them in through people's yards. In a San Juan neighborhood, a yellow excavator scoops thick mud. Over the years, a nearby lagoon has taken over a right-of-way, filling it with goop that's bogging down workers' trucks.

IN A BALLROOM AT THE SHERATON HOTEL in San Juan, dozens of utility engineers and supervisors gather on a December morning. Newly arrived on the island, they hail from utilities in Arizona, California, Massachusetts, New York, and Texas, and they've come to help.

It took PREPA officials more than a month to formally request such mutual aid. On the mainland, these requests typically occur much sooner—perhaps even before a major storm strikes—triggering a flow of personnel, equipment, and material to the affected area. PREPA, however, turned to private contractors, a move that proved controversial and eventually led its CEO to step down (more on that later).

In the ballroom, Eric Silagy, president and CEO of Florida Power & Light, gives the workers a pep talk. "Back home, you know how devastating [a storm like this] would be," Silagy says. "The people of Puerto Rico are counting on you. These U.S. citizens deserve to get back up on their feet as quickly as possible."

Later that day, I run into crews returning from the field. The dirt-streaked, sweaty linemen shuffle into the Sheraton's sprawling lobby and make a silent beeline for the elevators.

During my time on the island, electricity had been largely restored in the bigger cities, including San Juan, Ponce, and Mayagüez. But the more remote areas and even a few urban neighborhoods still lacked power. Service continued to be unreliable, with transmission lines occasionally faltering or crews de-energizing wires to do repairs.

Col. John Lloyd, the officer leading the Army Corps' power-restoration mission in Puerto Rico, explains the frustratingly slow progress. A week after Maria, the U.S. Federal Emergency Management Agency (FEMA) tasked the Army Corps with restoring Puerto Rico's grid to prestorm conditions. The military agency has since provided the lion's share of manpower and resources on the island.

At his task force's headquarters in San Juan, Lloyd runs through the complications confronting his team: decades-old grid infrastructure in disrepair, including broken "blackstart" diesel generators that would ordinarily be used to jump-start larger generators after an outage; the island's mountainous, forested interior, which necessitates transporting crews and material by helicopter; the fact that Puerto Rico is an island, which means much-needed equipment gets hung up at the port.

"I can't overstate enough the magnitude of some of these challenges," Lloyd tells me. "The amount of material necessary to do the restoration and the terrain we're operating in are huge factors that drive a lot of the schedule and timeline."

As of early April, the Army Corps was still subsidizing grid power with 870 emergency generators. Truck-size 1-MW units were deployed at hospitals and other critical facilities, while 25-MW units were operating at damaged power plants. The Corps also received nearly 7,900 km of wire and more than 50,000 wood, concrete, and galvanized steel poles. The group was preparing to wind down its operations, perhaps as early as mid-May.

A final factor slowing the recovery is PREPA's poor choices in the storm's aftermath. In November, Ricardo Ramos, PREPA's CEO at the time, said at a U.S. Senate hearing that his cash-strapped utility was "unable to meet the requirements" for mutual assistance, so he didn't request it. These requirements include providing water, food, and shelter for the visiting workers.

Instead, PREPA quietly inked a one-year, no-bid contract for $300 million with Whitefish Energy Holdings, a two-person firm in Montana with little experience in grid repair or disaster recovery. Ramos said that of the six contractors he considered, Whitefish was the only one that hadn't stipulated a large up-front deposit. Close scrutiny of the contract revealed unusual provisions, such as higher-than-normal rates for labor, per diem expenses, and travel—as well as a clause stating the work could not be audited.

A second no-bid contract for $187 million went to Cobra Acquisitions, a subsidiary of the Oklahoma-based fracking company Mammoth Energy Services. Like Whitefish, Mammoth has no experience with a recovery project this big. Its contract also stated that the firm could not be audited, although Cobra eventually agreed to remove that language. The contract has since swelled to $945 million, a fivefold increase.

PREPA officials have denied any wrongdoing, and Whitefish and Cobra note that they each deployed hundreds of crew members and shiploads' worth of heavy equipment. The contractors' linemen helped advance initial repair work along a handful of transmission lines, PREPA's Soto confirms.

However, the controversy over the contracts and the slow recovery infuriated Puerto Ricans and further eroded public trust in the utility. Finally, on 31 October, Ramos announced that PREPA was canceling the Whitefish contract, and he requested mutual aid from the American Public Power Association and the Edison Electric Institute, industry groups that represent hundreds of utilities. By early November, more

TEMPORARY HOME: Sol Ríos [right] has been living at a solar-powered shelter in Maricao. Jose Garcia [far right] is president of Pura Energia, which donated the system.

SLOW PROGRESS: Obed Santos, manager of a solar farm in Guayama [above], says payments from PREPA are running late. Repair work has been complicated by the mountainous terrain [right and below right].

than a thousand public utility workers were making their way to the island. On 17 November, Ramos resigned.

MANY PUERTO RICANS haven't been inclined to wait patiently in the dark. They are finding ways, big and small, to help themselves and one another, to share information and even electricity. At Bebo's Café, a well-known restaurant in San Juan, the owner set up outlets fed by rooftop generators so that people could charge their phones. Ivette Vizcarrondo would bring her 5-year-old son, Sergio, to the restaurant several times a day. Sergio has severe asthma and uses a nebulizer, a plug-in device that dispenses medication through a face mask.

One afternoon at Bebo's, they happened to meet solar power engineer Gabriel Rivera, who suggested a better way. Rivera had been volunteering in the neighborhood, collecting the names of residents in need of medical assistance. He saw that many, like Sergio, used simple but essential devices that could easily run off small emergency solar systems. Rivera got to work assembling and donating the systems. One of the first recipients was Sergio.

Rivera and I visit the Vizcarrondo apartment and climb the stairs to the rooftop. He shows me the single 255-watt solar panel he's placed there. A long yellow cord runs from the panel, over the roof's edge, and onto the apartment's balcony. The cord feeds a 20-ampere charge controller, a 500-W inverter, and two deep-cycle lead-acid batteries, all sitting inside a black plastic tub. (Rivera has since refined the systems to use sealed absorbent glass mat batteries and larger inverters stored inside white cabinets.)

After Maria, such off-grid solutions have proliferated across the island. The German energy-storage manufacturer Sonnen and the solar installation firm Pura Energia pooled their resources to donate 15 systems to hard-hit rural communities, at a cost of around $350,000.

Jose Garcia, Pura Energia's president, takes me to see an installation in Maricao, a tiny town in the western mountains. Fallen boulders and dried mud still cover the narrow, winding roads. The Maricao system is set up in an abandoned grade school that became a temporary shelter after the hurricane. Two former classrooms serve as communal areas, with some computers, large fans, fluorescent lighting, and a washer and dryer. A pair of 3.5-kilowatt solar arrays on the roof charge two 8-kilowatt-hour battery banks.

Sol Ríos has been living at the Maricao shelter since her apartment flooded during Maria. As of mid-December, she hadn't yet found an affordable alternative. "We lost everything," Ríos says, clutching her small, short-legged dog, Chivi. The shelter, even with electricity, is not home; she longs to return to her daily routine of cooking and running her household. "Here I don't have anything to do," she says, exasperated.

But for solar installers, the hurricane has been good for business. Garcia says there's strong demand for solar-plus-storage systems as an alternative to the PREPA grid. "Now people are starting to talk about using PREPA as their backup," Garcia says. "Two years ago, nobody was talking about that."

LOOKING AHEAD: Carlos Reyes of EcoEléctrica says natural-gas generation will make the grid more flexible.

ON 24 JANUARY, PREPA announced a milestone: One million customers—roughly two-thirds of its residential, commercial, and industrial users—had their lights back on. Since then, the utility has continued to boost generation, which is now at about 90 percent of what it was last year. Most of that power is coming from PREPA's oil-fired units and a natural-gas-fired plant. Other sites, though, sit idle.

For example, PREPA didn't authorize the 24-MW solar farm in Guayama, on the south coast, to begin exporting power to the grid until late February, and then only at a 10 percent level. The utility says it's concerned that intermittent flows of solar power would create instability on the recovering grid and that the area's transmission network couldn't support so much electricity.

Obed Santos, the solar plant manager, says the site was back to 74 percent capacity by mid-October. Under PREPA's contract with the solar plant's owner, AES Corp., the utility has to compensate AES for its lost revenue. But given PREPA's severe cash crunch, payments are running late. AES got paid for its July 2017 power exports only in mid-February, Santos says.

"It has us all a bit worried," he says as he walks through a field of solar panels. Flocks of sheep sit in their shade, chomping the grass.

Privately owned generation is a relatively recent addition to PREPA's nearly 80-year-old operation. Post-Maria, independent companies will likely play a much greater role in Puerto Rico's electric system. In January, Governor Ricardo Rosselló said he planned to privatize the insolvent utility, in a last-ditch attempt to ease the island's energy and debt crises.

Efrain O'Neill-Carrillo, a power expert at the University of Puerto Rico-Mayagüez, worries that selling off PREPA's centralized fossil-fuel plants risks locking in the existing system and slowing momentum toward renewable and distributed energy projects.

"Those new owners will want to maximize their investments. They would like to sell kilowatt-hours," he says. "I'm not sure you'll get many investors willing to buy those assets just to play a supporting role [on the grid]."

IF PUERTO RICO'S GRID RECOVERY has been slow and contentious, modernizing the island's electric system will likely take many years, billions of dollars, and a lot of creative thinking. Of the last, there is no shortage.

In December, for example, a consortium of U.S. and Puerto Rican energy labs, agencies, and utilities published *Build Back Better*, a report that lays out a sweeping decade-long plan for strengthening and hardening the island's transmission, distribution, and generation systems. The anticipated cost, at $17.6 billion, is fairly reasonable. In New York City, for comparison, Consolidated Edison has estimated that stormproofing its distribution network by burying its overhead lines would cost an estimated $60 billion.

The Puerto Rico report recommends commonsense moves like installing Category 4-rated poles, wires, and insulators; building flood barriers around vulnerable substations; and adding fiber-based, high-speed data links between the field and control centers.

The report also champions distributed renewable energy and microgrids. The latter are small electricity networks that can connect to the grid and also operate in isolation, combining solar power, batteries, backup generators, and control equipment. The report identified 159 sites where microgrids could be deployed, including hospitals, fire stations, and wastewater treatment plants.

Other ideas for fortifying Puerto Rico's grid abound. Blake Richetta, a senior vice president for Sonnen, suggests adding software and data systems that could turn clusters of residential solar and battery systems into "virtual power plants." These systems could be remotely controlled to supply power to the grid when and where it's needed most.

"All the homes work together to share energy," Richetta explains. "It makes it so there's no way a Category 5 hurricane could bring down the grid—and it's carbon free."

Carlos Reyes, general manager at EcoEléctrica, which operates a 500-MW natural-gas power plant on the south coast, sees an expanded role for natural gas. His company also owns an import terminal for liquefied natural gas (LNG) and a regasification plant. Later this year, the company will begin trucking LNG to a handful of factories that have large generators. That should get the sites up and running more quickly after a grid outage and be less polluting than, say, diesel. Adding small-scale natural-gas generation to the island's energy mix will help make the grid more flexible, Reyes says.

These disparate ideas share a common theme: a shift away from traditional centralized power plants and toward more distributed systems. For that to happen, government agencies have to agree on the plan. Microgrids, for example, still can't connect to the main grid. The Puerto Rico Energy Commission is only now finalizing the rules to allow them to do so.

Power expert O'Neill-Carrillo urges such regulatory roadblocks to be cleared quickly. "The present system is vulnerable to these disasters, and we cannot just build what was there before. We need to build something different," he says. "We need to move away, as far as possible, from the centralized model and into something else." ■

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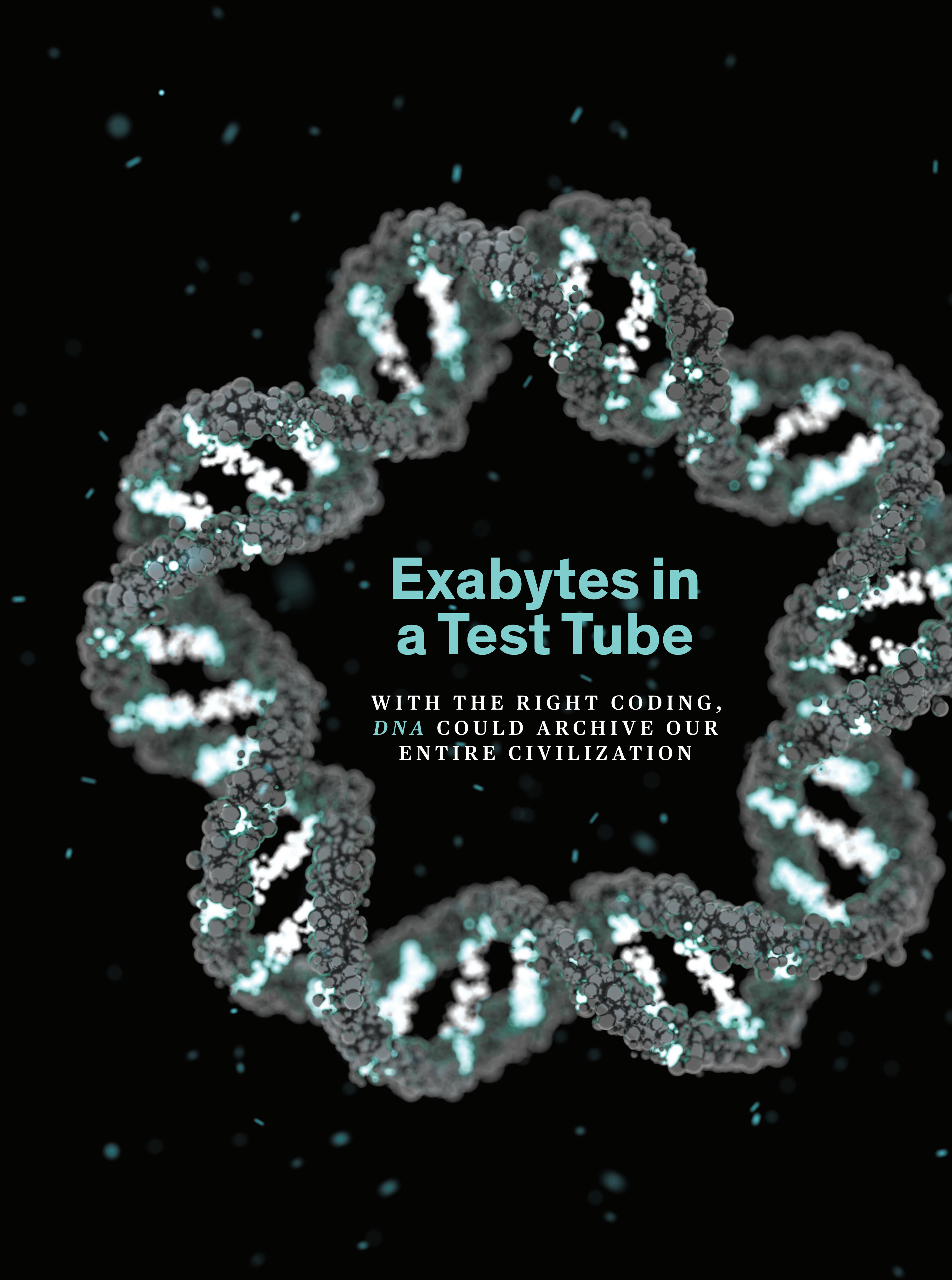
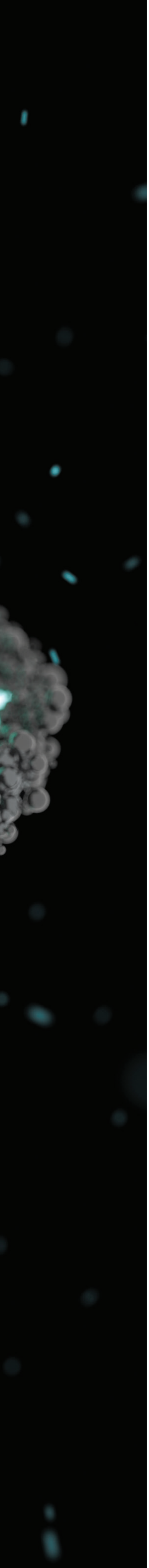


Exabytes in a Test Tube

WITH THE RIGHT CODING, *DNA* COULD ARCHIVE OUR ENTIRE CIVILIZATION



FIVE THOUSAND YEARS AGO, a man died in the Alps. It's possible he died from a blow to the head, or he may have bled to death after being shot in the shoulder with an arrow. There's a lot we don't know about Ötzi (named for the Ötztal Alps, where he was discovered), despite the fact that researchers have spent almost 30 years studying him. • On the other hand, we know rather a lot about Ötzi's physiological traits and even his clothes. We know he had brown eyes and a predisposition for cardiovascular diseases. He had type O positive blood and was lactose intolerant. The coat he was wearing was patched together using the leather of multiple sheep and goats, and his hat was made from a brown bear's hide. All of this information came from sequencing the DNA of both Ötzi and the clothing he wore. • DNA can store remarkable amounts of genetic information and, as Ötzi demonstrates, can do so for thousands of years. The DNA molecule is a double-helix staircase of billions of molecular blocks, called base pairs, whose arrangement determines much of what makes each of us unique. Only recently have we contemplated using DNA to store electronic, digital data. And while DNA isn't currently a viable alternative to memory sticks or hard-disk drives, it might be one of our best options to cope with the increasingly vast quantities of data we'll create as data mining, analytics, and other big-data applications proliferate.

By Olgica Milenkovic, Ryan Gabrys, Han Mao Kiah & S.M. Hossein Tabatabaei Yazdi

ILLUSTRATION BY ANATOMY BLUE

It was back in 2003 when some researchers, notably a group at the University of Arizona, became intrigued with the idea of using DNA to store data. But there were plenty of skeptics: Conventional mass-storage systems were doing the job cheaply and reliably. There was no compelling reason to seek out new options.

The situation has changed drastically over the last 15 years. We face an unprecedented data deluge in medicine, physics, astronomy, biology, and other sciences. The Sloan Digital Sky Survey, for example, produces about 73,000 gigabytes of data annually. At the European Organization for Nuclear Research (CERN), the Large Hadron Collider generates 50 million GB of data per year as it records the results of experiments involving, typically, 600 million particle collisions per second. These CERN results churn through a distributed computing grid comprising over 130,000 CPUs, 230 million GB of magnetic tape storage, and 300 million GB of online disk storage.

In the life sciences, DNA sequencing alone generates millions of gigabytes of data per year. Researchers predict that within a decade we will be swamped with 40 *billion* (10^9) GB of genomic data. All of that data will have to be stored for decades due to government regulations in the United States, Europe, and elsewhere.

Yet even as our data storage needs surge, traditional mass-storage technologies are starting to approach their limits. With hard-disk drives, we're encountering a limit of 1 terabyte–1,000 GB–per square inch. Past that point, temperature fluctuations can induce the magnetically charged material of the disk to flip, corrupting the data it holds. We could try to use a more heat-resistant material, but we would have to drastically alter the technology we use to read and write on hard-disk drives, which would require huge new investments. The storage industry needs to look elsewhere.

DNA-BASED STORAGE has come a long way since the early 2000s, when the technologies for reading DNA, let alone writing it, were still in their infancy. In those days, the Human Genome Project had only recently completed a draft of the human genome, at a mind-boggling cost exceeding US $2.7 billion, which works out to about $1 to read each base pair.

By the end of 2015, the cost for obtaining a highly accurate readout of an entire human genome had fallen below $1,500, according to the National Human Genome Research Institute. And today, roughly $1,000 is enough for you to get your entire genome sequenced. The cost of DNA sequencing is one three-millionth what it was 10 years ago.

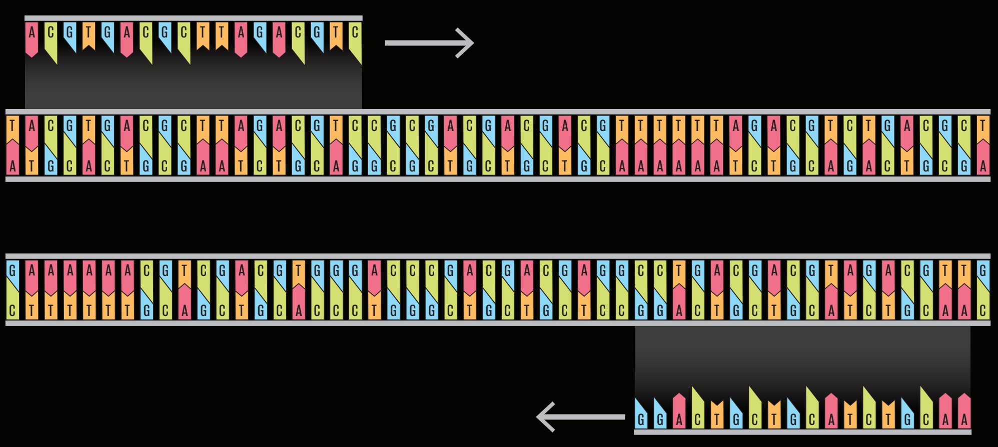
Our ability to sequence, synthesize, and edit DNA has advanced at a previously inconceivable speed. Far from being expensive and impractical, these DNA technologies are the most disruptive in all of biotechnology. It's now possible to write custom DNA strands for pennies per base pair, at least for short strands. Two companies, GenScript Biotech Corp. and Integrated DNA Technologies, provide DNA synthesis for 11 and 37 cents per base pair, respectively, for strands no longer than several hundred base pairs. Biotech startup companies buy their services and use the synthesized DNA to repair organs or create yeasts that produce unusual flavors to use in brewing beer.

For companies purchasing synthetic DNA, the cost depends on the length of the sequence being synthesized, because it is usually much more difficult to create long DNA strands. There are a handful of specialized efforts to synthesize longer strands–for example, an ongoing multilab effort is building an entirely synthetic yeast genome. Even so, commercially purchasing anything beyond 10,000 base pairs is currently impossible. (For reference, your genome has about 3.08 billion base pairs, a slightly smaller number than that of an African clawed frog.)

When reading DNA, sequencing devices produce fragments ranging in length from several hundred to tens of thousands of base pairs, which are then analyzed fragment by fragment before being stitched back together for a full readout. The whole process of reading an entire human genome takes less than a day. Researchers are now starting to sequence large quantities of fragments using nanopore technologies, which feed DNA through pores as if they were spaghetti noodles slipping through a large-holed strainer. As DNA passes through a pore, it can be read base by base.

Using primers to replicate DNA

Primers are short strands of bases that match, base for base, the ends of DNA strands. Primers kick-start the polymerase chain reaction in order to replicate a particular DNA strand, making it easier to pick out at random from a soup of DNA strands.



DIAGRAMS BY Mark Montgomery

In addition, DNA may be replicated exponentially at a low cost using the polymerase chain reaction, which duplicates a strand of DNA by splitting it apart and then building two identical strands by matching up the corresponding base pairs. These advances in reading DNA as well as in replicating it allow us, for the first time, to seriously consider DNA as a data-recording medium.

It still may not match other data storage options for cost, but DNA has advantages that other options can't match. Not only is it easily replicated, it also has an ultrahigh storage density—as much as 100 trillion (10^{12}) GB per gram. While the data representing a human genome, base pair by base pair, can be stored digitally on a CD with room to spare, a cell nucleus stores that same amount of data in a space about 1/24,000 as large. DNA does not have to be powered by an external energy source to retain data, as long as it's stored in a controlled environment. And it can last for a long time: DNA can survive in less than ideal conditions for hundreds of thousands of years, although it often becomes highly degraded. After all, the Alps preserved Ötzi's DNA for more than 5,000 years. Researchers once recovered DNA from the toe bones of a horse that had been preserved in a glacier for about 700,000 years.

Despite these appealing attributes, exploiting DNA for digital storage involves significant challenges. When it comes to building a storage system, the first task is to model the system's structure and operation. To that end, two research groups—one at Harvard in 2012 and the other at the European Bioinformatics Institute, in the United Kingdom, in 2013—proposed conceptually simple designs for DNA-based storage.

The basic idea was to convert the data into the DNA alphabet—adenine (A), thymine (T), cytosine (C), and guanine (G)—and store it in short strings with large amounts of overlap. The overlap would ensure that the data could be stitched back together accurately. For example, if the information was stored in strings that were 100 base pairs long, the last 75 base pairs from the previous string could be used as the first 75 base pairs for the next, with the next 25 base pairs tacked onto the end. With this strategy, the estimated cost of encoding 1 megabyte of data was over $12,000 for synthesizing the DNA and another $220 for retrieving it—rather prohibitively expensive at the moment.

Since then, research groups have demonstrated the long-term reliability of DNA-based data storage, the feasibility of using some traditional coding techniques, and even storing small amounts of data within the genomes of living bacteria. Our work, at the University of Illinois at Urbana-Champaign, in collaboration with the labs of Jian Ma and Huimin Zhao, pioneered random-access storage in DNA. We have been focused on solving the problems of random access, rewriting, and error-free data recovery for data that is read from DNA sequencing devices. Random access (the ability to directly access any information you want) and addressing (which tells you where to find that information) are key to any effective data storage method.

DNA-based storage systems are new and uncharted territory for coding theorists

Our interest in DNA-based data storage emerged from our backgrounds in coding theory. Coding theory has made modern storage systems possible by enabling the proper data formatting for specific systems, the conversion of data from one format to another, and the correction of inevitable errors.

DNA-based storage systems are a tantalizing challenge for coding theorists. We were initially drawn to the challenge of identifying the sources of errors from both writing and reading DNA, and of developing coding techniques to correct or mitigate such errors. Coding improves the reliability of ultimately fallible storage devices and the feasibility of using cheaper options. But DNA-based storage systems are new and uncharted territory for coding theorists.

TO UNDERSTAND THE CODING challenge presented by DNA, first consider a compact disc. The data is nicely organized into tracks, and we can easily access that data with the readily available hardware. DNA isn't so simple. It's inherently unordered; there are no tracks to follow to access the data.

A complete storage system would encompass many DNA molecules, so how would you even locate and select the specific molecule carrying the data you want? It would be like trying to fish a specific noodle out of a bowl of chicken noodle soup. It's highly unlikely you'd grab the right noodle at random, but if you could replicate that specific noodle again and again, until you filled the bowl, any noodle you nab would likely be the right one.

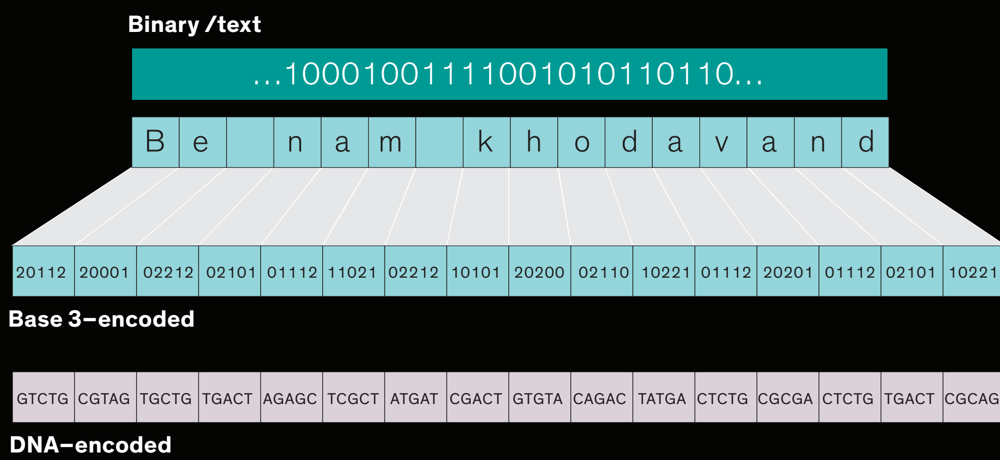
Our idea for DNA data access is to synthesize each encoded strand with an additional sequence that acts as an address. Carefully designed sequences of the bases, called primers, would match that address sequence and begin the process of replicating the DNA of interest. In this way, we could exponentially reproduce DNA strands carrying the data of interest using the polymerase chain reaction, making it easy to find a copy of the right strand.

Of course, with DNA, it's not quite so simple as plucking the right noodle out of your soup. Think of a primer as a sticky tape that binds to a specific set of rungs, or "complements," on the DNA "ladder." A primer should bind only to the specific address sequence it's looking for. To make matters more difficult, not all primers are created equal: G and C base pairs typically bind more tightly than A and T, meaning that a primer constructed with too many A and T bases may not bind as strongly. Poorly designed primers can cause a lot of problems.

We're encountering intriguing coding questions in figuring out how to construct primers that will not only bind tightly but to the right targets. For example, because each primer will bind with its complement—A to T, G to C, and vice versa—how can we ensure that each address sequence doesn't appear anywhere in the encoded data except as the address of the DNA strand you're looking for? Otherwise, the primer may bind to the wrong location and replicate unwanted DNA.

Encoding text or binary code as DNA

We can take a simple phrase like "*Be nam khodavand*" (Persian for "in the name of God") and encode it in base 3. We can then convert those numbers into DNA. Each base-3 digit will be encoded as any of the bases A, T, G, and C, depending on the letter in the strand that came before. For example, a 0 will be encoded as G if the previous base was C. This method complicates the encoding process, but it prevents creating strands with several repetitions of the same base, which can cause errors when sequencing the strand later. To recover the original text, the process can be done in reverse.

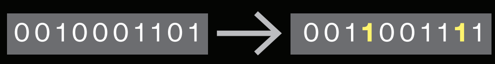


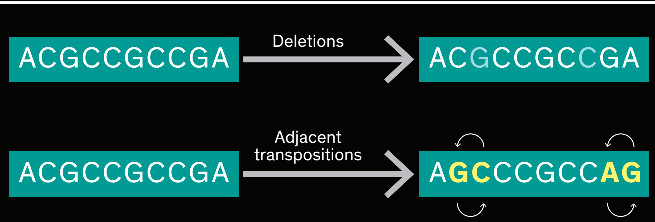
Ensuring redundancy in DNA

Encoding data into a single long strand of DNA is asking for trouble when it comes time to recover the data. A safer process encodes the data in shorter strands. We then construct the first part of the next strand using the same data found at the end of the previous strand. This way we have multiple copies of the data for comparison.

Substitution errors in binary code

Damerau distance codes, which in natural-language processing are used to catch errors like misspellings (for example, "smrt" instead of "smart"), can identify the spots in binary code where 1s and 0s have likely been substituted by mistake during copying or transcription.





Substitution errors in DNA

Damerau distance codes can also be used to address the errors that occur in DNA, even though they're more complex than binary errors. Sometimes bases are inadvertently deleted, and sometimes two will swap positions, errors that do not often occur in binary code.

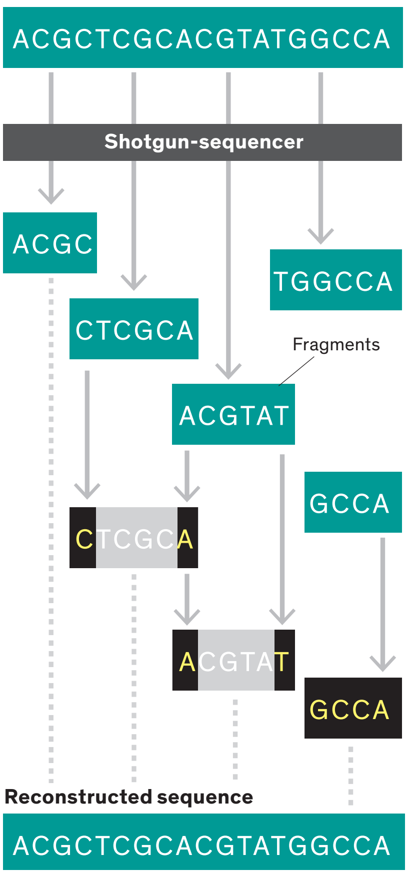
Fortunately, coding theorists have been solving similar problems for traditional storage media for decades. Other challenges, for example, like those that emerge in connection with reading the DNA, aren't typically encountered in conventional mass-storage systems. There are plenty of devices on the market that sequence DNA: Illumina's HiSeq 2500 system, PacBio's RS II and Sequel systems, and Oxford Nanopore Technologies' MinION are just three examples. All such sequencers are prone to introducing different types of readout errors as they determine the exact sequence of As, Cs, Gs, and Ts that make up a DNA sample. Illumina devices, for example, sometimes substitute the wrong base when reading the strand—say, an A instead of a C. These errors become more frequent the further into the strand you get. The accidental deletion of entire blocks is also a concern, and nanopore sequencers often insert the wrong base pairs into readouts or omit base pairs entirely.

Different sequencers all require different code to compensate for their flaws. For Illumina sequencers, for example, we've proposed a coding scheme that adds redundancy to the sequence to eliminate the substitution errors that arise from the devices' "shotgun-style" approach to sequencing. It's tricky to rebuild a genome after breaking it apart to read individual sequences without occasionally inserting the wrong segment in the wrong location. Redundant sequences will improve the odds

Reading DNA with a shotgun sequencer

"Shotgun-style" sequencing breaks copies of the long, unwieldy DNA strand into fragments of varying lengths. After those shorter segments are read, they can be compared with different fragments to reconstruct the entire sequence, although this method can introduce uncertainty about the placement of individual fragments.

Original sequence



of recovering data even if a segment is corrupted as a result of being reassembled incorrectly.

For nanopore sequencers, we developed codes to address different types of substitution errors that arise from sequencing the strand too quickly. In traditional data storage, it's just as likely that a 0 could be changed to a 1 as it is that a 1 could be changed to a 0. It's not so simple with DNA, where an A could be rewritten as a T, C, or G, and the substitutions don't happen with equal frequency. We've written codes to account for that fact, as well as codes to handle the base-pair deletions and swaps that naturally occur as DNA ages.

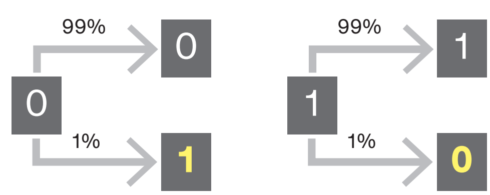
DNA-based storage, like any other data storage system, requires random access and efficient reading. But the biggest challenge is writing data inexpensively. Synthesizing DNA is still expensive, partly because of the molecule's sheer complexity and partly because the market is not driving the development of cheaper methods. One possible approach to reduce costs is to prevent errors in the first place. By placing redundancies in the DNA sequences that store data, you can skip expensive after-the-fact corrections. This is common practice in every data storage method, but synthesizing companies currently aren't equipped to pursue this—their production processes are so automated it would be prohibitively expensive to adjust them to produce these types of redundant strands.

Making DNA-based storage a practical reality will require cooperation among researchers on the frontiers of synthetic biology and coding theory. We've made big strides toward realizing a DNA-based storage system, but we need to develop systems to efficiently access the information encoded into DNA. We need to design coding schemes that guard against both synthesis and sequencing errors. And we need to figure out how to do these things cheaply.

If we can solve these problems, nature's incredible storage medium—DNA—might also store our music, our literature, and our scientific advances. The very same medium that literally specifies who we are as individuals might also store our art, our culture, and our history as a species. ■

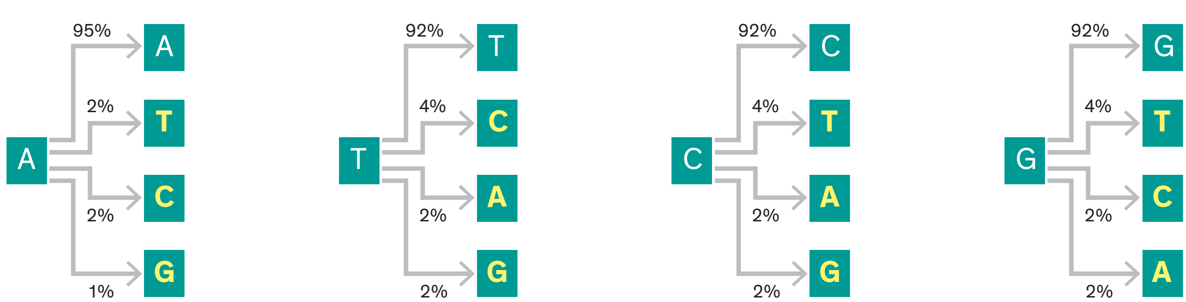
Transcription errors in binary code

When reading binary data from a traditional storage medium, there's always a small chance that a 1 could be read as a 0 by mistake, or that a 0 could be read as a 1. Because we're dealing with a simple two-state system, we can expect that each situation will occur with equal frequency.



Nanopore-sequencer transcription errors in DNA

Nanopore sequencers read long strings of DNA bases one by one, and because of the speed at which they do so, they will occasionally misread a particular base. Unlike the simple misreading of 1s and 0s, however, the odds of bases being mistaken for one another varies, due to their complex molecular structures and even the orientation the strand is in as it passes through the nanopore.



↗ POST YOUR COMMENTS at http://spectrum.ieee.org/dnastorage0518

GPS's NAVIGATOR IN CHIEF

BRAD PARKINSON LED GPS DOWN THE PATH FROM NOTION TO NECESSITY

BY TEKLA S. PERRY

PHOTOGRAPHY BY GREGG SEGAL

A S I DRIVE THROUGH THE VINEYARD-COVERED HILLS OF SAN LUIS OBISPO, CALIF., THE TINY GLOBAL POSITIONING SYSTEM receiver in my phone works with Google Maps to alert me to upcoming turns. The app reassures me that I'll arrive at my destination on time, in spite of a short delay for construction. ■ How different this trip would have been in the pre-GPS era, when the obscured road sign at one intersection would likely have sent me off track. I have a weak sense of direction, and getting lost—or worrying about getting lost—was a stressful part of my life for a long time. ■ This GPS-guided journey is taking me to Bradford W. Parkinson, the person who made GPS technology—a tool we now take for granted—come together. Parkinson is being awarded the 2018 IEEE Medal of Honor for leading the development of GPS and pushing its early applications. ■ "Just don't call me the inventor of GPS," he says moments after we meet. "I was a chief advocate, the chief architect, and a developer, but I was not the inventor." ■ How about "leader"? "Even that's overblown. I surrounded myself with guys who would not fail."

Brad Parkinson may be modest about his contributions, but it's hard to dispute that he was the person who turned a pie-in-the-sky vision of navigating by satellite into a reality.

PARKINSON'S PREPARATION FOR HIS GPS ROLE began early, with a passion for maps. The walls of Parkinson's boyhood bedroom were covered with large maps of northern Minnesota's Boundary Waters—lakes and streams he loved to explore by canoe. "It was easy to get lost," he recalls. "You had to keep your wits about you."

Then there was his summer job in 1957, just after graduation from the U.S. Naval Academy, as a surveyor on a large construction project.

His graduate education put down another stepping-stone. Sent to MIT in 1960 by the U.S. Air Force, which he'd joined rather than the Navy, he took several courses in inertial navigation. Charles Stark Draper was teaching them, and so it was an irresistible opportunity. That coursework led to a three-year post as chief analyst for inertial navigation systems testing at Holloman Air Force Base.

In 1964, he headed off to Stanford for Ph.D. studies. His thesis advisor was Benjamin Lange. "Ben wanted to put a free-rotor gyroscope in orbit to test the general theory of relativity," Parkinson says.

Parkinson invented a sensor that could tell the position of the rotor relative to the desired axis. Using an algorithm he called hemispheric torquing, he could then apply a magnetic field to adjust the rotor's position, sending it spinning along the desired axis without changing its overall position in space. Parkinson's technology is still in use today in some highly accurate inertial navigation systems.

AS PARKINSON'S KNOWLEDGE of navigation and space systems grew, the seeds that became GPS were being planted by others. In 1960, the U.S. Navy began testing its Transit program, a satellite-based method of updating the inertial guidance systems used by submarines. Transit's system worked with as few as four satellites (though the constellation typically included more) in low polar orbits. Along with a network of ground stations, the satellites allowed slow-moving vessels to determine their longitude and latitude a few times a day with an accuracy of about 100 meters.

Ivan Getting, president of the Aerospace Corp., didn't think that was good enough. In 1962, he started campaigning for a three-dimensional satellite-positioning system that would be more accurate and always available. Getting told me some years ago that he promoted this vision to the presidential science advisor, the heads of the armed forces, and anyone else he thought could have influence, trying "to get the damn thing funded."

Getting's evangelism led to an Air Force–sponsored study of space-based navigation. The final report, by James Woodford and Hiroshi Nakamura, was published in 1966, although it remained classified until 1979. It laid out 12 main techniques, including the one that became GPS.

← **GPS ON BOARD:** Brad Parkinson, with a model of the GPS IIF satellite, gazes across the farmland near his California home. He sometimes spots GPS-guided automated tractors at work in the fields.

In 1972, Parkinson's path and satellite navigation's evolution collided. Parkinson had spent the previous year studying at the Naval War College, in Newport, R.I., and sailing whenever he could. Up next would likely be an assignment in the Pentagon.

Then he got a call from a colonel who was part of a group known as the Air Force's inertial guidance mafia. "This wasn't a black-hat organization," Parkinson explains, "just people who had gone through the MIT inertial guidance course who looked out for each other." The colonel recommended that if Parkinson wanted to build systems rather than just analyze them, he should join the Advanced Ballistic Reentry System (ABRES) program, in Los Angeles.

Parkinson, just promoted to colonel himself, took the advice and moved to Los Angeles. He'd been at ABRES a little over three months, working on advanced nose cones and other missile technology, when he was identified as a perfect fit to take over a satellite navigation program called 621B. Parkinson had the right qualifications, but he didn't want the job.

"The consensus was that the program was going nowhere, that it was absolutely dead," he says.

But it was a three-star general making the offer, Parkinson recalls, and you don't say no to a general—usually. Parkinson said he'd take the job if he could be named program manager. Anything less, he said, would have been a downward move and wouldn't have allowed him to control the program—"and the program was in deep trouble."

The general refused. "So I said, 'Then I don't volunteer,' " Parkinson recalls. "He wasn't used to brand-new colonels saying 'No' to him."

Parkinson walked out of the office—but he had barely gotten through the door, he says, when the general called him back. Parkinson got his title and took over 621B in mid-1973.

THE 621B PROGRAM aimed to create a satellite-based navigation system that would work almost anywhere in the world. The team had already developed much of the plan and wanted to demonstrate it using four satellites—not an inexpensive proposition.

Parkinson began by going through every piece of the proposal with his engineers.

"We were a little worried when he first came on," recalls Walter Melton, an engineer assigned to the project from the Aerospace Corp. "We heard that he was from the inertial mafia." The engineers were concerned that Parkinson would be biased against satellite navigation, which was considered a competitor to inertial navigation. "But after the first several weeks it became clear he understood and was a supporter."

In August 1973, Parkinson presented the proposal to the Defense Systems Acquisitions Review Council at the Pentagon. "I told all these generals and senior civilians sitting around a table what I was trying to do, and then they took a vote," he recalls. The vote was "No."

BRADFORD W. PARKINSON

Date of birth: 16 February 1935

Birthplace: Madison, Wis.

Education: B.S. in general engineering, U.S. Naval Academy, 1957; M.A. in aeronautics and astronautics, Massachusetts Institute of Technology, 1961; Ph.D. in aeronautics and astronautics, Stanford University, 1966

First jobs: Supermarket carryout and stock boy, general laborer in construction, newspaper delivery

First tech job: Surveyor for construction projects

Most surprising job assignment: As an instructor at the Air Force Academy, flying 26 air combat missions to troubleshoot the electronics on the AC-130 gunship

Favorite book: *Tortilla Flat,* by John Steinbeck

Most recent book read: *The Winter Fortress: The Epic Mission to Sabotage Hitler's Atomic Bomb,* by Neal Bascomb

Favorite music: Classical, particularly Sergei Rachmaninoff, Edvard Grieg, and Ludwig van Beethoven

After hours/leisure activity: Now, hiking, snowshoeing; past, sailing, skiing

IEEE Medal of Honor: "For fundamental contributions to and leadership in developing the design and driving the early applications of the Global Positioning System"

Malcolm Currie, then undersecretary of defense research and engineering, chaired that meeting. At the time, Currie was spending a lot of time near his home in the Los Angeles area, preparing to move his family to Washington, D.C. During one of Currie's Los Angeles trips, Parkinson gave him a one-on-one tutorial on satellite navigation that took up most of an afternoon.

Parkinson now thinks that afternoon was the reason satellite navigation didn't die after the "No" vote. Indeed, it made an ally of Currie, who quickly reminded Parkinson that the concept presented was merely one he had inherited, not developed himself.

Parkinson reported in an oral history that Currie told him, "Listen, you did a very, very nice job, but you and I know that this is not truly a joint program.... Go back, reconstitute it as a joint program, and bring it to me as quickly as you possibly can, and I am very, very certain that we are going to approve it."

TALKING SATELLITES: Brad Parkinson [center] discusses GPS navigation with the Aerospace Corp.'s Frank Butterfield [left] and the U.S. Navy's Bill Huston in the mid-1970s.

U.S. AIR FORCE

Parkinson and his engineers worked over Labor Day weekend to develop a new architecture for their satellite-navigation system. They met at the Pentagon rather than in L.A., he says, "because too many people associated with the program were entrenched in old ideas." Gathering in offices that were vacant because of the holiday, Parkinson says, "We hammered out what we wanted to do, and we summarized it in seven pages."

PARKINSON RECALLS THAT THE "LONELY HALLS" MEETING, as it came to be known, led to several key changes: The system's code-division-multiple-access (CDMA) radio signal was modified to include a civilian signal as well as the protected military signal; the orbits of the satellites were adjusted to reduce the number of satellites needed at the optimal altitude, considering the range of available launch vehicles; and the design embraced orbiting atomic clocks, which would free ground-based receivers from the need to keep precise time.

Parkinson says this third change was the most risky—atomic clocks that could handle space radiation did not yet exist. But he knew that Roger Easton at the Naval Research Laboratory was developing a space-qualified atomic clock as part of the Navy's Timation satellite navigation program—and he bet that some version of that clock would be available for the demonstration satellites.

This decision turned out to be critical for the cheap, small GPS receivers that consumers use today. If instead we all had to carry around superaccurate clocks, the receivers would be vastly more expensive and as large as a stack of dictionaries, Parkinson says. They also would require periodic synchronization to maintain accuracy. They certainly wouldn't have turned into a tiny package of electronics costing a fraction of a dollar, tucked inside every cellphone.

And Parkinson badly wanted consumers to use the new system. The mission of the project, in his view, was always twofold—extraordinary accuracy and affordability. He even hung a wooden plank above the entrance to the project's offices in Los Angeles to reinforce the message: "The mission of this office is to drop five bombs in the same hole and to build a cheap set that navigates—and don't you forget it."

Parkinson spent the months after the Lonely Halls meeting selling the proposal to Pentagon staff and decision-makers.

He flew to Washington as often as twice a week, holding some 60 meetings in two months (he still has a list).

He parried every doubt: Yes, the signal would be powerful enough to be detected in the surrounding noise. Yes, the system's 10-meter accuracy was achievable. Yes, US $180 million would cover the constellation of four satellites and related ground equipment. (The final price was about $250 million, but that included two added satellites–not a horrible overrun, Parkinson says.)

"He was quite the salesman," says Melton, his colleague in the 621B program.

The Defense Council approved the proposal in December 1973. Parkinson led the program for three and a half years, until the first GPS satellite was up in space and initial tests verified that the system worked as designed.

Easton's atomic clock, it turns out, was not ready for that initial launch, but Parkinson had engineers at Rockwell International also working on a space-worthy atomic clock, which was ready. Parkinson still gives Easton credit.

"Easton convinced me that we could do it–and that made a heck of a difference," he says.

The full 24-satellite system became operational in 1995. The Russian GLONASS system, a similar project begun during the Soviet era, was also completed in 1995. Both the European Union's Galileo system and China's BeiDou system are expected to be completed in 2020.

PARKINSON RETIRED IN 1978 from the Air Force, but he didn't leave GPS behind. After several positions in industry (including vice president of Rockwell International's Space Systems Group and vice president at Intermetrics), he returned to Stanford in 1984, this time as a professor of aeronautics and astronautics. He immediately rejoined the orbiting gyroscope project, now called Gravity Probe B, as program manager and a coprincipal investigator; it successfully launched in 2004.

He also led a research group aimed at developing civilian applications for GPS technology. That work led to a robotic sailboat, the first GPS-guided landing of a commercial aircraft, and a system of ground stations that would improve the accuracy of GPS positioning by monitoring and correcting the satellite data. The last project evolved into the Federal Aviation Administration's Wide Area Augmentation System, which uses data from ground stations to improve GPS's accuracy by correcting errors in the signal caused, for example, by orbital drift and delays introduced by the atmosphere.

Parkinson's group also developed the application he is most passionate about today: automated tractors. He had kept automated tractors in his sights for some time; he listed the application as part of GPS's future in talks he gave as early as 1978.

It wasn't until around the 1990s, though, that he got his chance to push the technology along. At Stanford, he met with a representative from John Deere who was building ties between the company and universities. Parkinson demonstrated a GPS-guided self-driving golf cart.

"Think tractor," he told the visitor.

The Deere representative was skeptical that farmers would buy such a system, Parkinson recalls, but the company was eager to partner with Stanford and agreed to fund a development project.

"They sent us about $900,000 and two huge tractors," Parkinson says. A team of students spent several years developing the technology, first demonstrating a fully functional system in 1997.

Watching the rise of GPS-guided precision farming since then has been gratifying, he adds. Parkinson's home overlooks a farm, and he often walks in the fields, sometimes spotting, to his delight, a GPS-guided tractor at work. "The tractors pay for themselves in savings in fertilizer and in time."

"I think he likes the agricultural application because it brings home that GPS is for everyone," says Penina Axelrad, a former Ph.D. student of Parkinson's who is now a professor at the University of Colorado. "Now, of course, GPS is in everyone's smartphones, but that was an early application that everyone could value."

PARKINSON IS NOW MOSTLY RETIRED, though he still has research projects running at Stanford.

He remains one of GPS's biggest fans–he has more than a dozen devices in his house and car that use GPS, including a watch he wears most of his waking hours.

"He just gets so excited when he sees cool things enabled by GPS," says Axelrad.

He is also quick to protect GPS when he feels that it's threatened. Right now, he sees a big threat coming from Ligado Networks, which aims to create a broadband wireless network using the 1,525- to 1,559-megahertz frequency band. This band is adjacent to the frequencies used by GPS, which are between 1,164 and 1,587 MHz, nestled among other bands essentially reserved for satellite communications. Ligado's band is reserved for Earth-to-satellite communications with some limited use of cell towers to help users connect to the network. Back in 2011, however, the U.S. Federal Communications Commission considered giving Ligado's predecessor, LightSquared, a conditional waiver to use the frequency band for unlimited ground-based communication. The GPS industry protested, showing data on interference, and in 2012 the waiver was pulled. But Ligado recently came back with a proposal for a lower-power system that it says won't interfere with GPS.

That proposal is still before the FCC. But testing by the Department of Transportation shows extensive interference, Parkinson says, particularly for the most accurate devices. He's been working on an editorial to alert the public to the danger of the proposal. Ligado aims to change the designation "of a quiet signal from space to powerful ground transmitters," he writes. "They would apparently use this to compete with the existing broadband companies. This country already has at least four broadband providers but has only one GPS."

Says Parkinson, "We endanger it at our peril." ■

ELECTRIC BLUE SKIES

CONTINUED FROM PAGE 29

put a subscale model of the QEP in a test cell to evaluate its performance and aerodynamics. Next, we'll take our power train aloft on an existing airframe to gain flight experience. Then we'll integrate it with our own aircraft. Meanwhile, we are using computer simulations to determine how big the various components should be and to optimize overall performance.

A big part of our preliminary work involved developing the tools and methods for optimizing a hybrid-electric aircraft. Only afterward were we able to start looking at the sizing, which now extends far beyond just the four to six passenger seats we originally envisioned. At one point, we were writing a proposal for NASA for a 150-seat single-aisle aircraft. It was impressive how well the advantages of the technology held up at this size (albeit with shorter ranges). That was when we realized just how big our opportunity was.

Although the hybrid design of our 12-passenger craft is unprecedented, it makes use of components with established flight records. The importance of aircraft safety and reliability typically requires a rigorous process of qualification to advance the technology readiness level (TRL) for any product. That is part of the reason for a long development cycle and the slow adoption of new technologies for aircraft. The Zunum power-train team is therefore making use of tools, technologies, and methods that have proved themselves over decades. So, while a particular piece of new hardware may be only at the proof-of-concept level, all of the underlying technologies that support its design are at mission-proven TRL 9, the highest level. This approach has allowed us to accelerate our development cycle, rather than having to reinvent the wheel—or wing, as it were.

The Zunum Aero 12-seater will offer many attractive features to operators and passengers. Service will be flexible: walk-on and walk-off, more akin to hopping on a bus or train than boarding an airliner.

The direct costs for energy and maintenance work out to 8 cents per seat mile, or $250 per hour for the aircraft, comparable to the economics for conventional airliners. The hybrid-electric range enabled by the propulsion system is 1,125 km, well suited to converting day- or day-and-a-half-long road trips into a mere few hours.

Consider a trip from Boston to Washington, D.C., a distance of 640 km (400 miles). By car, the journey takes more than 8 hours. By air, using the traditional hubs of Boston Logan International Airport and Ronald Reagan Washington National Airport, the estimated door-to-door travel time clocks in at around 4 hours and 50 minutes. Flying a Zunum plane out of secondary airports, though, could get passengers from door to door in as little as 2 hours, 30 minutes.

Electric flight will probably be cheaper, too, because of its greatly reduced fuel costs. According to the economic analyses we've done, average fares from regional Massachusetts airports in Beverly, Hanscom, and Norwood to regionals in Maryland and Virginia such as College Park, Washington Executive, Manassas, and Leesburg would cost about $140 one-way—fully a third below today's average commercial rates, as reported to the Federal Aviation Administration. Significant hurdles remain, of course, before Zunum can change the way people fly. But these challenges are being met. On the regulatory side, for instance, we are working with other business and government partners to help the FAA craft a new framework for the certification of electric aircraft, which is expected to be rolled out later this year.

With continued advances in electric propulsion, we can see in the not-too-distant future a time when hybrid-electric aircraft will become all-electric, and even long-haul carriers will begin retiring their fossil-fueled fleets. Energy-storage technologies still have a long way to go to meet the requirements for all-electric aircraft propulsion, but the motivation will be strong.

Currently, the international aviation sector contributes about 2 percent of global carbon emissions. With the climbing rates of airline travel, especially in developing countries, this level is expected to rise to 5 percent after 2020. In an effort toward responsible stewardship of our planet, 191 countries agreed at a 2016 assembly of the International Civil Aviation Organization, in Montreal, to limit aviation emissions to 2020 levels or to pay carbon-offset fees. Hybrid and electric aircraft will figure prominently in accomplishing this goal.

Change is in the air, figuratively, and, soon, literally. And it's been a long time coming. After all, the Wright brothers used gasoline in their historic 1903 flyer. Following the rollout of hybrid and electric vehicles onto our roads and just now entering our waterways, conventional fossil-fueled aircraft will likewise become relics of the past. Air travel, which has been increasingly relegated to fewer and fewer connecting points, will become personal and local again. In a few years, traveling a thousand kilometers will be as simple as arriving at your nearest regional airport, strolling onto a hybrid plane, and taking a quick flight to the regional airport closest to your final destination. There, the car you rent will, no doubt, run on electricity, too. ■

Service will be more akin to hopping on a bus or train than boarding an airliner

↗ POST YOUR COMMENTS at http://spectrum.ieee.org/zunum0518

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

The University of Alabama Department of Electrical and Computer Engineering invites applications for a tenure-track faculty position in RF electronics focused on radar device fabrication. The position requires a PhD in electrical/computer engineering or a closely related field. More information may be found at **http://ece.eng.ua.edu**.

Applicants should apply online at **http://facultyjobs.ua.edu**.

The University of Alabama is an equal opportunity employer.

THE UNIVERSITY OF ALABAMA®

Professor/Associate Professor/Assistant Professorship in the Department of Electrical and Electronic Engineering

SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY 南方科技大学

The Department of Electrical and Electronic Engineering at the Southern University of Science and Technology (SUSTech) now invites applications for the faculty position in the Department of Electrical and Electronic Engineering. It is seeking to appoint a number of tenured or tenure track positions in all ranks.

Candidates with research interests in all mainstream fields of electrical and electronic engineering will be considered, including but not limited to IC Design, Embedded Systems, Internet of Things, VR/AR, Signal and Information Processing, Control and Robotics, Big Data, AI, Communication/Networking, Microelectronics, and Photonics. These positions are full time posts. SUSTech adopts the tenure track system, which offers the recruited faculty members a clearly defined career path.

Candidates should have demonstrated excellence in research and a strong commitment to teaching. A doctoral degree is required at the time of appointment. Candidates for senior positions must have an established record of research, and a track-record in securing external funding as PI. As a State-level innovative city, it is home to some of China's most successful high-tech companies, such as Huawei and Tencent. We also emphasize entrepreneurship in our department with good initial support. Candidates with entrepreneur experience is encouraged to apply as well.

To apply, please send curriculum vitae, description of research interests and statement on teaching to eehire@sustc.edu.cn. SUSTech offers internationally competitive salaries, fringe benefits including medical insurance, retirement and housing subsidy, which are among the best in China. Salary and rank will commensurate with qualifications and experience.

More information can be found at **http://talent.sustc.edu.cn/en** and **http://eee.sustc.edu.cn/en**. Candidates should also arrange for at least three letters of recommendation sending directly to the above email account. The search will continue until the position is filled.

For informal discussion about the above posts, please contact Chair Professor Xiaowei SUN, Head of Department of Electrical and Electronic Engineering, by phone 86-755-88018558 or email: sunxw@sustc.edu.cn.

To learn more about working & living in China, please visit: **http://www.jobs.ac.uk/careers-advice/country-profiles/china**.

Washington State University Endowed Chair Position, Power Engineering

WASHINGTON STATE UNIVERSITY

The School of Electrical Engineering and Computer Science (EECS) at Washington State University (WSU), Pullman, WA, invites applications for the Edmund O. Schweitzer III Chair in Power Apparatus and Systems, a full-time tenured/tenure-track faculty position in Electrical Engineering, with core research and teaching emphases in the fundamentals of power engineering or related fields. Applicants at the assistant, associate, or full professor level will be considered.

This Endowed Chair position is made possible through the generous contributions from Dr. Ed and Mrs. Beatriz Schweitzer and Schweitzer Engineering Laboratories. Funds from the Endowment will be available to the Chair. The new faculty member will join a strong group of thirteen faculty in the area of power engineering, which is a signature area of the Voiland College of Engineering and Architecture at WSU. There are over 100 upper division EE students in the power track and over 60 graduate students specializing in power. A long-term strength of the School, the faculty in this area contribute to activities in research, teaching and outreach within the Energy Systems Innovation Center (ESIC) **https://esic.wsu.edu/**.

WSU is one of the nation's top 70 public research universities according to U.S. News and World Report. WSU is among 108 public and private universities in North America recognized with the "very high research activity" categorization, and among 240 national universities and colleges that earned the "community engagement" classification from the Carnegie Foundation. To apply and for more information, visit **https://www.wsujobs.com/postings/37279**. Application review will begin on **May 1, 2018** and will continue until the position is filled.

DIVISION OF WORK & INDUSTRY/NATIONAL MUSEUM OF AMERICAN HISTORY/SMITHSONIAN INSTITUTION

AUDIO ARCHAEOLOGY

MP3, CD, cassette, 8-track, LP. Have you struggled with the technological obsolescence of your music collection? Imagine, then, trying to play this wax disc recording from 1885. A team from the Lawrence Berkeley National Laboratory, in conjunction with the Smithsonian Institution and the Library of Congress, managed to do just that. By scanning the surface of the disc and then digitally reconstructing the sound waves, they recovered the only confirmed recording of Alexander Graham Bell. What did he say? "Hear my voice." Thanks to technology, we can do so again. ■

↗ For more on Bell and the technology of audio restoration, see https://spectrum.ieee.org/pastforward0518.

IEEE

Endless Possibilities...

and countless risks

Protect your savings and retirement nest egg with Long-Term Care Insurance

Your "golden years" ahead offer endless possibilities. Travel. Golf. Grandkids and more all await the day you retire. And advancements in medical technology and treatments can allow you to live longer to enjoy it all. But it also comes with increased long-term health concerns. *What if a chronic illness or disease happens? How will you pay for your care?*

As you age, you'll face countless risks. Most people turning age 65 can expect to use some form of long-term care during their lives.[1] Long-term care services can be costly (average annual cost of nursing home care is $97,455).[2] Unfortunately, most health care plans and Medicare limit coverage for these services—which can quickly deplete your personal savings and retirement nest egg if you're not prepared.

IEEE understands the importance of preparing for the future. That's why IEEE members have access to a valuable benefit—the Long-Term Care Resources Network. One simple phone call is all it takes to start protecting your savings and nest egg from long-term health risks. A licensed long-term care representative will help you compare benefits and rates from top providers and offer options for your personal situation. You're under no obligation!

- Educational materials about Long-Term Care Insurance and why it is important to start planning now
- Access to plans from top-notch companies
- Free, no-obligation consultations
- Customized Long-Term Care Insurance proposals

Prepare for the future and keep your retirement nest egg intact with Long-Term Care Insurance today!

1-800-588-7421 | IEEEinsurance.com/LTCAD

1 www.longtercare.gov

2 Genworth Cost of Care Survey, 2017

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