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FOR THE TECHNOLOGY INSIDER | 07.17

Your Smartphone Will See You Now

Digital psychiatry apps that collect and monitor data can spot when something's wrong—and then help you get back on track P. 44

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On the cover and above **Photo-illustrations by Edmon de Haro for *IEEE Spectrum***

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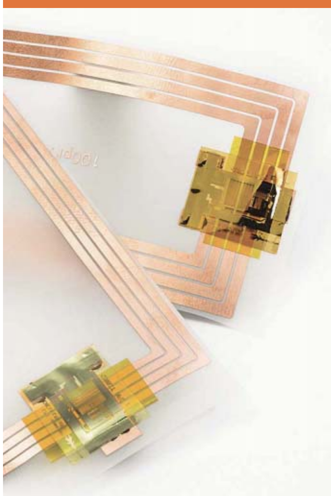

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- **HIGH-SPEED TRAVEL** An IEEE graduate student member and her teammates at MIT took top honors at a competition held by SpaceX to design a pod for the Hyperloop. Dreamed up by Elon Musk, the Hyperloop is a steel tube in which people ride from city to city in pressurized pods at nearly the speed of sound.
- **OUT OF THIS WORLD** The Nobeyama 45-meter telescope, in Nagano, Japan, was honored with an IEEE Milestone. The telescope was the largest of its kind when it was built in 1982 and led to discoveries of black holes and new interstellar molecules.
- **SHOWCASE YOUR WORK** Members can now post videos on IEEE.tv of projects they're working on or an event they've attended.

FROM LEFT: IMEC; ZHONG ZHENBIN/GETTY IMAGES; ALEXANDRA SAPP

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BACK STORY_

KEVIN DRISCOLL

Hello, World!

NOW THAT EVERYONE USES the Internet daily, it's getting hard to recall the magic of logging on to an online service back when they were new. Happily enough, we've got Julien Mailland [standing] and Kevin Driscoll, who've been researching the history of France's pioneering Minitel telematics system and who wrote "The French Connection Machine" in this issue.

Mailland's first experiences with Minitel came as a youngster, after his parents brought a terminal home in the early 1980s. "I and millions of other French kids had very stern instructions not to use it, because it would run up the phone bill," he explains. "The deal I had with my parents was that if I got good grades, I could play solitaire or poker on it, but I didn't get good grades that often." For Mailland and almost everyone else in France at the time, Minitel soon became part of everyday life, something you'd use to look up a phone number, register for college, or, if you were more adventurous, chat with strangers online.

Although Driscoll had dabbled with online bulletin-board systems in his youth, he didn't become familiar with Minitel until he met Mailland in graduate school in 2008, at which point the system was on its last legs. The two began collecting vintage Minitel equipment as a hobby, which wasn't particularly difficult. "Terminals were considered e-waste in France," says Driscoll. So it was just a matter of snatching them up from the trash on the side of the road. Their curation led to further research and a book, published just last month: *Minitel: Welcome to the Internet* (MIT Press).

Now that the pair has accumulated a veritable museum of Minitel hardware, they are trying to find and archive the software that powered many of the system's services. That amounts to "begging people to go down to their basements, dig out their old servers, and give them to me," says Mailland. With luck, they'll harvest whatever is left before all memory of those pioneering online services fades away. ■

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CONTRIBUTORS_

Subhashish Bhattacharya

Bhattacharya is a professor of electrical and computer engineering at North Carolina State University. Since 2008, he's been developing solid-state transformers that could allow electrical grids to handle a massive influx of distributed energy, such as rooftop solar [p. 38]. "I'm so excited about this," he says. "I think once we as human beings take responsibility for actually generating something we consume, we understand the value of it more."

David C. Brock

Brock is director of the Center for Software History at the Computer History Museum, in Mountain View, Calif., and a member of *IEEE Spectrum*'s editorial advisory board. In this issue [p. 52], he writes about an early coin-operated computer terminal through which people accessed an electronic bulletin board. The first terminal, installed in a Berkeley, Calif., record shop in 1973, gave many users their initial interaction with a computer, Brock notes.

Martin Doppelbauer

Doppelbauer holds the chair for hybrid electric vehicles at the Institute of Electrical Engineering of the Karlsruhe Institute of Technology, in Germany. While he and coauthor Patrick Winzer, a Ph.D. candidate, were preparing a lecture on electric drive, they came up with the idea for an energy-saving "asymmetric" machine–one optimized as a motor rather than as a generator. Then they built one [see "A Lighter Motor for Tomorrow's Electric Car," p. 26].

Jacques Mattheij

A pioneer in live online video streaming, Mattheij has been playing with technology "since the ripe old age of 3." In this issue, he describes how he automated the sorting of two tons of Lego pieces [p. 17], which ultimately required dipping into machine learning. "I never *ever* thought this would be such a hard problem to solve. It's good I didn't know what I got into, or it would have never happened," says Mattheij.

John Torous

Torous began reading *Spectrum* as a 12-year-old, when his grandfather, an IEEE Fellow, got him hooked. Torous chaired the IEEE student section at the University of California, Berkeley. Now a psychiatrist, he treats patients, codirects the digital psychiatry program at Beth Israel Deaconess Medical Center in Boston, and conducts mobile mental health research, which he writes about in "The Case for Digital Psychiatry" [p. 44].

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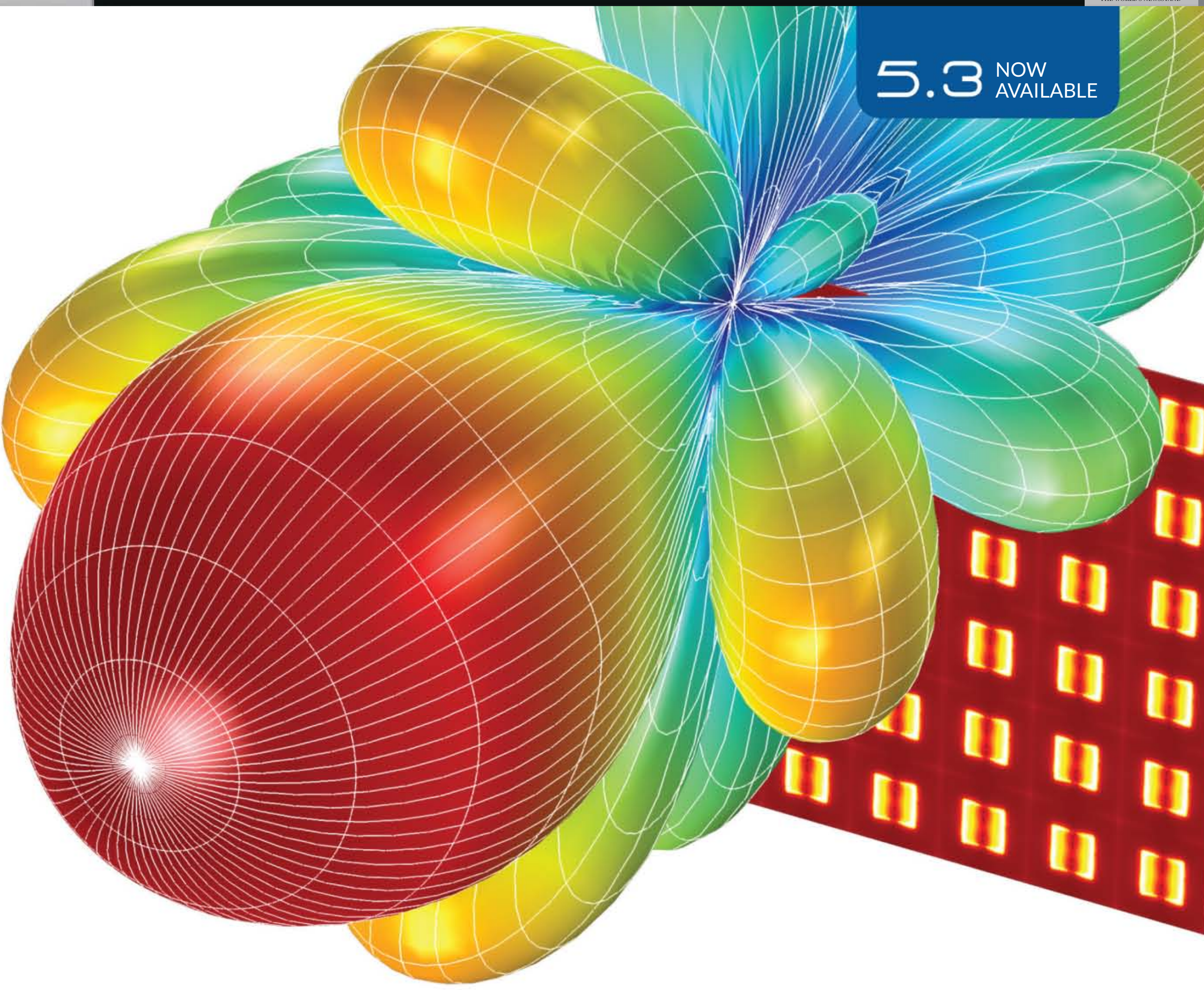
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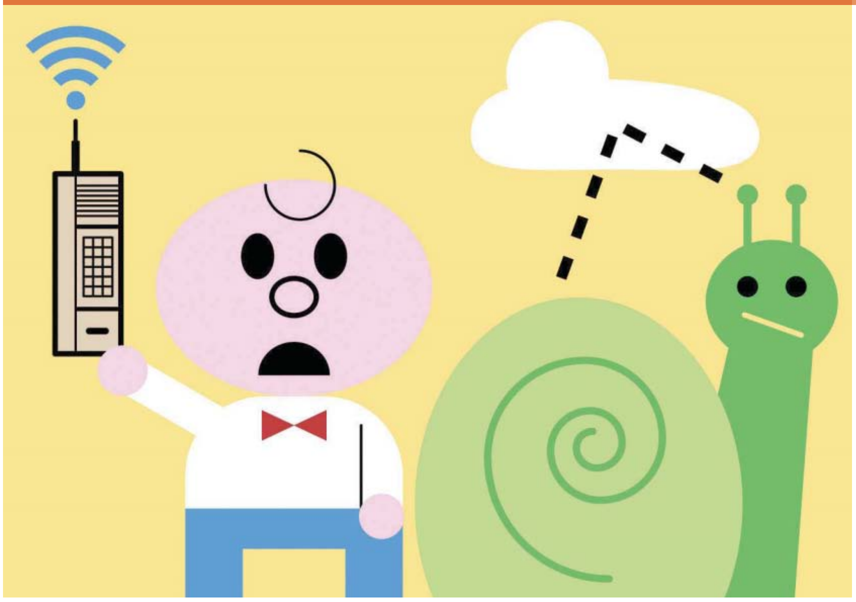

When Innovation Moves Too Fast

We can adopt technologies early, but adaptation takes time

My go-to laptop is out of storage space and I refuse to put my stuff in the cloud. I'm a digital Robinson Crusoe, alone on an island of hard disks and memory sticks. Resisting the cloud hurts only me, but I'm stubborn—and a victim of an insidious, unseen force: Lag. ¶ Lag is the failure to adapt to changes in our engineered world. Lag is everyone's problem. Many people fall behind; most perpetually feel they will never *catch up*. ¶ The problem isn't new. In the 1920s, the sociologist William Ogburn crafted an entire theory around the idea that social and cognitive traits make people slow to adapt to emerging technologies—and thus delay gaining their benefits. Lag hurts the pocket, too. In 1930, John Maynard Keynes, the great economist, partly blamed the Great Depression on "growing pains of over-rapid changes." Improvements in technology, he wrote, were "taking place faster than we can deal with [them]." ¶ Today's early adopters of new technologies—those folks storing their digital lives in the cloud—can pretend that by adopting they are adapting. Not always. ¶ The problem of rampant misinformation on Facebook is a prime example of how adoption isn't adaptation. While facebooking is an everyday experience for millions, decoding the quality of information remains difficult if not impossible. New norms for behavior and technological fixes to stop "fake news" don't yet exist. Lag is the chief culprit. ¶ Similarly, online education appears to sharply reduce costs and expands access to great teachers. Yet early adopters encounter the paradox that they quickly reach a level of knowledge where they gain more from face-to-face instruction. ¶ The pernicious effects of lag persist longer than expected. The peril may be getting worse, in part because adoption of new digital tools is accelerating. Amazon, Twitter, Instagram—all seemed to have established themselves with the rapidity of a hurricane. ¶ In the distant past, adoption rates were slower, easing the challenge of overcoming social and cognitive lag. The telephone provides a classic example. When Bell patented telephony in 1876, the main benefit was to deliver a better form of telegraphy—of sending coded messages more cheaply and easily than Western Union. Many years passed before the telephone's dominant purpose was *talking* to others. As late as 1940, barely one in three households had a phone.

AT&T's slow appreciation for the social uses of the telephone reflected confusion over value. As the preeminent scholar of telephony, Claude Fischer, showed in his book *America Calling*, the national Bell system only belatedly realized the telephone "will keep your personal friendships alive and active." By the end of the 20th century, after relentless marketing, the Bell slogan "Reach out and touch someone" was synonymous with telephony. People happily spent hours a day on the phone.

The mobile phone revolution at first gave new life to disembodied chatting. Yet today, many prefer texting. The telephone mainly provides a Web connection. Once more, as a century ago, human conversation occurs best face to face.

If we are condemned to lag behind technological shifts, can we do anything to more quickly close the gap?

Surprisingly, the history of touch screens reveals much about the complexities of lag. Business first adopted touch screens to assist cashiers in the 1970s and '80s. The equipment was bulky, slow, and expensive. Another 20 years passed before Steve Jobs standardized Apple handheld devices around touch screens. Jobs insisted that touch screens be the main way to control Apple's small devices. He even gambled that Apple's high volumes would dramatically drive down the cost and improve the quality of these screens. Because the underlying technology was mature, Jobs's gamble paid off. Without his bold move on "forward pricing," touch-screen technology might have remained trapped in the limbo of lag.

For me, lag is a bittersweet reminder that facing the future with courage involves a willingness to let go of cherished traditions in the name of pragmatic adjustments.

Which means I'll soon be announcing, "Hey cloud, welcome to my world!" —G. PASCAL ZACHARY

G. Pascal Zachary is a professor of practice at Arizona State University's School for the Future of Innovation in Society.

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ILLUSTRATION BY J.D. King

NEWS

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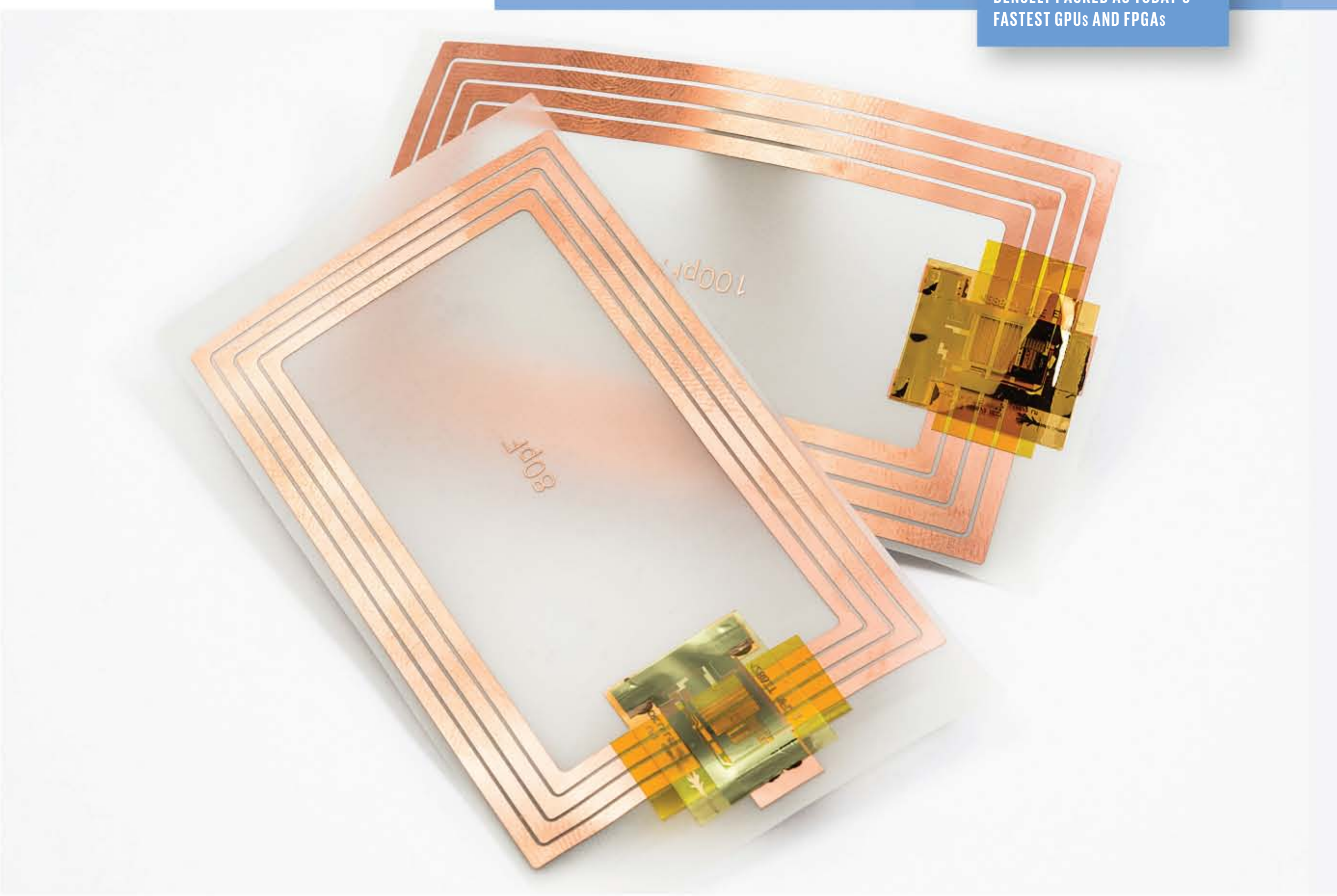
GENERATIONS OF MOORE'S LAW-LIKE DOUBLING NEEDED BEFORE THIN-FILM TRANSISTORS ARE AS DENSELY PACKED AS TODAY'S FASTEST GPUs AND FPGAs



NEAR FIELD COMMUNICATOR: There are 1,700 transistors on the flexible chip in this NFC transmitter.

IMEC

PLOTTING A MOORE'S LAW FOR FLEXIBLE ELECTRONICS

A five-year project at Imec aims to make big boosts in the density of thin-film transistor circuitry

At a meeting in mid-town Manhattan, Kris Myny picks up what looks like an ordinary paper business card and, with little fanfare, holds it to his smartphone. The details of the card appear almost immediately on the screen inside a custom app.

It's a simple demonstration, but Myny thinks it heralds an exciting future for flexible circuitry. In January, he began a five-year project at the nanoelectronics research institute Imec in Leuven, Belgium, to demonstrate that thin-film electronics has significant potential outside the realm of display electronics. In fact, he hopes that the project, funded with a €1.5 million grant from the European Research Council (ERC), could demonstrate that there is a path for the mass production of denser and denser flexible circuits—in other words, a Moore's Law for bendable ICs.

Five years ago, Myny and his colleagues reported that they had used organic thin-film transistors to build an 8-bit micro- »

processor on flexible plastic. In the years since, the group has turned its focus to IGZO—a metal-oxide semiconductor that is a mixture of indium, gallium, zinc, and oxygen. Thin-film transistors based on this substance can move charge significantly faster than their organic counterparts do; at the same time the transistors can still be built at or around room temperature—an important requirement when attempting to fabricate electronics directly onto plastic and other materials that can be easily deformed or damaged by heat.

To build that business card, Myny and his colleagues engineered a flexible chip containing more than 1,700 thin-film IGZO transistors. What sets the chip apart from other efforts is its ability to comply with the ISO14443-A Near Field Communication (NFC) standard. For flexible circuitry, this is a demanding set of requirements, Myny says, as it requires logic gates that are fast enough to work with the 13.56-megahertz standard carrier frequency.

Adding to the challenge is that while IGZO is an effective *n*-type semiconductor, allowing electrons to flow easily, it is not a particularly good *p*-type material; there is no comparable material that excels at permitting the flow of holes—the absence of electrons that are treated as positive charges. Today's logic uses both *p*- and *n*-type devices; the complementary pairing helps control power consumption by preventing the flow of current when transistors are not in the act of switching. With just *n*-type devices to work with, Myny and his colleagues have to devise a different kind of circuitry.

With the ERC project, Imec aims to tackle a suite of interrelated problems in an effort to boost transistor density from 5,000 or so devices per square centimeter to 100,000. That figure isn't far from the density of thin-film transistors in conventional rigid-display backplanes today, Myny says. However, it's another matter to try to achieve that density with digital logic circuits—which require more complicated designs—and to make sure those devices are reliable and consistent when they're built on a delicate and irregular substrate.

The group also wants to prove this density is achievable outside the lab, by adapting manufacturing techniques that are already in use in display fabs. Myny says that if he and his team hit their goals, a square centimeter of fast, flexible circuitry could be built at a cost of 1 U.S. cent (assuming high-volume manufacturing). At the same time, while the density of the circuits increases, the group will also have to boost the transistor frequency and drive down power consumption to prevent overheating. The overall goal, Myny says, is to demonstrate "that you can indeed make flexible circuits—that it is not science fiction but that it is going to market."

When it comes to the fabrication of complex digital circuits on flexible substrates, "Imec is in my opinion the biggest player," says Niko Münzenrieder, a lecturer at the University of Sussex, in England, who specializes in flexible electronics. He notes that metal-oxide flexible circuitry is already starting to make commercial inroads, and he expects the first big applications to be in RFID and NFC technology. "It's not a mature technology," he says, "but it's nearly ready for everyday use."

—RACHEL COURTLAND

POST YOUR COMMENTS at http://spectrum.ieee.org/flexible0717

SILICON VALLEY'S LATEST CRAZE: BRAIN TECH

Elon Musk, Mark Zuckerberg, and other big players have started neurotech initiatives

Silicon Valley's biggest influencers want to get inside your head. Over the past year, four leading figures have announced plans to make gadgets that will either nestle into the fleshy folds of your brain or sit atop your head to read your thoughts from the outside.

The proposed hardware and applications are varied, but all signify ambitious—even audacious—undertakings. Whether working on medical devices to fix a neural deficiency or consumer gizmos to augment normal brainpower, each of the four Valley visionaries promises to have something ready for the market in just a few short years.

Neural engineers have mixed feelings about these high-profile announcements from the likes of Elon Musk and Mark Zuckerberg. "There's a lot of excitement when this cast of characters gets involved," says Paul Sajda, a professor of biomedical engineering at Columbia University, in New York City, and an expert on advanced technologies for brain research.

But Sajda wonders if these deep-pocketed individuals know what they're getting into. "The typical Silicon Valley attitude is that if you throw enough money at something, you can solve the problem," Sajda says. While that approach may work for applied technology, he says, it doesn't necessarily work if there are fundamental science

OPEN YOUR MIND: Facebook CEO Mark Zuckerberg announced plans for a typing-by-brain project in April.

questions that need to be answered–and there are many unanswered questions in neuroscience.

John Donoghue, director of the Wyss Center for Bio and Neuroengineering, in Geneva, has steadily worked on a brain-computer interface (BCI) for decades; his team's BrainGate system has enabled paralyzed people to control robotic arms and computer cursors. Donoghue says he can't decide whether the sudden Silicon Valley buzz around BCIs will ultimately help or harm his field. "It is valuable to set a really ambitious goal that gets everyone really excited, especially if it drives investment," he says. "On the other hand, they may be setting false expectations for what can be achieved, which will then create disillusionment."

Here are the four ventures that could signify the beginning of a new era of neurotech–or the beginning of a brain-tech bubble.

1 – FACEBOOK'S "TYPING-BY-BRAIN" PROJECT

"We're working on a system that will let you type straight from your brain about 5x faster than you can type on your phone today," wrote Mark Zuckerberg in an April post. Arguing that invasive brain implants won't be accepted by the masses, Zuckerberg put the Facebook R&D team to work on inventing a noninvasive wearable technology that can detect "intended speech" in the brain without the user having to say the words aloud. The gear will supposedly translate these thoughts into text at a rate of 100 words per minute.

At a recent conference, project leader Mark Chevillet said the team aims to demonstrate the feasibility of a commercial product within two years. Skeptical neuroscientists note that the current record for typing-by-brain is eight words per minute, a feat achieved with an invasive brain implant.

2 – OPENWATER'S WEARABLE TECH FOR CONSUMER TELEPATHY

Mary Lou Jepsen is a seasoned Silicon Valley executive who quit a high-powered job at Facebook last August to launch a startup called Openwater. Jepsen says she's working on an optical-imaging system that provides high-resolution images comparable to MRI scans. The system uses flexible components that could be incorporated in a bandage or tucked inside a hat.

She sees a host of uses for such a technology, including medical imaging to detect clogged arteries and tumors. But the true disruption, Jepsen says, will come from high-resolution brain scans that enable BCI systems to interpret the patterns of neural activity associated with thoughts. "I know it seems outlandish to be talking about telepathy, but it's [based on] completely solid physics and mathematical principles," she says. "It's in reach in the next three years."

3 – ELON MUSK'S NEW COMPANY, NEURALINK

You might think Elon Musk already has his hands full as CEO of both Tesla, the electric car company, and SpaceX, the reusable rocket company. Yet in March he revealed a new firm, Neuralink, devoted to building high-bandwidth BCI systems that will be implanted in the brain. Musk has said that an ideal technology won't require brain surgery, and he has floated the idea of components that could be injected into the bloodstream. While he hasn't divulged further technical details, neuroscientists say he may be basing his plans on cutting-edge research involving tiny "neural dust" electrodes or mesh electrodes that unfurl in the brain.

Musk's long-term goal is to invent a BCI that everyday people will use to augment their cognitive abilities. But to get to that general consumer market, Neuralink will first develop a medical product that can gain regulatory approval. "We are aiming to bring something to market that helps with certain severe brain injuries (stroke, cancer lesion, congenital) in about 4 years," he told a blogger. "I think we are about 8 to 10 years away from this being usable by people with no disability."

4 – KERNEL'S IMPLANT

Bryan Johnson made his fortune with the 2013 sale of his online payment company, Braintree, to eBay. Last October he announced that he was putting US $100 million of his money into his new startup, Kernel, to develop an implanted brain prosthetic. The company's initial goal was to design an implant that would help people with failing memories, including Alzheimer's and stroke patients. However, neuroscientists say Kernel has since pivoted to focus on a more general implant that will enable the recording of signals from thousands of neurons at once–and that the company will figure out the best medical applications of that technology down the road. –ELIZA STRICKLAND

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JUSTIN SULLIVAN/GETTY IMAGES

NEWS

SEARCHING THE SKIES: Black Sage Technologies' artificial-intelligence system spots flying objects and determines whether they're a threat.

BLACK SAGE TECHNOLOGIES

AI TO ENSURE FEWER UFOS

To respond to a plague of drones, airports and other venues deploy AI systems to track and identify intruders

Is it a bird? A plane? Or is it a remotely operated quadrotor conducting surveillance or preparing to drop a deadly payload? Human observers won't have to guess—or keep their eyes glued to computer monitors—now that there's superhuman artificial intelligence capable of distinguishing drones from those other flying objects. Automated watchfulness, thanks to machine learning, has given police and other agencies tasked with maintaining security an important countermeasure to help them keep pace with swarms of new drones taking to the skies.

The security challenge has only grown over the past few years: Millions of people have bought consumer drones and sometimes flown them into off-limits areas where they pose a hazard to crowds on the ground or larger aircraft in the sky. Off-the-shelf drones have also become affordable and dangerous weapons for the Islamic State and other militant groups in war-torn regions such as Iraq and Syria.

The need to track and possibly take down these flying intruders has spawned an antidrone market projected to be worth close to US $2 billion by the mid-2020s. The lion's share of that haul will likely go to companies that can best leverage the power of machine-learning AI based on neural networks.

But much of the antidrone industry still lags behind the rest of the tech sector in making effective use of machine learning AI, says David Romero, founder and managing partner of Black Sage Technologies, based in Boise, Idaho. "With machine learning, 90 percent of the work is figuring out how to make it so simple so that the customer doesn't have to know how machine learning works," says Romero. "Many companies do that well, but not in the defense community."

He and Ross Lam, his Black Sage cofounder, are poised to take advantage of this opening for the upstarts looking to take on the defense industry's giants. They initially collaborated on a project that trained machine-learning algorithms to automatically detect deer on highways based on radar and infrared camera data. Eventually, they realized that the same approach could help spot drones and other unidentified flying objects.

Since the self-funded startup's launch in 2015, it has won multiple contracts from the United States government—including for U.S. military forces deployed in Iraq and Afghanistan—and from U.S. allies.

Romero says it's fairly straightforward to apply machine learning to the task of automatically detecting and classifying flying objects. But because the stakes are high—mistakenly shooting down a small passenger plane or failing to take out an explosives-laden drone intruder could be equally disastrous—Black Sage puts its system through a rigorous training phase when it's installed at a new site. The system's radar and infrared cameras capture information about each unidentified flying object's velocity, size, altitude, and so forth.

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NEWS

Then a human operator helps train the machine-learning algorithms by positively identifying certain classes of drones (rotor or fixed-wing) as well as other objects such as birds or manned aircraft. For proof that it has learned its lessons well, the AI is tested against 20 percent of the positively identified data set–the part reserved specifically for cross validation.

Another company called Dedrone–originally based in Kassel, Germany, but currently headquartered in San Francisco–is taking a similar approach. When a Dedrone system is being installed at a new site, humans label unfamiliar objects as part of the training process, which also updates the company's proprietary DroneDNA library. Since its launch in 2014, Dedrone's machine-learning software has helped safeguard events and locations such as a Clinton-Trump presidential debate, the World Economic Forum, and CitiField, home of the New York Mets baseball team.

"Each time we update DroneDNA, we process over 250 million different images of drones, aircraft, birds, and other objects," says Michael Dyballa, Dedrone's director of engineering. "In the past eight months, we've annotated 3 million drone images."

Though Black Sage's and Dedrone's automated detection systems are said to be capable of running without human assistance after their respective training phases, the companies' clients may choose to put humans in the loop for engaging active defenses, such as jammers or lasers, to take down flying intruders. Such caution is critical at sites like airports, where drone detection accuracy greater than 90 percent still means the occasional false alarm or case of mistaken identity. Even so, a human's interpretive ability can only supplement the ceaseless vigilance that AI systems will need to provide as the number of drones continues to rise. –JEREMY HSU

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DONG ENERGY

OFFSHORE WIND POWER TO BE PROFITABLE WITHOUT SUBSIDIES

In Europe, new tech boosts the appeal of previously pricey offshore wind

Europe's offshore wind power industry recently achieved a major milestone: three projects to be built without government subsidy. Bent Christensen, who is responsible for energy-cost projections for Siemens's wind power division, credits industry-wide cost cutting that has outstripped expectations. "We're three to four years ahead of schedule," says Christensen.

Projects taking shape in European waters this summer, meanwhile, will demonstrate the ongoing innovation required to deliver on those bids–innovations that could make offshore wind farms more attractive to both financiers and grid operators.

BIG BRITISH BLADES: A platform for installing one of the world's biggest turbines stands off the east coast of England.

Detractors have long derided offshore wind power as a niche segment. In spite of fantastically strong wind gusts, building offshore-ready equipment and installing it in the punishing marine environment has been pricey.

In 2013, when new projects were delivering electricity for about €160 (US $179) per megawatt-hour, the industry collectively set what Christensen calls a "realistic stretch goal" to squeeze that to €100/MWh by 2020. Christensen, who is also senior vice president of Siemens's wind turbine business, Siemens Gamesa Renewable

NEWS

THE NORTH WIND: Three proposed offshore projects [orange] will be competitive without government subsidies. They depend on technology developed for recent projects such as Hornsea [in blue] and bigger turbines. Innovative transmission links [in purple] will make wind farms more valuable by connecting them to more countries.

Energy, says that by his math the industry is already there.

Christensen's estimate is echoed by the financial advisory firm Lazard, which projects the unsubsidized cost of newly commenced projects at €105/MWh ($118/MWh)—a 27 percent reduction since 2014. Lazard's December 2016 analysis finds that offshore wind is cheaper or on par with coal-fired generators, rooftop solar arrays, and nuclear reactors.

Recent bids for near-shore projects, meanwhile, rival the cost of onshore wind and utility-scale solar energy. Several projects in Denmark and the Netherlands promise offshore wind power for less than €75/MWh, and then there are the subsidy-free German bids this April by Copenhagen-based Dong Energy and the German utility Energie Baden-Württemberg. Ulrik Stridbaek, Dong's senior director for regulatory affairs, estimates its projects' power cost at €62/MWh.

According to Stridbaek, competition, innovation, and scale all contribute to the rapid cost declines that have been achieved throughout the industry's supply chain—from turbine manufacturing to installation to power transmission. But Stridbaek says that "the decisive factor is scale."

Dong's 1.2-gigawatt Hornsea Project One wind park, which it will begin installing next year at a spot 120 kilometers off the United Kingdom's Yorkshire coast, is nearly twice the output of the current record holder. The turbines populating offshore farms are also beefing up. Offshore turbines topped out at 3.9 MW each in 2013, whereas today's biggest deliver 8 MW. Dong installed the first of those mass-produced giants at another U.K. wind farm in December.

Zero-subsidy projections for those German projects, meanwhile, rely on 13- to 15-MW turbines that don't yet exist. Dong is betting, says Stridbaek, that suppliers such as Siemens Gamesa and MHI Vestas Offshore Wind will have such giants ready for the North Sea projects' completion, in either 2024 or 2025.

New tech is also needed for the transmission systems that bring wind power ashore. Several novel approaches are now being tested in the Baltic Sea, where a 30-km patch cord between German and Danish wind farms will create an extra interconnector between the Nordic and European grids. The cable's seabed route across the shallow Baltic sandbar known as Kriegers Flak is being cleared of unexploded World War II ordnance this month, and the link is expected to be completed next year.

When the Baltic wind farms are idle—about 50 percent of the time—Europe's software-integrated power markets will use their cables to exchange electricity between northern Europe and Scandinavia. Peter Jørgensen, vice president for the Danish grid operator Energinet.dk, expects the link to deepen the region's existing pattern of power swaps, in which European wind power and Nordic hydropower balance each other.

What made the project feasible, says Jørgensen, is a low-cost arrangement of the high-voltage direct-current (HVDC) converters needed to exchange 400 MW between the two grids, which are not in sync with each other. Early designs would have placed one converter offshore at Kriegers Flak. Instead, the project will place both converters back-to-back in Germany onshore, thus avoiding the roughly 50 percent premium for an offshore platform.

A supersize version of this dual-use cable design hatched last year by the Dutch-owned grid operator TenneT calls for offshore transmission hubs for the North Sea. The proposal, recently joined by Energinet, calls for one or more artificial islands whose power systems would gather up to 100,000 MW of offshore wind generation and parcel it out to the North Sea countries.

These "power link islands" would—like the Kriegers Flak link—minimize transmission costs by keeping HVDC converters on dry land and maximize their value by trading power between grids. They would also host technicians, spare parts, service vessels, and an airport offshore, thus reducing the cost of wind farm maintenance.

The North Sea proposal is in prefeasibility studies, according to Jørgensen, and may not work out. But industry participants say it is the kind of creative thinking needed to keep costs falling—especially given the massive scale of renewable energy deployment required to meet Europe's ambitious decarbonization goals.

—PETER FAIRLEY

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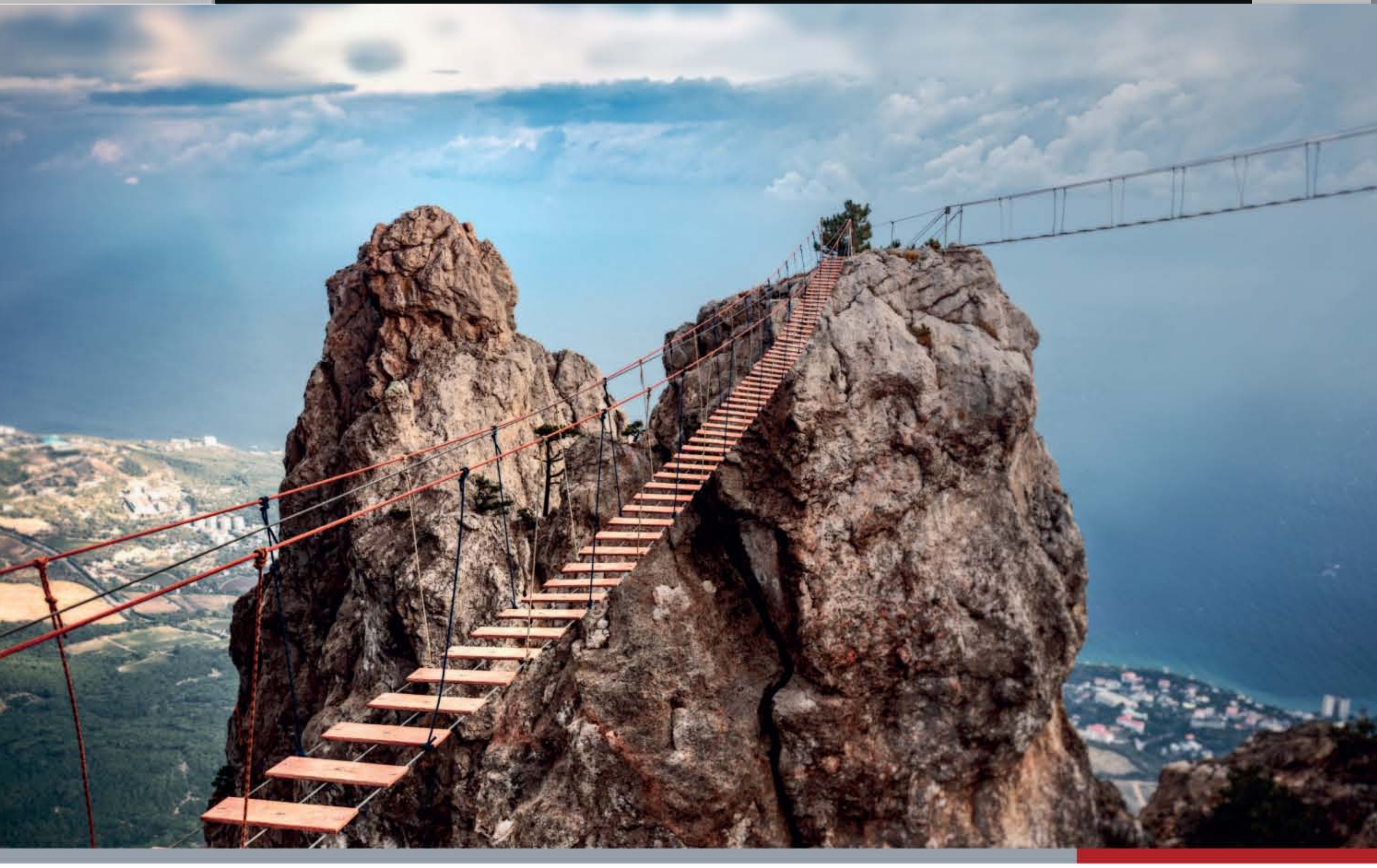
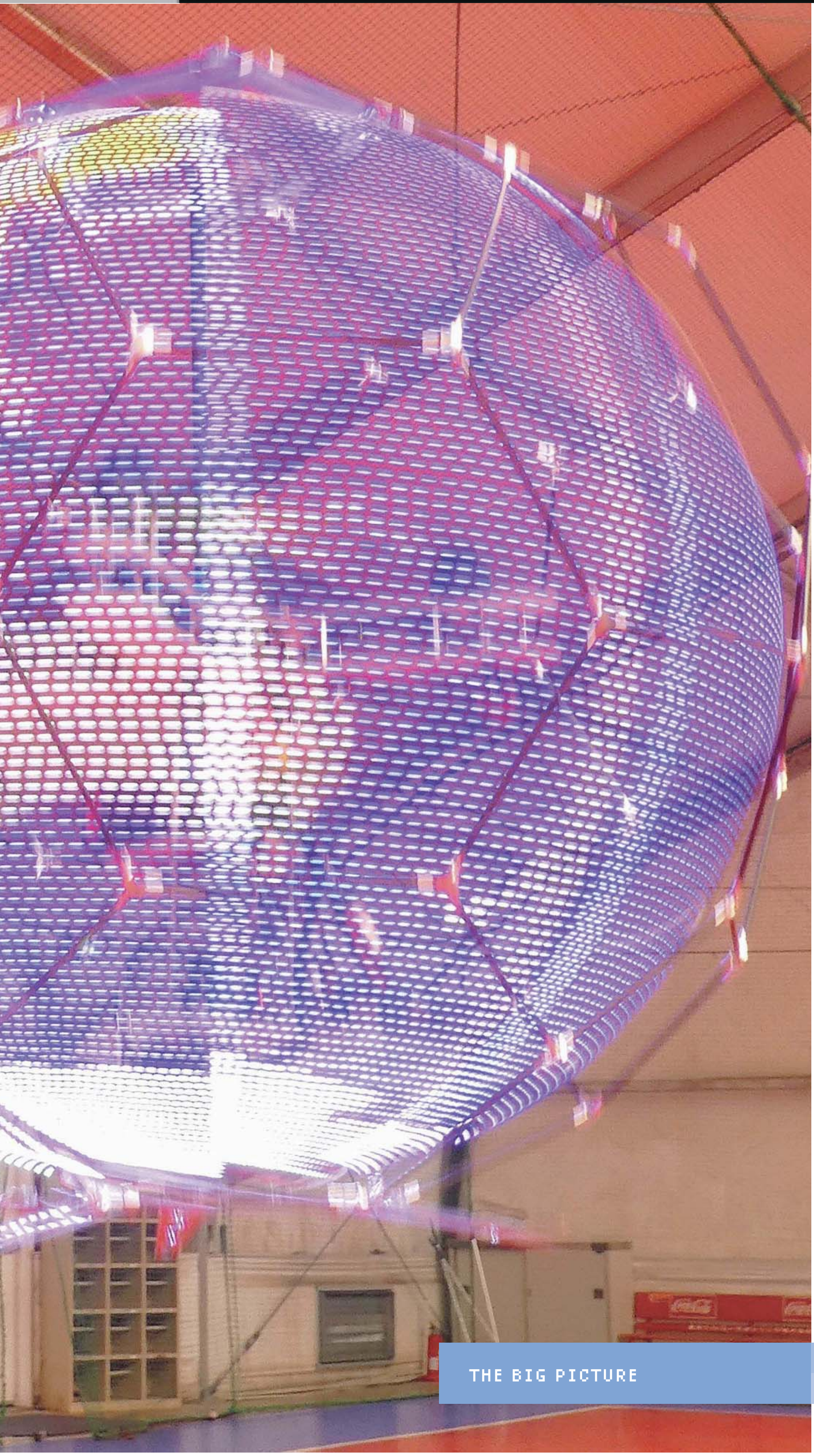
ISTOCKPHOTO



PHOTOGRAPH BY The Asahi Shimbun/Getty Images



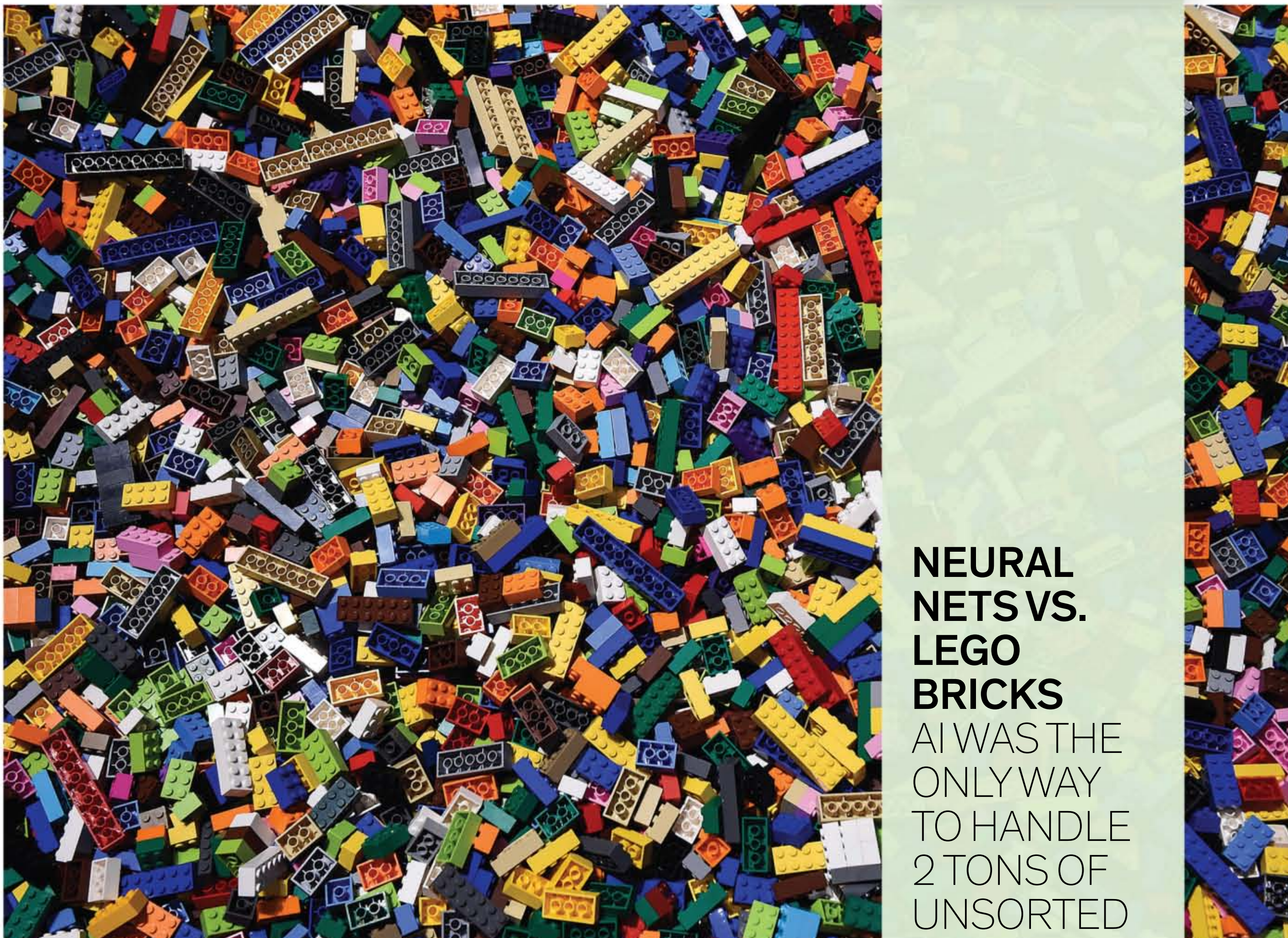
YOUR AD HERE

DRONES DO A LOT. They surveil enemy territory and drop bombs, help meteorologists track weather systems, and whiz around obstacle courses for sport. Soon, advertisers will deploy them, filling the skies with flying electronic displays. In April, the Japanese telecom company NTT Docomo showed off the unmanned aerial vehicle seen here, calling it the "world's first spherical drone display." The 88-centimeter-diameter frame surrounding the drone provides enough space for a viewer to see a 144-by-136-pixel section of the LED display. There are eight curved LED strips that rotate around the frame as it moves, giving the visual effect of a solid globe. But it's mostly hollow–a concession to the need to avoid blocking the airflow from the drone's propellers and keep the aircraft's weight down.

THE BIG PICTURE NEWS

RESOURCES

US $80.8 MILLION: THE AMOUNT SPENT BY THE LEGO GROUP ON R&D IN 2015



ZHONG ZHENBIN/GETTY IMAGES

NEURAL NETS VS. LEGO BRICKS

AI WAS THE ONLY WAY TO HANDLE 2 TONS OF UNSORTED PLASTIC PIECES

For many years as a child, I did nothing but play with Lego. Eventually I had children of my own, who had a nice Lego collection themselves, but nothing you'd need machinery to sort. That changed after a trip to Legoland in Denmark. ● I noticed adults at the park buying Lego in vast quantities, despite its high price. Even second-hand Lego isn't cheap, sold as it is by the part on specialized websites, or by the boxed set and in bulk on eBay. I noticed that bulk unsorted Lego sells for roughly €10 per kilogram (about US $11/kg), boxed sets go for €40/kg, and collections of rare parts and Lego Technic pieces (the sort used to build complex mechanical creations) go for hundreds of euros per kilo. Consequently, there exists a cottage industry of people who buy new sets and bulk Lego and manually sort all the pieces into more valuable groupings. ● I figured this would be fun to get into. I put in some eBay bids on locally available large lots of Lego and went to bed. The next morning, I woke up to a rather large number of congratulatory emails from eBay sellers (eBay lesson one: If you win that many auctions, you are bidding too high). ● And so, after I picked up my winning lots of Lego, my garage was stacked top to bottom with crates and boxes—about two metric tons, all told. Sorting this by hand was never going to work. I decided to build something that would scan and sort each part accordingly. ● The first problem was that feeding Lego from a hopper mounted above a conveyor belt is surprisingly hard. I've yet to find a configuration so wide and deep that a random assortment of descending Lego could not spontaneously form a pretty sturdy bridge across the opening. Consequently, I use a slow belt to pull parts up out of my ▸

RESOURCES_HANDS ON

hopper before dropping them onto a much faster transport belt. This belt moves parts past a $30 magnifying camera connected via USB to a PC for identification.

Once identified, the parts have to be moved from the transport belt to the correct bin. After some experimenting I settled on putting air nozzles next to the belt. A well-timed puff knocks the part into the desired bin.

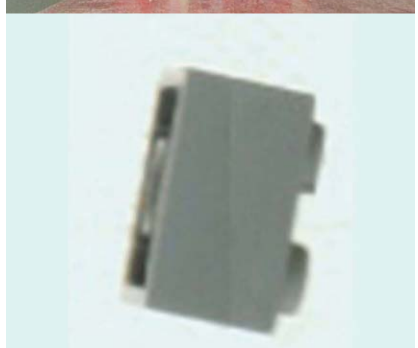
The biggest challenge of course was identification. First, I had to capture a good image of each piece. There were all kinds of gotchas here. For instance, parts may be longer than a single image frame, parts can be a color that is extremely close to that of the background, and so on. It was several weeks before I could reliably stitch and crop scans automatically, so that I was generating images containing one complete piece of Lego.

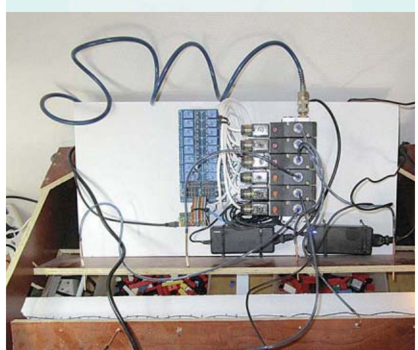
Then came the really hard part: identifying each piece. Lego bricks come in thousands of distinct shapes and over 100 colors (you can roughly tell how old someone is by asking them what Lego colors they remember from their youth). Initially, I tried to classify this zoo with the OpenCV computer vision library. Using things like contour matching and circle detection, the system could tell the differences among the basic Lego bricks, but not much more than that.

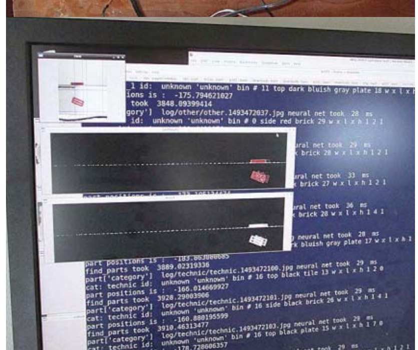
Next, I tried Bayesian classification: I chose distinguishing features and built software detectors for those. I came up with around 18 features, which included things such as the height of the part, whether or not it had any holes, how many studs were visible, and so on.

Building and testing the detectors took quite a while, but eventually I was able to identify pieces with impressive accuracy. But the system was too slow to keep up with the machinery. After a few other failed approaches, and six months in, I decided to try out a neural network. I settled on using TensorFlow, an immense library produced by the Google Brain Team. TensorFlow can run on a CPU, but for a huge speed increase I tapped the parallel computing power of the graphics processing unit in my US $700 GTX1080 Ti Nvidia video card.

TensorFlow has an arduous learning curve, but eventually I was pointed to Keras, a Python language library by François Chollet. Keras acts as a wrapper for TensorFlow and







LEGO EX MACHINA: A slow conveyer belt pulls pieces from a hopper [top]. A camera captures images of individual pieces [second from top] and a neural net identifies them [second from bottom]. Air puffs from valves [bottom] knock sorted pieces into bins.

JACQUES MATTHEIJ (4)

makes it much easier to use, especially after looking at Jeremy Howard and Rachel Thomas's excellent starter course on machine learning.

I started building my neural net system in earnest. Within several days I had the sorter working and handling more than a few classes of parts for the first time.

The next step was to get a training set for my neural network that was large enough to make working with over 1,000 types of Lego pieces possible. At first this seemed like an insurmountable problem: I could not figure out how to photograph and label enough sample parts by hand. Even the most optimistic calculations had me working for six months or longer flat out.

Then I realized I didn't need to make the training set all by myself. The *machine* takes and labels images. All I need to do is spot the ones where the computer was wrong and relabel the image correctly. As the neural net learns, there are fewer mistakes, and the labeling workload decreases.

The first day I managed to label a starter set of about 500 assorted scanned pieces. Using those parts to train the net, the next day the machine sorted 2,000 more parts. About half of those were wrongly labeled, which I corrected. The resulting 2,500 parts were the basis for the next round of training. Another 4,000 parts went through the machine, 90 percent of which were labeled correctly! So, I had to correct only some 400 parts. By the end of two weeks I had a training data set of 20,000 correctly labeled images.

Some classes are still underrepresented in the training set, so I need to increase the number of images for those. I'll probably just run through a single sample batch consisting of nothing but those parts. Once the software is able to reliably classify across the entire range of parts in my garage, I'll be pushing through the remainder of those two tons of bricks. And then I can finally start selling off the results! **—JACQUES MATTHEIJ**

An extended account of the sorter construction is available on Mattheij's blog at Jacquesmattheij.com.

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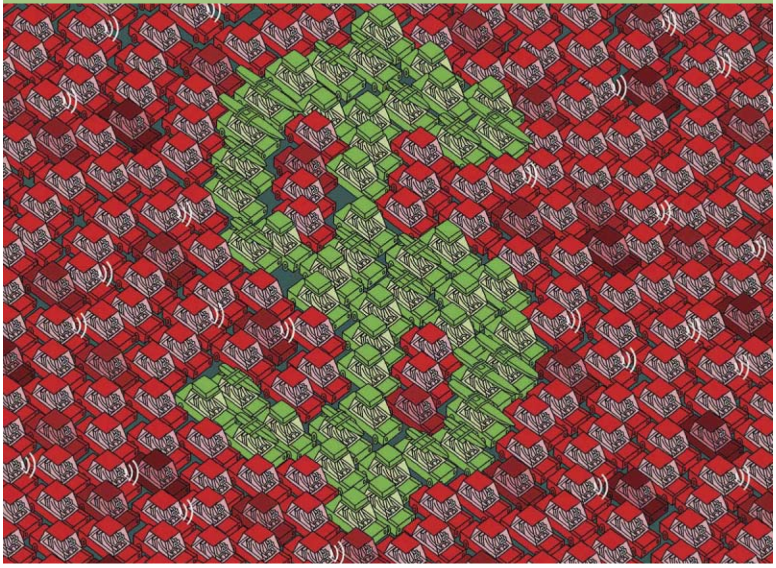
RESOURCES_STARTUPS

PROFILE: PLEX.AI
CAN IT SHAKE UP AUTO INSURANCE WITH AI AND THE BLOCKCHAIN?



GETTY IMAGES

If Internet-connected cars, the blockchain, and machine learning are each going to change the world in its own unique way, what happens when all three are combined? One startup company, based in Kitchener, Ont., Canada, is exploring this question in the unlikely arena of insurance.

According to Plex.ai cofounder Terek Judi, the advent of always-connected cars represents a seismic shift. "We're trying to reengineer certain aspects of the insurance business around reliably connected cars," Judi says.

The connectivity, he says, will force car companies toward using open platforms in their vehicles, just as Android and iOS killed off closed platforms when smartphones came to mobile telephony. In such an ecosystem, car software developers could then use open standards like the blockchain—the distributed and secure data ledger on which Bitcoin is based—for communication between cars and with trusted third parties.

"What blockchain technology has introduced is the ability to have a shared database that is open to everybody to contribute to, yet you can still count on security," he says. "People can't go and change things in ways that are malicious."

Secure and reliable but still open communication between cars, Judi says, will then enable a car's insurer to provide continuously updated car insurance rates that are based on the car's reported actual use. Plex, Judi says, will be using machine-learning algorithms to process the incoming streams of data from its customers' cars to optimize each customer's bottom-line price on the fly.

The attraction for consumers would typically be lower rates, he says, because they're based on real-world car usage data, not just the generic actuarial profiles of drivers used today.

"Today I write you a policy for one year, and you only talk to me if you had an accident. And if you had an accident, that'd increase your rates," Judi says. "But if I'm able to look at the functioning of the vehicle, I might be able to introduce variable ways of assessing the risk you pose."

So, drivers who speed and drive recklessly or face treacherous conditions or weather might find their rates go up after a bad day on the road. But such real-time responsiveness of their rate plans could also induce them to reduce their risky behavior in order to lower future insurance payments.

"I see the insurance industry becoming more of a technology business," Judi says. But big insurance companies today are typically far removed from the technological vanguard. So, he says, "This inefficiency that exists will provide an opportunity for small companies like ours to slide through the cracks, establishing a presence in an otherwise heavily fortified industry."

Plex launched in 2016 with a far simpler vision: connecting drivers in the province of Ontario to the best traditional insurance plan for them. Plex, subsisting on revenues from this business as well as development grants, is currently a team of three engineers working on its more ambitious vision. It is now exploring applying to be an insurance carrier in Ontario.

Collin Thompson, Hong Kong–based cofounder of the blockchain venture-capital fund Intrepid Ventures, says he thinks Plex.ai has a lot of promise. Comparing the company's development to Facebook's incubation on college campuses, Thompson says Plex is smart to tackle larger industry-size problems first in the context of the Ontario insurance market.

Intrepid hasn't invested in Plex, Thompson says. But he is keeping a close eye on the company. "Our interest is in the global expansion of Plex and what they're doing," he says. "[Judi] doesn't necessarily have to figure out North America in the first two years. I think if he figures out Toronto and the Canadian insurers, platforms, and aggregators, that's significant business." —MARK ANDERSON

Incorporated: June 2016 **Headquarters:** Kitchener, Ont., Canada **Founders:** Terek Judi, Ashish Malhotra, Greg Raymond, Jovan Sardinha **Funding:** C$60,000 **Funders:** University of Waterloo **Employees:** 3

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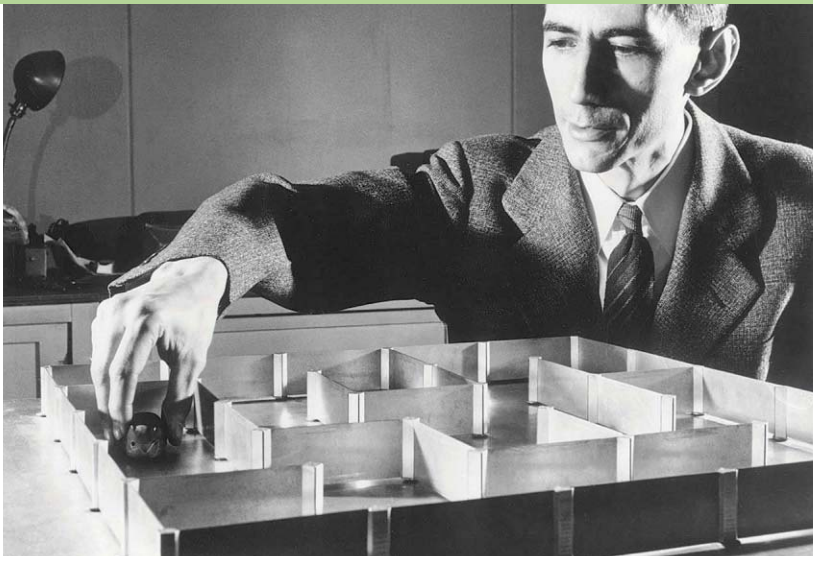
RESOURCES_Q&A

MEET THE AUTHORS OF *A MIND AT PLAY*

JIMMI SONI AND ROB GOODMAN WROTE THE FIRST BIOGRAPHY OF CLAUDE SHANNON



KEYSTONE/GETTY IMAGES

The spirit of Claude Shannon looms large over *IEEE Spectrum*, and indeed the entire modern world. His 1937 demonstration that Boolean logic and algebra could be implemented using electric switches was a tremendous contribution to the computer age just by itself. Then Shannon topped this in 1948 by founding information theory, which provides the mathematical framework for all digital communication. Given his significance, we were surprised to find there was no book-length biography of Shannon, at least until now. This July, Simon & Schuster is publishing *A Mind at Play: How Claude Shannon Invented the Information Age* by Jimmi Soni and Rob Goodman. *Spectrum* senior editor Stephen Cass spoke with them about Shannon and their book.

Stephen Cass: *Why did you write this biography?*

Jimmi Soni: I realized that Shannon was an incredibly interesting figure. I went looking for a biography, and it turned out there wasn't one. And I was just really drawn to his personality. He was someone who had both the gifts and the opportunity to work on whatever he wanted. He was someone who really followed his scientific interests in a way that just enabled him to do remarkable, creative work that was just years in advance of whichever field he was in.

S.C.: *What was the most surprising thing you learned?*

J.S.: Probably one of the more surprising elements of Shannon's life and his work was that he was a pretty artistic guy: He had a flair for the visual. He built a flame-throwing trumpet. He constructed Theseus, the maze-solving mouse. What's interesting about that mouse is the actual maze solving is happening underneath, but he knew that in order to make people understand what was going on, he had to use an image that everybody could understand, which is a mouse going through a maze.

Rob Goodman: As someone with a humanities and social science background, learning about Shannon's life and work really called into question the whole "two cultures" paradigm, that math and science and the humanities on the other hand have very little to say to each other. [Shannon was asking] questions that are really interesting to humanists as well, like, What is the nature of language? What makes a message surprising?.... What Shannon was doing was not all simply hard math. It was thinking about problems that really, at the same time, consumed people in linguistics and philosophy as well.

S.C.: *How important was his familiarity with practical technology to developing his more abstract theories?*

J.S.: It's hard to explain the leaps he took if you don't think back to his work on things like the telephone network at Bell Labs, on things like speech encryption during World War II, and even things like studying the physical properties of motion when he worked on antiaircraft gun directors as part of the war effort. It's difficult to say exactly where his ideas came from, but I think Shannon was someone who always thought in this extraordinarily hands-on manner. Who knows what his work would have been like with those experiences out of the equation? But as far as we can tell, they were an essential part of his thought and creativity.

S.C.: *All good biographies are exercises in curation. What was the hardest thing to leave out of your book?*

R.G.: It would've been interesting to go and take a look at some of Shannon's contraptions in more depth. We did it to some degree with the chess-playing machine and a couple of the other things, but there's a room full of these kind of contraptions, and so we could have gone down the road of those curiosities to the tune of 100, 150 pages!

An excerpt from A Mind at Play *is available online at http://spectrum.ieee.org/shannon0717.*

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TO DESIGN BETTER HARDWARE, THINK LIKE A CYBER-CRIMINAL

IMPROVING SECURITY CAN BE INEXPENSIVE—WITH THE RIGHT MIND-SET

The future of cybersecurity is in the hands of hardware engineers, says Scott Borg, director of the U.S. Cyber Consequences Unit, a nonprofit think tank based in Vermont. He spoke in May at the MEMS & Sensors Technical Congress, held at Stanford University, in California, to an audience of 130 chief technical officers, engineering directors, and key researchers from microelectromechanical systems and sensors companies and labs. Borg warned that "the people in this room are now moving into the crosshairs of cyberhackers in a way that has never happened before."

Borg should know. He and his colleagues at the Cyber Consequences Unit predicted the Stuxnet attack as well as some major developments in cybercrime over the past 15 years.

Today, he says, hackers are increasingly focusing on hardware, not on software, particularly industrial equipment. "Initially," he said, "they focused on operations control, monitoring different locations from a central site. Then they moved to process control, including programmable logic controllers and local networks. Then they migrated to embedded devices and the ability to control individual pieces of equipment. Now they are migrating to the actual sensors, the MEMS devices."

The move to attacking hardware, Borg says, comes because hackers are thinking about the economics, just as in any cyberattack. Hackers always profit in some way from their attacks, though the gain isn't always monetary. One way hardware hackers can profit by hurting a company would be by taking advantage of the resulting drop in its stock price due to, say, quality control failures. "There is a limit to how much you can steal from credit card fraud; there is no limit to how much you can make in taking a position in a market and making something happen," says Borg.

PETER DAZELEY/GETTY IMAGES

It is going to be up to engineers to stop this coming hardware cybercrime wave. And it's not going to be easy because "engineers aren't as easy to fool as scientists, but they are still really easy to fool.... Engineers believe in data, in gauges, in measurements. They are a little less easy to fool than scientists in that they build physical systems that operate, and when they fail, they do have to try to figure out why and what real world effects are. But engineers aren't used to dealing with unkind adversaries. They believe in statistics, where statistical distributions are normal, where probabilities can deal with independent variables. And statistics doesn't work in a cyberworld. If you are up against a cunning adversary who will behave in ways outside of normal, it is hard to use any of the techniques we use in the natural world. A cyberadversary will take advantage of unlikely circumstances."

So what can engineers do? There's just one guiding concept. Look at products from the standpoint of the attacker, and consider how the attacker would benefit from a cyberattack. Then make undertaking that attack costly. Fortunately, if engineers, particularly design engineers, learn to understand the cybercriminal and think proactively about cyberattacks, they can often improve cybersecurity—and do it cheaply.

"Increasing security isn't always about layering on security [to a completed system], but about how you implement a certain function in the first place, and that choice often doesn't cost more," Borg says. "Decisions that are made in engineering at really fine-grained levels affect the costs of carrying out a cyberattack."

It's also important to start thinking like a cybercriminal right away: "As we move into embedded controllers and microdevices, we move into a realm that cybersecurity specialists like me haven't explored that much yet," he says. "The hackers haven't explored it yet either," but, Borg warns, they will: "[Design] decisions you are making will have powerful security implications." **—TEKLA S. PERRY**

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

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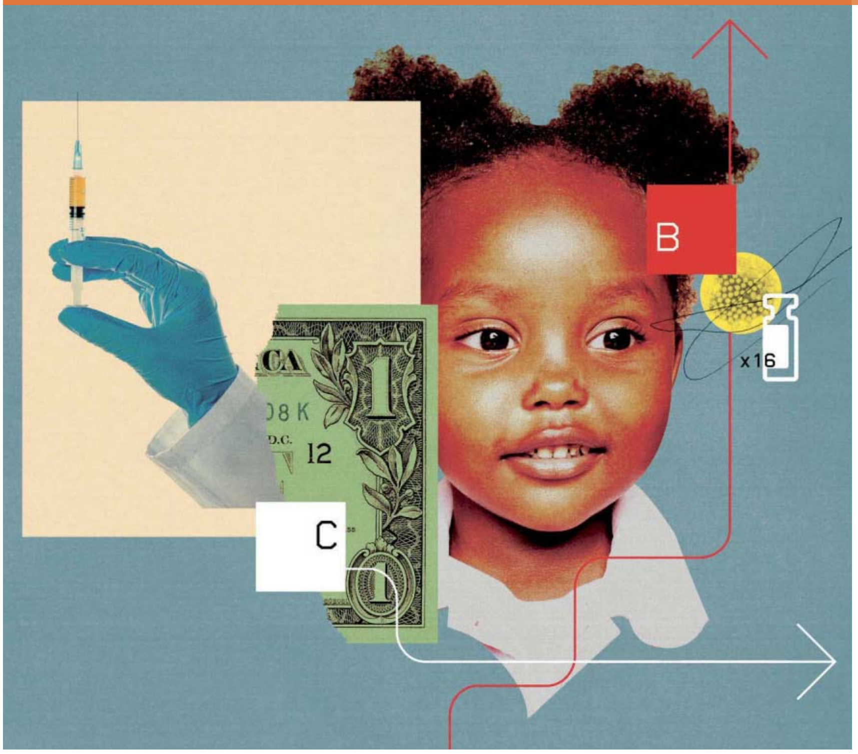

VACCINATION: THE BEST RETURN ON INVESTMENT

DEATH DUE TO INFECTIOUS DISEASES IN INFANCY and childhood remains perhaps the cruelest fate in the modern world and one of the most preventable. Measures needed to minimize this untimely mortality cannot be ranked as to their importance: Clean drinking water and adequate nutrition are as important as disease prevention and proper sanitation. But if you judge them by their benefit-cost ratios, vaccination is the clear winner. • Modern vaccination dates back to the 18th century, when Edward Jenner introduced it against smallpox. Vaccines against cholera, anthrax, and plague were added before the First World War, and others against tuberculosis, tetanus, and diphtheria before the Second. The great postwar breakthroughs included vaccines against pertussis and polio (the 1950s), and Hib, or *Haemophilus influenzae* type B (1985). Today's standard practice is to inoculate children with a pentavalent vaccine that prevents diphtheria, tetanus, pertussis, and polio as well as meningitis, otitis, and pneumonia, three infections caused by Hib. The first dose comes after six weeks of age; the other two follow at 10 and 14 weeks. Each pentavalent vaccine costs less than US $1, and every additional vaccinated child reduces the chances of infection among unvaccinated peers. • Given these realities, it has been always clear that vaccination has an extraordinarily high benefit-cost ratio but one that is not easy to quantify. Finally, thanks to a 2016 study supported by the Bill & Melinda Gates Foundation and conducted by U.S. health-care professionals in Baltimore, Boston, and Seattle, we can measure the payoff. The study's focus was on the return on investment associated with projected vaccination coverage levels using 10 antigens required to prevent diseases in nearly 100 low- and middle-income countries during the second decade of this century, the Decade of Vaccines.

Benefit-cost ranges were based on the costs of vaccines and of their supply and delivery chains, on one hand, and on estimates of the costs of averted morbidity and mortality, on the other. This appraisal indicated a net return 16 times as great as the costs, with an uncertainty range of 10 to 25 times.

And when the analysis went beyond the restricted cost-of-illness approach and looked at broader economic benefits, it found the net benefit-cost ratio more than twice as high, reaching 44 times, with an uncertainty range of 27 to 67. The highest rewards were for averting measles: a 58-fold return, with a range from 29 to 105. The Gates Foundation released the finding of the 44-fold benefit in the form of a letter to Warren Buffett, the foundation's largest outside donor. Even he must be impressed with such a return on investment!

But there is still some way to go. After generations of progress the basic vaccination coverage is now nearly universal, at around 96 percent, in high-income countries, and great advances have been made in low-income nations, where the coverage has risen from only 50 percent in the year 2000 to 80 percent in 2016. That still leaves an inexcusable gap.

The hardest part might be to eliminate the threat entirely. Polio is perhaps the best illustration of this challenge: The worldwide infection rate dropped from some 400,000 cases in 1985 to fewer than 100 by the year 2000, but in 2016 there were still 37 cases in violence-beset regions of northern Nigeria, Afghanistan, and Pakistan. And, as illustrated recently by the Ebola and Zika viruses, new infection risks will arise. Vaccines will remain the best way to keep them in check. ■

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PHOTO-ILLUSTRATION BY Stuart Bradford

TECHNOLOGICAL DISTRACTION

I CAN'T HELP IT. My attention span has shrunk alarmingly, and I'm easily distracted. Worse, I seem to look for and welcome distractions. I should be focusing my attention on the task at hand, which is writing this small essay. Instead I keep checking the Internet with my smartphone. I look around me at this coffee shop and everyone seems to be staring at their cellphones. I don't think we used to be like this, and I wonder: Has technology done this to us, and if so, is this bad or good? • A recent book by Adam Gazzaley and Larry Rosen, *The Distracted Mind: Ancient Brains in a High-Tech World* (MIT Press, 2016), examines this phenomenon from the viewpoints of neuroscience and psychology. The authors contend that, just as ancient humans foraged for food, we now forage for information. "We are information-seeking creatures," they affirm. I assume that they do mean to include personal communications and entertainment in the general concept of information, as otherwise the sheer number of emoji-laden texts and kitten videos consumed daily would militate against their thesis. • Our behavior is likened by Gazzaley and Rosen to that of squirrels foraging for food in a patchy environment. As a squirrel experiences diminishing food in its present patch, it instinctively decides when to move to another patch. The squirrel is apparently subconsciously aware of the marginal value theorem, which establishes when the rate of diminishment in a given patch justifies the cost and time of moving to a new patch with a greater expected return. This probably was worked out many years ago by a great squirrel mathematician and then widely circulated in the squirrel community.

Yet, looking around, it seems we're not as smart as squirrels. As we browse in an information patch, we are led astray by boredom and anxiety. We're easily bored, and there is the FOMO effect, the great fear of missing out. So we constantly overvalue the perceived return of a new patch, and jump quickly, in spite of what intelligent application of the marginal value theorem might say. For example, most of the time, we remain on a Web page just a few scant seconds.

Of course, we think to ourselves that we're good at this multitasking, but is this really true? Our ancient brains weren't shaped by evolution for this behavior. In spite of the parallel architecture in our brains, we are effectively thinking with a one-core processor, and every task requires a switch in context that is costly in resources and lost time. And as we get older, these costs become greater. Experiments show that from 20 years of age on, it's all downhill.

Technology, in its development of the Internet, smartphone, and social media, has not had a passive part to play in this behavior either. As the authors of *The Distracted Mind* say, technology "reaches out to us." It is alluring, and the behavior it induces has many consequences. Studies have shown that the more children multitask, the lower their test scores and grades. Multitasking is often a dangerous activity, as when we are driving and talking or texting or fiddling with GPS controls or.... A proclivity for multitasking also leaves us less inclined to introspective thinking. Instead of awaiting deep thoughts, we seek instant gratification.

But I keep coming back to my dilemma. If this is all so bad, why do we do it? Maybe there are benefits that have not yet been quantified. But if there are not, and this trend continues, what will life be like in another couple of decades? So many questions, so few answers.

If this essay seems disjointed, please forgive me. I'm kind of old, and this ancient brain is all I have. ■

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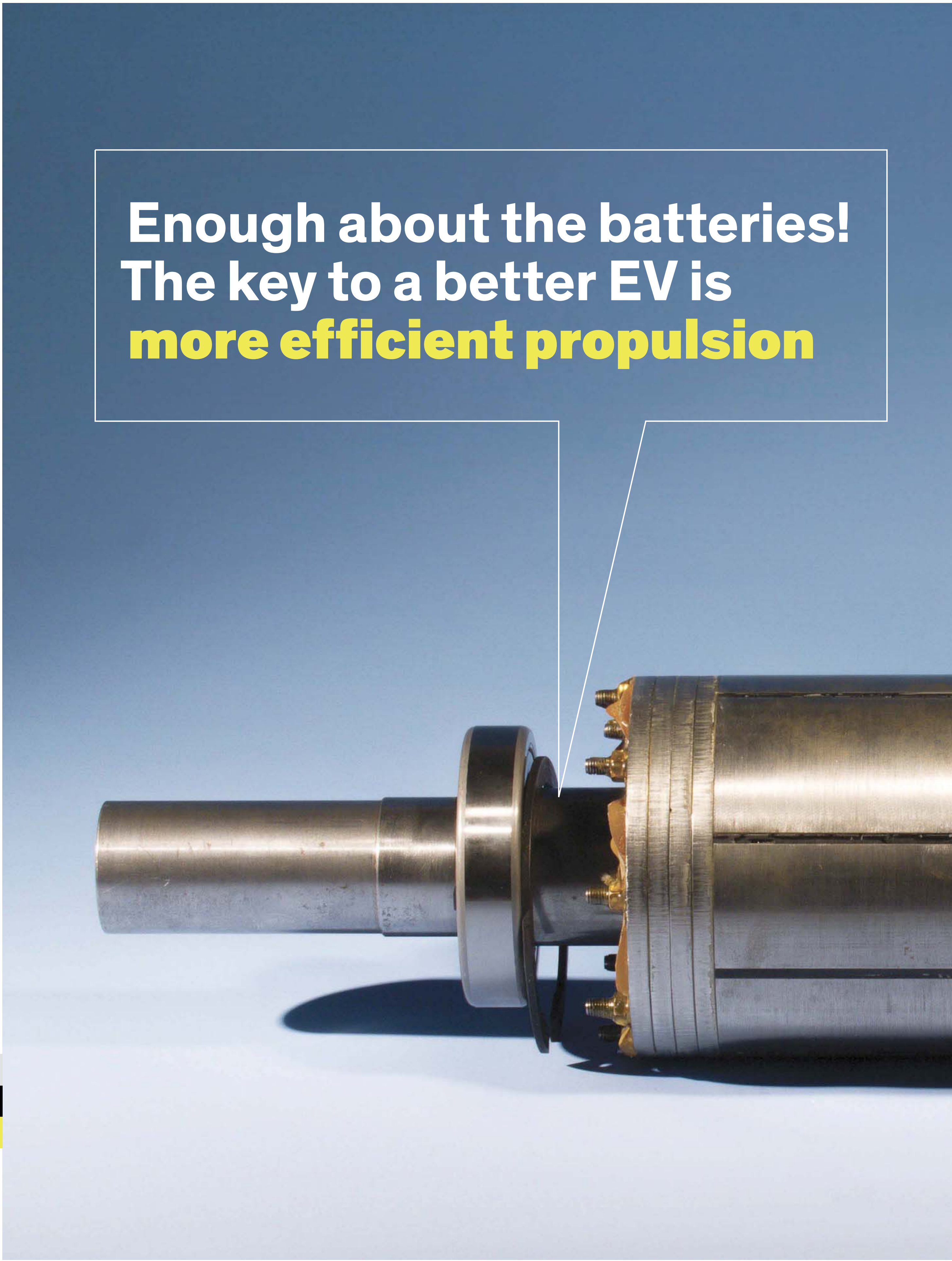
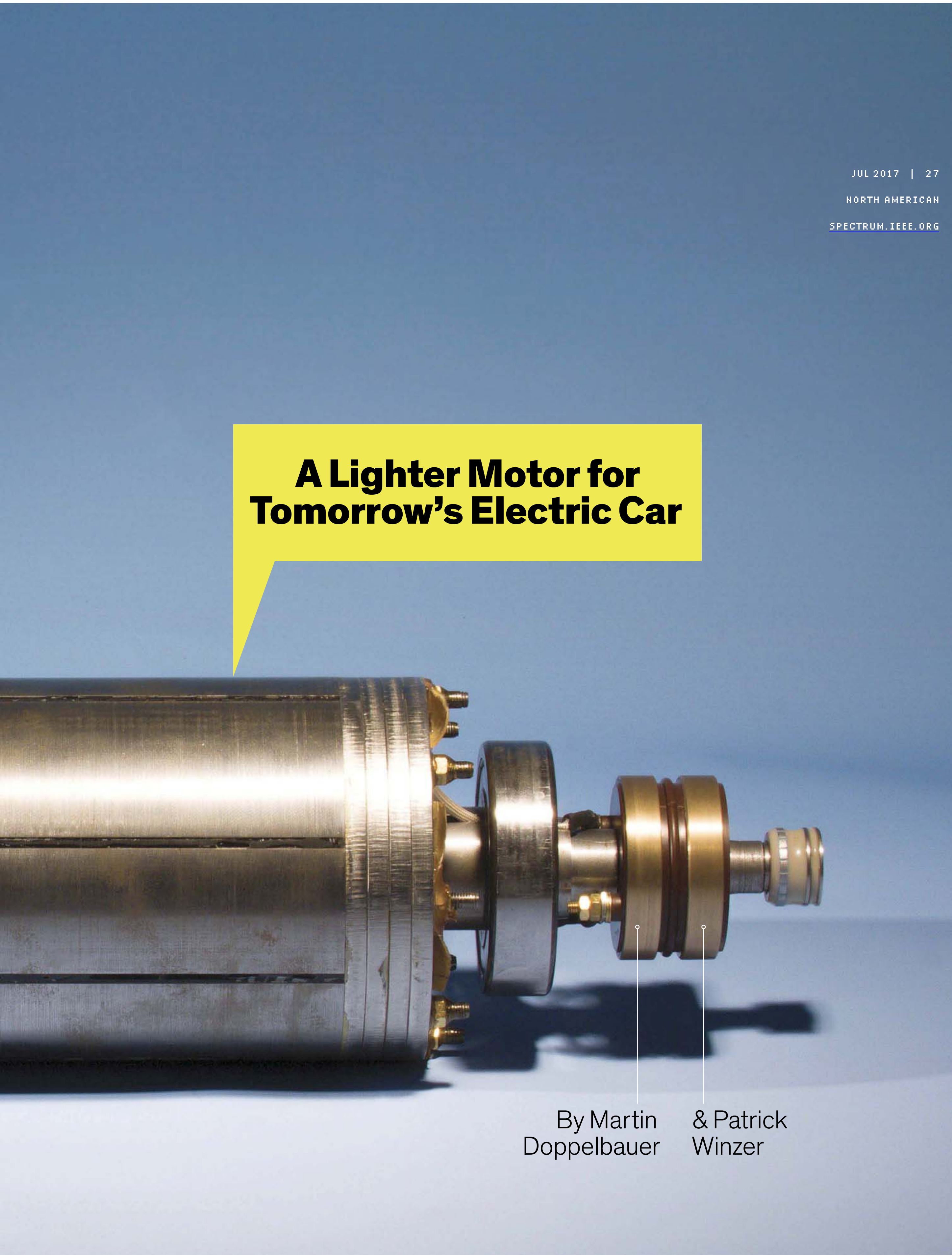
ILLUSTRATION BY Serge Bloch


Enough about the batteries!
The key to a better EV is
more efficient propulsion



A Lighter Motor for Tomorrow's Electric Car

By Martin Doppelbauer & Patrick Winzer

DURING THE FIRST DECADE OF THE 1900s, 38 percent of all cars in the United States ran on electricity, a share that declined to practically zero as the internal combustion engine rose to dominance in the 1920s. Today's drive to save energy and reduce pollution has given the electric car new life, but its high cost and limited range of travel combine to keep sales figures low. ● Most attempts to solve these problems involve improving the batteries. Of course, better electric storage systems–whether batteries or fuel cells–must continue to be part of any strategy for improving electric vehicles, but there's plenty of room for improvement as well in another fundamental vehicle component: the motor. For the past four years we have been working on a new concept for an electric traction motor, the kind used in electric cars and trucks. Our latest design improves efficiency quite a bit in comparison with that of conventional designs–enough to make electric vehicles more practical and affordable.

Last year we proved our prototype motor in extensive tests on the laboratory bench, and though it will be a while before we can put the machine in a car, we have every reason to expect that it will perform just as well in that setting. Our motor could therefore extend the range of today's EVs even if there is no further progress in battery technology.

TO UNDERSTAND THE CHALLENGE, a quick review of the basics of electric motor design is in order. Compared with internal combustion engines, electric motors are simple, with just a handful of critical components. For mechanical reasons, a housing is required; it's called a stator because it stays put. A rotor is needed to spin a shaft and create torque. To make the motor work, the stator and the rotor need to interact magnetically so as to convert electrical energy to mechanical energy.

This magnetic interface is where the electric motor concepts differ. In brushed direct-current motors, direct current flows through brushes that slide over a commutator. The current goes through the commutator to energize windings in the rotor. These windings are repelled by permanent magnets or electromagnets in the stator. As the brushes slide over the commutator, it periodically reverses the current flow so that the rotor and stator magnets repel each other over and over again in a sequence that causes the rotor to spin. In other words, the spinning motion is caused by a changing magnetic field, produced by a commutator that connects the coils to the power source and reverses the current cyclically as the rotor turns. However, this technique limits torque and is subject to wear; therefore, it is no longer used for traction drives.

Modern electric cars instead use alternating current, supplied by an inverter. Here the dynamic, rotating magnetic field is created within the stator rather than the rotor. This characteristic eases the design constraints on the rotor, generally the more complicated of the two, which in turn eases the overall design challenge.

There are two kinds of AC motor: asynchronous and synchronous. We will focus on the synchronous ones because they generally perform better and more efficiently.

Synchronous motors also come in two varieties. The more common is the permanent-magnet synchronous machine (PMSM), which uses permanent magnets embedded in the rotor. To make the rotor spin, a rotating magnetic field is set up in the stator, as noted above. This rotating field is produced by windings in the stator that are connected to an alternating-current source. In operation, the poles of the rotor's permanent magnets are locked to the stator's rotating magnetic field, which causes the rotor to spin.

This design, which is used in the Chevrolet Volt and Bolt, the BMW i3, the Nissan Leaf, and many other cars, can reach peak efficiencies as high as 97 percent. Their permanent magnets are generally made of

KEEP ON TURNING: The authors' motor represents an advance on another design—one that did not use magnets to shift the field.

rare earths; notable examples are the very powerful neodymium magnets developed in 1982 by General Motors and Sumitomo.

Salient-pole synchronous machines (SPSM) use electromagnets inside the rotor rather than permanent magnets. The poles are coils shaped like tubes, which point outward from the hub of the rotor like so many spokes on a wheel. These electromagnets in the rotor are powered by a DC source that's connected to the coils via slip rings. Slip rings–unlike the commutator in a DC machine–don't reverse the current in the rotor coils. The north and south poles of the rotor are therefore static, and the brushes don't wear out as fast. And, as in the PMSM, the motion of the rotor is caused by the rotating magnetic field of the stator.

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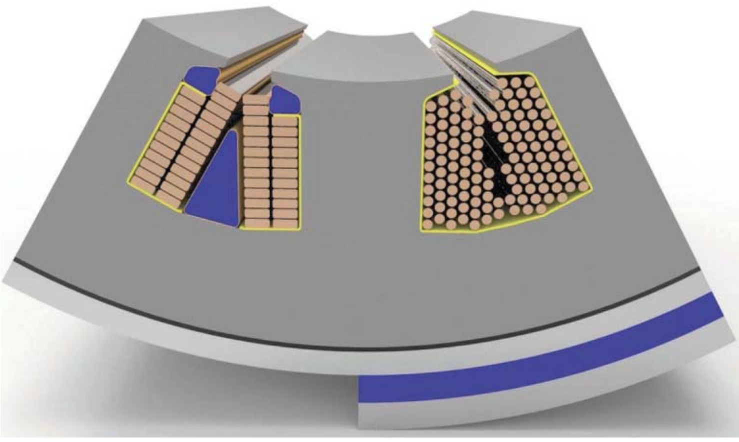


A RIVER RUNS THROUGH IT: Advanced cooling puts water directly through the coil [left] rather than through a water jacket on the outside of the housing [right].

MARTIN DOPPELBAUER & PATRICK WINZER

Because of the need to energize the rotor's electromagnets through the slip rings, these motors typically have slightly lower peak efficiency, in the range of 94 to 96 percent. The advantage they have over PMSMs lies in the adjustability of the rotor field, which allows the rotor to develop torque efficiently at higher speeds compared with the PMSM. The overall performance, when used for car propulsion, can therefore be greater. The only manufacturer that uses this kind of motor in production cars is Renault, in its Zoe, Fluence, and Kangoo models.

EVs must be built with components that are not only highly efficient but also lightweight. The most obvious approach to improving the power-to-weight ratio of a motor is to reduce the size of the machine. However, such a machine will produce less torque for a given rotational speed. Therefore, to get the same power you'd then need to run the motor at higher revolutions per minute. Today's electric cars run at around 12,000 rpm; motors for up to 20,000 rpm are being prepared for the next generation; and machines reaching 30,000 rpm are under investigation. The problem is that higher speeds require gearboxes of ever greater complexity, because the rpms are so great in comparison to what is needed to spin the tires. These complex gearboxes incur relatively high energy losses.

A second approach to improving the ratio of power to weight is to increase the strength of the motor's magnetic field, which increases torque. That's the point of adding an iron core to a coil, for although this step increases weight, it boosts magnetic-flux density by two orders of magnitude. Therefore, nearly all electric machines today use an iron core in the stator and in the rotor.

However, there is a drawback. When the strength of the field increases beyond a certain limit, iron loses all of its ability to boost flux. This saturation limit can be slightly influenced by the blending and the production process of the iron, but the most cost-effective materials are limited to some 1.5 Vs/m^2 (Volt times second per square meter, or tesla). Only very costly and rare cobalt-iron vacuum steel materials can reach magnetic-flux densities of 2 teslas or more.

Finally, the third standard way of raising torque is to strengthen the field by sending more current through the coils. Again, there are limitations. Push more current through a wire and the resistive losses will increase, reducing efficiency and creating heat that can damage the motor. You could use wire made of a metal that conducts better than copper. Indeed, silver wire is available, but it would be absurdly expensive in this application.

The upshot is that the only practical way to increase the current is by controlling the heat. State-of-the-art cooling designs send cooling water directly alongside the windings rather than putting the water line further away, on the outside of the stator [see illustration, "A River Runs Through It"].

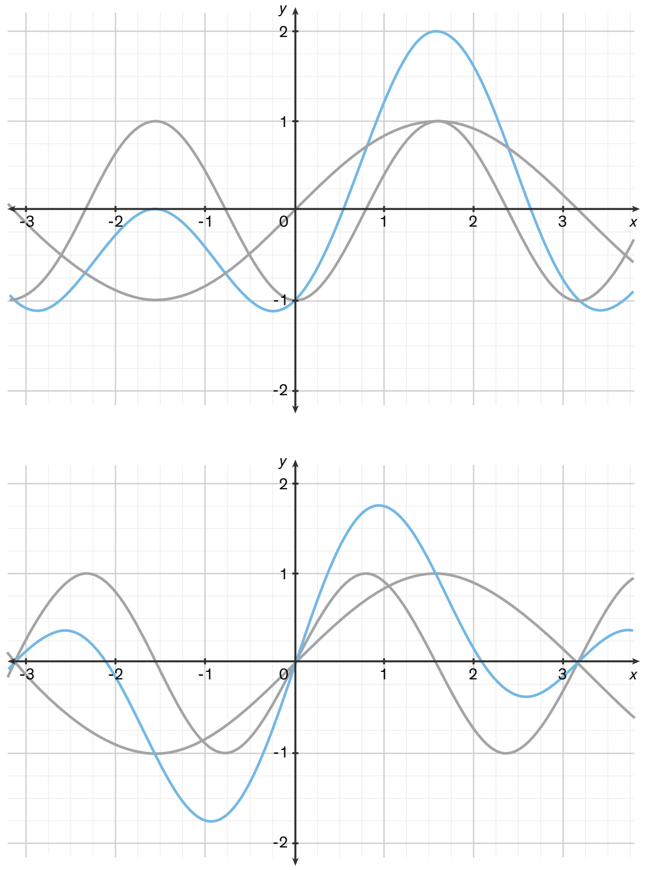
THESE STEPS ALL HELP TO IMPROVE the weight-to-power ratio. In electric racing cars, where cost is no object, motors can weigh as little as 0.15 kilogram per kilowatt of output, on par with the best Formula One combustion engines.

In fact, we and our students designed and built such high-performance electric motors for a car entered in the Formula Student Racing Series three years ago. We built the motors at our laboratory in the Electrotechnical Institute at the Karlsruhe Institute of Technology, in Germany. Each year, the team built a new car with improved motors, gearboxes, and power electronics. There are four motors per car, one for each wheel. Each is just 8 centimeters in diameter, 12 cm in length, and 4.1 kg in weight, and each produces 30 kW of continuous power and peaks at 50 kW. In 2016, our team won the world championship.

So it can indeed be done, when cost is not an issue. The real question is, can such performance-boosting technologies be used in a mass-market motor, of the sort that might be used in a car you could buy? We have built such a motor, so the answer is yes.

WE STARTED WITH A SINGLE IDEA. Electric motors run equally well whether they are acting as motors or as generators, although such symmetry is not really needed for electric vehicles. With a car, you want an electric motor that performs better in motor mode than in generation mode, which is used only to charge the batteries during regenerative braking.

To understand the idea, consider a fine point of how a PMSM motor works. In such a motor, there are actually two forces that create motion. First, there is the force caused by the permanent magnets in the rotor. When currents flow through the copper coils of the



A PERFECT STORM: In the authors' design [top], the Lorentz force and the shifted inductance force [gray] sum at a maximum total force [blue] of 2. In a conventional motor [bottom], adding the two forces—the Lorentz force and the reluctance force [gray]—gives a total force [blue], which peaks at only 1.76, at a polar wheel angle of 0.94 rad. The difference in this example comes to 14 percent.

stator, they create a magnetic field. Over time, the current is advanced from one coil to the next and thereby causes the magnetic field to rotate. This rotating stator field attracts the permanent magnets of the rotor so that the rotor starts moving. This principle depends on what is known as the Lorentz force, which affects a charged particle moving through a magnetic field.

But modern electric motors also get extra power from reluctance–the force that attracts a block of iron to a magnet. So the rotating stator field attracts both the permanent magnets and also the iron of the rotor. The Lorentz force and the reluctance work hand in hand, and–depending on the motor design–they are about equally strong. Both forces are nearly at zero when the rotor's magnetic field and the stator's are perfectly aligned. As the angle between the fields increases, the machine develops mechanical power.

In a synchronous machine, the stator field and the rotor rotate in tandem, without the lag found in asynchronous machines. The stator field has a particular angle with respect to the rotor, an angle that can be varied freely moment by moment during operation for highest efficiency. The optimum angle for producing torque at a given current can be calculated beforehand. It is then adjusted–as the current changes–by a power electronics system that feeds alternating current to the stator windings.

But here's the problem: As you move the stator field with respect to the rotor position, the Lorentz force and the reluctance force each wax and wane. The Lorentz force increases according to a sinusoidal function that reaches its peak at a point 90 degrees from the reference position (which is the point at which the stator and rotor fields are aligned). The reluctance force, however, cycles at twice the frequency and therefore peaks at a 45-degree displacement [see graphs, "A Perfect Storm"].

Because the two forces reach their peaks at different points, the peak of the motor's overall force is less than the sum of its parts. Let's say in a particular machine design, at a particular point in the operation of the motor, 54 degrees happens to be the optimum angle for peak overall force. In this case, that peak would be 14 percent less than the peaks of the two forces combined. That's the best compromise that this design can provide.

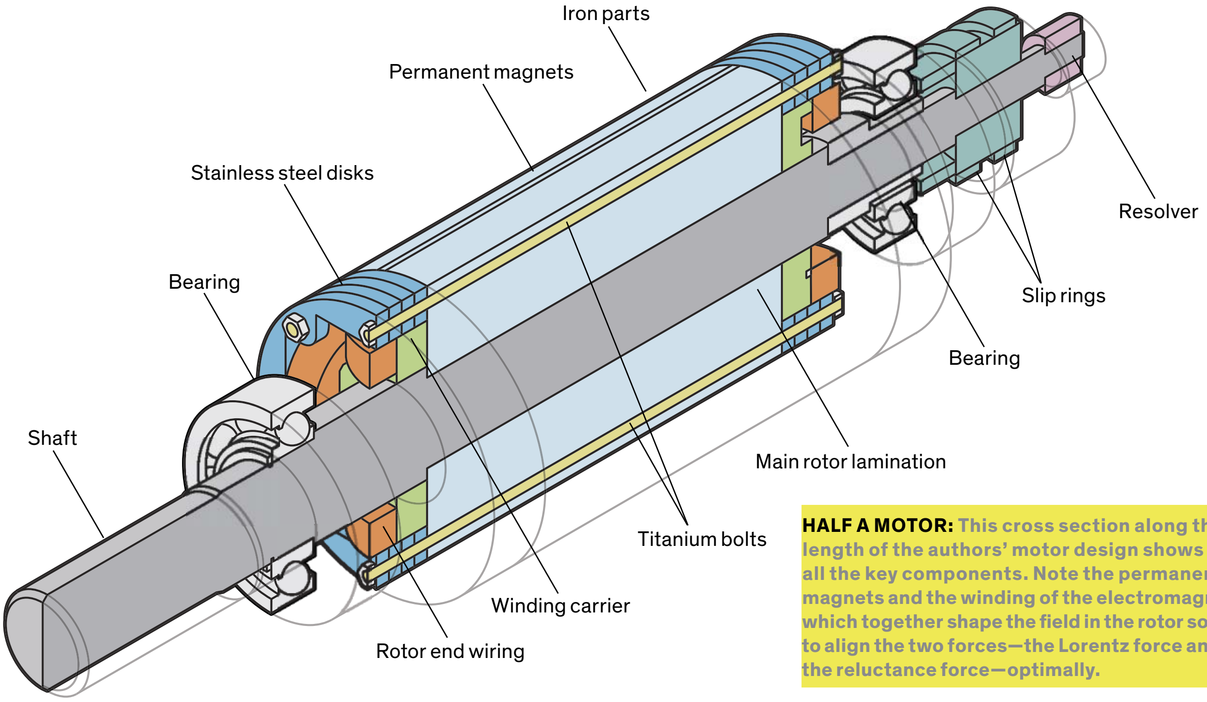
If we could reengineer this motor so that the two forces peaked at the same point in the cycle, motor power would improve by 14 percent–at no extra cost. The only feature you would lose is the efficiency of the machine when it is operating as a generator. And, as we'll explain later on, we have found a way to restore even this feature, so the machine can better recover energy during braking.

DESIGNING A MOTOR that perfectly aligns the stator field with the rotor field is no easy task. The challenge, basically, comes down to combining the PMSM and SPSM into a new hybrid design. The result is a hybrid synchronous machine with a displaced reluctance axis. In a nutshell, this machine uses both wires and permanent magnets to create a magnetic field within the rotor.

Others had tried (and then abandoned) this idea, but they had wanted to use permanent magnets only to strengthen the electromagnetic field. Our innovation was to use the magnets only to shape the field precisely, so as to optimally align the two forces–the Lorentz force and the reluctance force.

Our main design problem was in finding a rotor construction capable of shaping the field, yet sturdy enough to run at high speeds without coming apart. Our design's innermost part is the rotor lamination, which car-

CHART SOURCE: PATRICK WINZER



HALF A MOTOR: This cross section along the length of the authors' motor design shows all the key components. Note the permanent magnets and the winding of the electromagnets, which together shape the field in the rotor so as to align the two forces—the Lorentz force and the reluctance force—optimally.

A CLASS PROJECT: This Formula Student racing car used special motor-cooling techniques.

ries the copper winding on an iron core. We glue permanent magnets to the shoulders of the poles of this core; additional nibs on the poles prevent them from ever flying away. To hold everything in place, we drove strong but lightweight titanium rods through the electromagnetic poles of the rotor using nuts to tighten the rods to stainless steel rings on both faces of the rotor.

We also found a way around our original motor's flaw of reduced torque when running as a generator. We can now alter the direction of the field in the rotor so that the generation needed for regenerative braking is just as powerful and efficient as the motor operation.

We accomplished this by reversing the current in the rotor winding when the machine is acting as a generator. Here's why that works. First, consider the rotor of our original design. Moving along the perimeter of the rotor reveals a particular sequence of the north (N) and south (S) poles of the electromagnetic (E) and permanent magnetic (P) sources: NE, NP, SE, SP. This pattern repeats itself as many times as there are pole pairs. By reversing the flow of the current in the rotor winding, the electromagnetic poles—and they alone—change direction, and the pole order now becomes SE, NP, NE, SP, and so forth.

If you take a closer look at these two progressions, you'll see that the second progression is like the first one, only backward. This means that the rotor can be used either in motor mode (the first sequence) or in generator mode (the second sequence), with the rotor current going in the opposite direction from the first. This way, our machine works more efficiently than conventional motors both as a motor and as a generator. On our prototype, changing the current takes less than 70 milliseconds, which is easily fast enough for use in cars.

Last year we built a prototype motor on a workbench and subjected it to thorough testing. The results are clear: Using the same power electronics, stator parameters, and other design constraints as a conventional motor, the machine is able to produce almost 6 percent more torque and attain 2 percent higher peak efficiency. And in the driving cycle the improvement is even better: It requires 4.4 percent less energy. That means a car that would have gone 100 kilometers on a charge can, with this motor, go 104.4 km. The extra range comes cheaply because our design incorporates only a few additional parts, which are much less expensive than adding extra batteries.

We are in contact with several original equipment manufacturers that find the concept interesting, though it will be some time before you see one of these asymmetric motors in a production car. When it does show up, though, it should eventually become the new standard, because getting all you possibly can from the energy you have at hand is a top priority for carmakers—and for society at large. ■

↗ **POST YOUR COMMENTS** at http://spectrum.ieee.org/electricmotor0717

ILLUSTRATION SOURCE (TOP): MARTIN DOPPLEBAUER; PHOTO: KA-RACEING

ILLUSTRATIONS BY James Provost

The French Connec
Machine

By Julien Mailland & Kevin Driscoll

A decade before the Internet went mainstream, French citizens were interacting via Minitel, a computer network open to anyone with a telephone

SSPL/GETTY IMAGES

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tion

IT was the late 1970s. Former French presidents Charles de Gaulle and George Pompidou had recently died. The Arab oil embargo caused energy prices to quadruple for a time. Marseille remained gripped by drug lords. And France had to face the fact that its telephone network was one of the worst in the industrialized world. Fewer than 7 million telephone lines served 47 million French citizens, and the country's elite felt that the domination of U.S. firms in telephone equipment, computers, databases, and information networks threatened their national sovereignty. Or at least it damaged their cultural pride.

In an influential 1978 report to President Valery Giscard d'Estaing, titled *The Computerization of Society*, government researchers Simon Nora and Alain Minc argued that the solution to France's telecom woes lay in "telematics"—a combination of *telecommunications* and *informatics*. They outlined a plan for digitizing the telephone network, adding a layer of interactive teletext video technology, and providing entrepreneurs with an open platform for innovation.

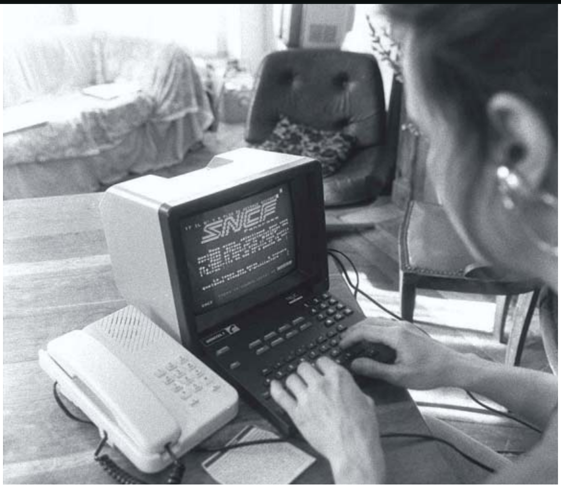
Taken with Nora and Minc's vision, the nation's leadership began to lay the groundwork for France's computerized future. In 1983, on orders from the president, computer engineers within the Post, Telegraph & Telephone (PTT) ministry began to roll out throughout France a telematics system that came to be known as Minitel. It allowed ordinary people to obtain and share information online, launching the country into the digital age and leapfrogging the United States by more than a decade.

The story of how Minitel came to be is a fascinating but largely forgotten one. To the extent that it's remembered today, Minitel is portrayed as a closed, centralized system encumbered by government bureaucracy that failed to change with the times. But back in 1983 it was like nothing anyone had seen before, eventually growing to have more than 20,000 online services before the World Wide Web even got off the ground.

IN SILICON VALLEY TODAY, those who lived through the Minitel era tend to view it as the epitome of how not to build and operate an online system: They believe that letting the government design and run it just invited disaster. In truth, Minitel was never fully controlled by the state. It was a hybrid system—a public platform for private innovation. And it worked pretty well.

To initiate a connection, a user manually dialed a local gateway using a telephone handset. The call, carried over the public switched telephone network, was answered by software running on the switch—typically a CIT-Alcatel E-10—which played an audible carrier signal back over the line. Hearing this tone, the user would place the handset back on its cradle and begin using the Minitel terminal, which would be carrying out a special handshake protocol with the switch.

The gateways, known as *points d'accès videotex*, or PAVIs, provided an interface to a directory of known Minitel ser-



SANS Y PENSER: During the 1980s, Minitel terminals proliferated throughout France, where they became just another part of ordinary life. People used them regularly without thinking much about it, in their homes, at work, or in various public places.

vices, identified by short mnemonic codes. For example, rail travelers bought tickets from 3615 SNCF (SNCF being an acronym for Société Nationale des Chemins de Fer, the French railroad), news junkies gathered at 3615 LEMONDE (*Le Monde* being a leading Parisian newspaper), and dudes (*mecs* in French) browsed the personal ads at 3615 MEC. Like URLs today, these codes were printed in magazines, shown in television commercials, and plastered on the sides of buses.

Once the user typed in the desired destination, the switch created a virtual circuit over a public data network known as Transpac, and data could begin to flow from the client's terminal to the host server and back. These virtual circuits used the X.25 network protocol, the paradigmatic packet-switching technique developed largely by researchers at the French Centre Commun d'Études de Télévision et Télécommunications.

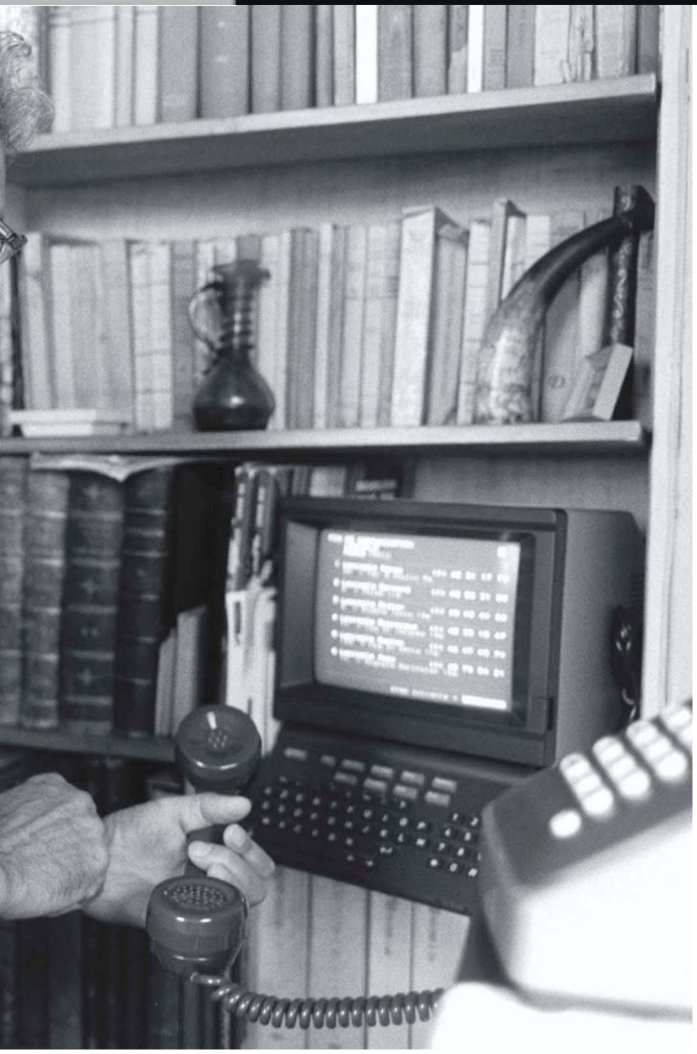
At the start, though, Minitel advocates faced a chicken-and-egg problem. Why would anyone adopt the system unless there were interesting things to do with it? And yet how could they convince entrepreneurs to create services unless the platform already had users? Somehow, Minitel needed to attract both users and service providers at the same time.

To kick-start the process, the PTT ordered millions of Minitel terminals (built by French manufacturers such as Telic-Alcatel and Matra) and made them available at no cost to everyone in the country who had a telephone line. Anyone curious about the new system being promoted on TV could simply go to the post office and return home with a shiny new Minitel box.

Minitel designers made the system fully plug and play: All you had to do was plug the terminal into the wall, dial the local gateway, *et voilà*, you were transported into cyberspace. Meanwhile, would-be cybernauts in the United States who wanted to get online had to buy expensive computer equipment, install confusing software, pay hefty long-distance phone bills, and prepay a separate subscription to each service provider they wanted to use.

The first service available on Minitel was an electronic phone book, or *annuaire électronique*. Equipped with a natural-language interface for search, this oft-used resource was an easy way to explore Minitel for free. Later, the government began to require that people use Minitel for certain administrative tasks such as university registration. These modest public services stimulated adoption of Minitel on France's fast-expanding telephone network. Whether from home, work, or at a public ter-

COLOR: LEFT: MICHEL GAILLARD/REA/REDUX; RIGHT: HELENE ROGERS/ALAMY



BLACK AND WHITE: OWEN FRANKEN/CORBIS/GETTY IMAGES (2)

minal on the street, by the end of the 1980s, every adult living in France had access to the network.

PROMPTED BY THE GROWTH of Minitel's user population, entrepreneurs jumped at the opportunity to create new services. These startups benefited from a novel payment system built into the Minitel platform that lowered the barrier to entry. Named after the newsstands that line the boulevards of Paris, the PTT's Kiosk system handled the accounting, collecting money from users at one end, cutting checks for service providers at the other, and keeping a tidy slice for itself. Small service providers could thus design lean information systems that generated profit without having also to manage customer relationships, take credit cards, or chase down past-due bills. Indeed, the app-store model employed by Apple, Steam, and others now is little more than a privatized version of the Minitel Kiosk.

Providers were allowed to use any hardware or software they liked so long as its output conformed to guidelines published by the phone company. As demand for Minitel grew, the market for server hardware became fiercely competitive. Providers built their systems on any machine capable of running a multiuser operating system, from proprietary mainframes and Unix-friendly minicomputers to Commodore Amigas and IBM PCs.

Beyond the iconic terminal equipment, France hoped to jump-start domestic production of server hardware as well. This part of the telematics project did not go as planned: Hacker-entrepreneurs demanded more Unix support, but French manufacturers such as Groupe Bull failed to provide it. As a result, Minitel services were often hosted on machines built by U.S. corporations such as AT&T, Hewlett-Packard, and Texas Instruments, and so, ironically, Minitel broadened rather than curtailed the U.S. presence in French telecom.

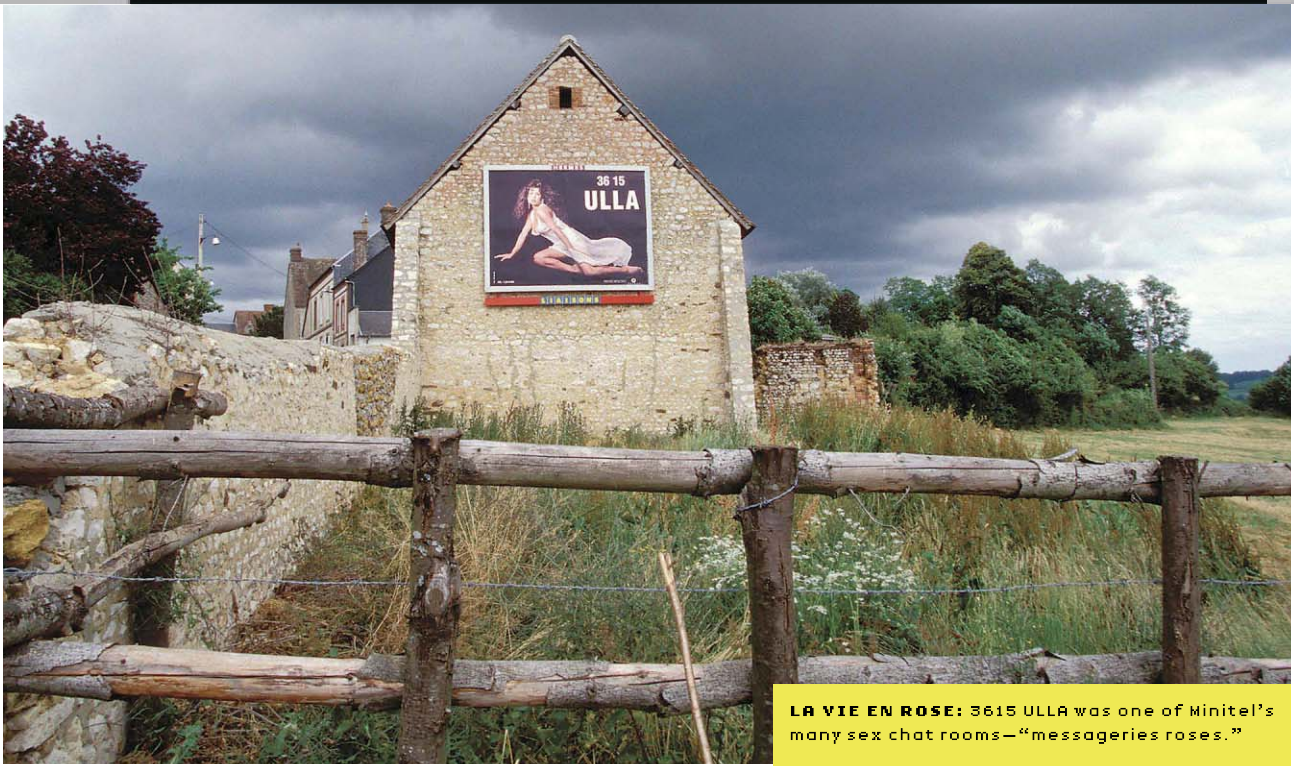
Those administering the system encouraged service providers by offering high-quality documentation for free. Over the course of two decades, France Telecom published dozens of brochures on user-interface standards, terminals, PAVIs, protocols, and so on. A quarterly newsletter, *La Lettre de Télétel*, informed industry participants of the latest technical improvements and business experiments.

French companies extended the Minitel platform with new kinds of terminals and peripherals. Terminals with built-in memory functions, chip-card readers, and high-resolution color displays began appearing on the market. Most Minitel terminals featured a serial port and multiple display modes, enabling users to connect the terminal to a printer, credit card reader, or PC. For small business owners, this flexibility transformed the Minitel terminal into a low-cost point-of-sale system. And long before the Internet of Things, Minitel was incorporated into a variety of home-automation schemes, allowing remote control of heaters, VHS recorders, security alarms, and sprinklers.

With this open platform for innovation, telematics electrified the country, making France of the 1980s a place of tremendous digital experimentation and excitement. And, unlike ventures during the speculative boom and bust of the dot-com years in Silicon Valley, the Kiosk system provided a reliable business model for Minitel entrepreneurs, enriching a relatively large number of service providers in the process. The technical infrastructure of the Minitel ecosystem enabled the French to benefit from a wealth of online services at a time when the online landscape in the United States was limited to local BBSs and fledging walled gardens like CompuServe.

ALTHOUGH IT WASN'T THE ONLY NETWORK to use X.25 or videotex technology during the 1980s, Minitel was unique in allowing the many service providers to operate their own machines. France Telecom oversaw only the network, whereas in most other countries, a single organization had centralized control of both the network and servers for the videotex system.

In the United Kingdom, for example, all content on the Prestel videotex system was hosted on an IBM mainframe housed at the General Post Office. Germany's BTX system was similarly arranged. In the United States, all of the con-



LA VIE EN ROSE: 3615 ULLA was one of Minitel's many sex chat rooms—"messageries roses."

tent from The Source, an early private provider of online information, was served up from a single computer center in McLean, Va. Even 101 Online, a Minitel spin-off that operated briefly in the San Francisco Bay Area, stored its data in an office on California Street. That degree of centralization ultimately hindered innovation by excluding the kinds of garage and college-dorm startups that made the Internet what it is today.

Minitel gave service providers considerable freedom over their systems, a feature that would become a staple of the Internet. Minitel's administrators also abided by an early form of net neutrality. The network did not favor one service over any other or otherwise discriminate. Occasionally, a service would be barred for breaking the law (by serving as a marketplace for prostitution, for example), but any such exclusion was subject to due process, and the system's administration could be sued if it acted arbitrarily. These guarantees of fairness stood in stark contrast to the situation in the United States, where private network operators could exclude content on a whim to serve their business interests.

Of course, the advantages of the Minitel design came at a cost. The network used a nonstandard implementation of the X.25 protocol that prevented privately run servers from connecting directly to one another. Instead, all connections were routed through the public data network, effectively centralizing communications between hosts. This constraint was necessary for implementing the Kiosk system, but it also required each host to be individually approved by the state.

Routing all traffic through the central network also enabled the state to attempt to implement a censorship policy on Minitel. Because of intense lobbying by existing print industries, only incumbent publishers got access to the Kiosk. In short order, however, would-be service providers began to route around this bureaucratic obstacle by printing fake newspapers, known collectively as the "ghost press," which qualified them for recognition by the state. Others bought and sold their access on a secondary market. In most cases, the Minitel administration was happy to connect these entrepreneurial mavericks, capturing one-third of their revenue in the process.

Minitel was thus hardly the rigid, static system imagined by many Internet advocates of the 1990s. The hybrid architecture—bridging public and private, open and closed—provided a rich platform for innovation and entrepreneurship at a time when online services elsewhere in the world were floundering.

FOR A GENERATION OF FRENCH CITIZENS, Minitel wasn't about hardware, switches, or software. It was about the people they chatted with, the services they used, the games they played, and the advertisements for these services they saw in newspapers and on billboards. Many of the services that we associate with the Web had predecessors in Minitel. Before there was Peapod, there was 3615 TMK (Tele-Market), a service that enabled Parisians to order groceries for same-day delivery. Before there was Cortana or Siri, there were Claire and Sophie, services that provided personalized information using natural-language interfaces. Before there was Ticketmaster, there was Billetel. And before there was telebanking, there was Minitel banking.

The services that most stand out in the popular memory of Minitel, though, were undoubtedly the *messageries roses*. These "pink chat rooms" were sites of flirtatious exploration that ranged from rather conventional online dating to discussions that were downright lascivious

SAGAPHOTO/ALAMY

and crude. Pink Minitel services were not only popular, they were also most lucrative. The profitability of these adult-oriented services led to an advertising war among pink providers in print media, on television, and over billboards, so the phenomenon was hard to escape, even if you never used Minitel. Telematics advocates were by turns thrilled by this enthusiastic embrace of the new technology and concerned by its rosy hue. One PTT minister lamented, "[I do] not want telematics to have its image tarnished by the exclusive use of fornicatory fellowship!"

The emergence of pink Minitel was the result of both low- and high-tech innovation. On the low end were the *animatrices*, a new type of information worker whose job was, in the words of one popular song of the period, to "digitally undress" users. Animatrices were often young men posing as women. Their task was to keep unsuspecting customers online for as long as possible. While many animatrices were paid, others were self-described Minitel addicts who bartered their services for free connection time.

The entrepreneurs behind these pink chat rooms, some of whom would later dominate France's telematics industry, also developed more sophisticated tools to maximize their revenue. PCs rigged up with software allowed animatrices to handle multiple conversations at once. Another practice—frowned on by many in the community but nonetheless widespread—was to use bots to engage in online solicitation. Minitel tycoon Xavier Niel deployed such automated animatrices, inviting users to "come hang out with me in another chat room."

The runaway popularity of adult-oriented services depended on certain privacy protections built into the network itself. Starting at the local gateway, all Minitel connections were anonymized. No usernames or credit card numbers were required, so the chat-room providers never knew the real identities of their customers, nor did they need that information to make money. Because billing was handled by the PTT, service providers received one lump sum per billing cycle, rather than dealing with thousands of individual accounts. This payment system, which effortlessly charged the user, is also the reason why Minitel was relatively free of advertising.

Privacy and anonymity extended to the user side as well. Consumers' telephone bills did not reveal which sites they had visited. Instead, the telephone company aggregated all activity for the billing period into a single charge. So it was easy for an employee assigned work-related Minitel tasks to sneak into a chat room, pink or otherwise. To some, the messagerie became the new water cooler (to the dismay of many business owners).

Minitel enthusiasts cherished the network's privacy and anonymity. In late 1984, Minitel engineers added a feature to the terminal that saved the last page visited and made it easier for the user to pick up an interrupted session—

SALLE D'ATTENTE: Junked terminals await disassembly for recycling.

BRUNO MARTIN/REUTERS/ALAMY

as a browser cookie does today. The public outcry was swift and brutal. Editorials in newspapers, which (rightly) saw Minitel as a competitor, warned that Big Brother had arrived. Some 3,000 terminals were returned in protest. The PTT soon dropped this feature.

MINITEL USE PEAKED IN 1993, when users logged more than 90 million hours at their terminals enjoying various Kiosk services. In the years to follow, usage declined as home computing and dial-up Internet access spread. Dedicated users could continue to access Minitel using terminal-emulation software, but many others simply moved on. The easy-to-use Minitel terminal and its straightforward videotex interface, once so groundbreaking but now proving inflexible, stymied further development.

Although hundreds of thousands of users continued to access the system each month through the 1990s and beyond, Minitel no longer seemed a shining symbol of France's telematics future. Rather, it was an unremarkable part of everyday life, no more dazzling than the radio or telephone. In 2012, after nearly 30 years of continuous operation, the PAVIs were shut down, and the Minitel era came to a close.

But it would be wrong to view Minitel as a failure. Indeed, it offers an intriguing model for fostering innovation without sacrificing the public's interests in fairness and privacy. The millions of curious *minitélistes* and risk-taking entrepreneurs who flocked to the platform during the 1980s were among the first people to confront the problems of trust, intimacy, privacy, and civility that characterize life online today. That grand telematics experiment is over, but it still has lessons to teach the many engineers and computer scientists struggling to make the Web a better place. ■

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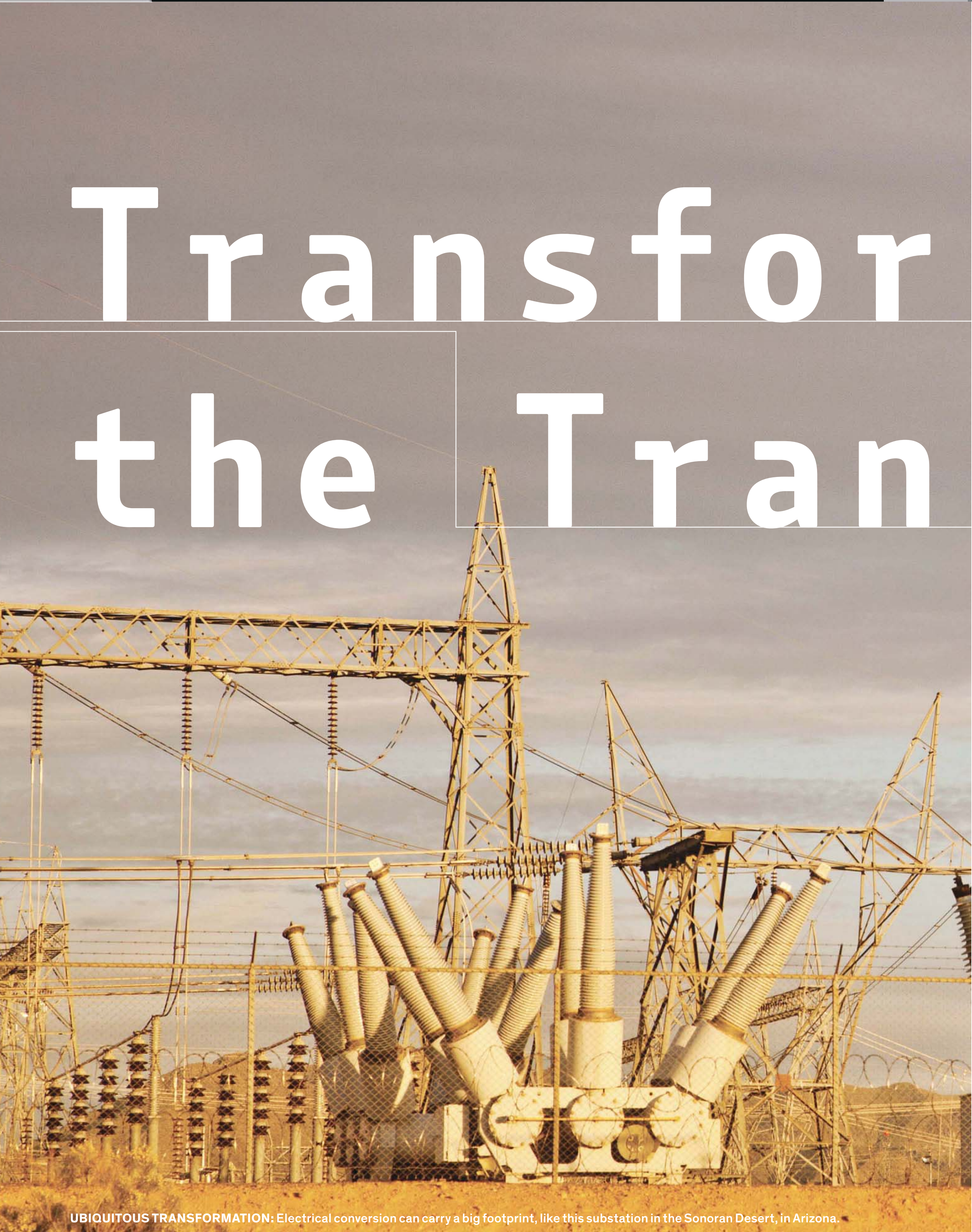

UBIQUITOUS TRANSFORMATION: Electrical conversion can carry a big footprint, like this substation in the Sonoran Desert, in Arizona.

ming sformer

Solid-state power electronics will bring a 19th-century technology into the 21st

By SUBHASHISH BHATTACHARYA

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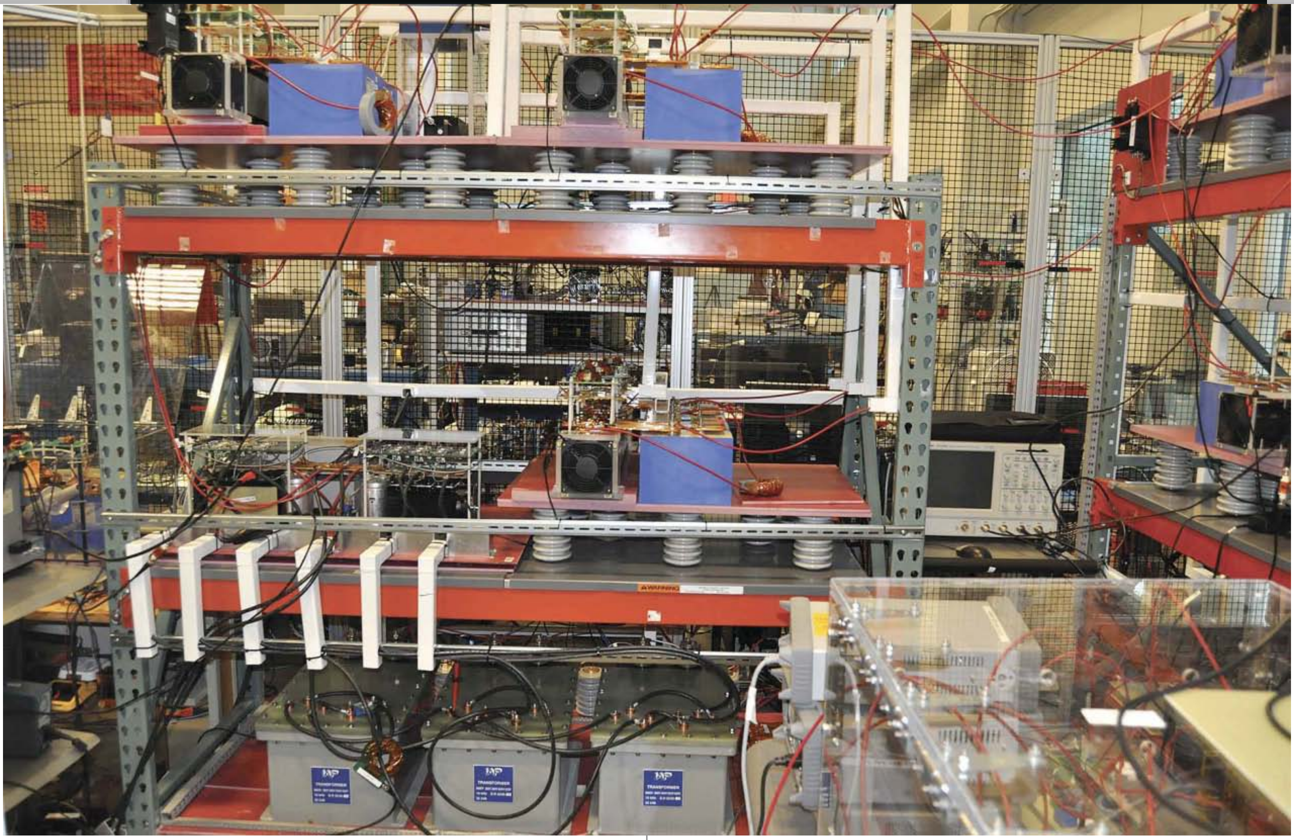


It would be hard to overstate the importance of transformers in our electrical networks. They're literally everywhere: on poles and pads, in substations and on private property, on the ground and under it. There are probably dozens in your neighborhood alone. It's hard to imagine a world without them. But my colleagues and I are doing just that.

In the distribution system, transformers typically take medium, or "primary," voltages measured in the thousands of volts and convert them to secondary voltages–such as 120, 240, or 480 volts–that can be safely delivered to homes and businesses all over the world. It's an approach that's been used since before alternating current won the war of currents in 1892. It is difficult to name another electrotechnology that has survived as long.

Nevertheless, it is time to start thinking beyond the conventional transformer. For one thing, transformers are bulky. They're often cooled with oil, which can leak and is difficult to dispose of safely. Crucially, transformers are passive, one-way tools. They aren't designed to adjust to rapidly changing loads. This shortcoming will fast become intolerable as distributed power sources such as wind turbines, solar panels, and electric-vehicle batteries feed more and more energy to the grid.

Happily enough, research into a new kind of technology–one that could address all of these limitations–has been making significant strides. Thanks to recent advances in power electronics, we can now contemplate building smart, efficient "solid-state transformers," or SSTs. They promise to handle tasks that are difficult if not impossible for a conventional transformer to accomplish, such as managing the highly variable, two-way flow of electricity between, say, a microgrid and the main grid. What's more, these smart transformers can be modular, making them easy to transport and install. And they can be significantly smaller than an equivalent conventional transformer–with as little as about half the weight and a third the volume.

In the near term, SSTs could be a boon for disaster-recovery efforts in places with damaged electrical infrastructure and for settings such as naval vessels, where volume and weight are at a premium. Further in the future, they could redefine the electrical grid, creating distribution systems capable of accommodating a great influx of renewable and stored energy, dramatically improving stability and energy efficiency in the process.

Alternating-current networks rely on voltages in the hundreds of thousands of volts to transmit power over long distances. But as the current gets closer to its loads, the voltage needs to come down again. Thus transformers are used throughout the grid, to step up the electricity exiting a power plant to a high voltage so that it can be transmitted with great efficiency, and to step it down at the distribution end, to the levels appropriate to power factories, businesses, and homes.

Although the transformer has been improved many times over the years, it is essentially a 19th-century technology, one that takes advantage of simple principles of electromagnetism. In the most basic version, two coils are wound around a magnetic core. Because the alternating current going through one coil of wire–the primary–varies with time, it produces a magnetic field in the core that also var-

PREVIOUS PAGES: ALAMY; THIS PAGE: SUBHASHISH BHATTACHARYA/NCSU

SHRINKING IT DOWN: This set of shelves at the FREEDM Systems Center houses part of TIPS, a three-phase solid-state transformer. The conventional transformer component of TIPS [gray boxes at bottom] can be small thanks to power electronics that convert the electricity to high frequency.

ies in time. That changing magnetic field in turn induces an alternating current and voltage in another coil—the secondary. The ratio of the input, or primary, voltage to the output, or secondary, voltage is determined by the ratio of turns in the primary and secondary coils.

Transformers have a number of great properties. They are efficient and rugged, and they offer a very useful feature called galvanic isolation. Because the input and output sides of a transformer are linked only by magnetic fields, there is no way for current to flow directly across the device from the primary to the secondary side. This isolation is an important safety feature that helps prevent high-voltage electricity from reaching places it shouldn't go.

Some transformers are capable of handling a measure of variability. Distribution transformers can be equipped with a tap changer, which mechanically toggles between different parts of a coil, reducing or increasing the number of turns in order to decrease or increase the voltage in response to big changes in load.

But these tap-equipped transformers are not well suited to the frequent and large voltage swings that can occur nowadays. Instead of changing once or twice a day, as they did years ago, tap changers can now easily change position upwards of a dozen times, resulting in significantly more wear and tear.

If we could design a transformer that doesn't need a mechanical tool to adjust its voltage, we could eliminate a significant expense in distribution infrastructure. The natural solution, of course, is to apply the best appropriate technology—namely power electronics.

And in fact, a number of engineers are exploring the idea of a "hybrid transformer," which adds power electronics to assist in controlling voltage. But new, high-voltage semiconductor devices are needed if we want to create more capable electronic distribution transformers. And until recently, there were no switches that had all the right properties.

Thyristors, for example, can be used to build converters that can be connected to high-voltage lines. But the converters would take up a lot of space. That's because thyristors aren't designed for high-frequency operation. The lower the frequency, the larger the system's passive elements—in particular, the inductors and capacitors—need to be. You can think of these components as charge-storage devices; the lower the frequency, the longer they need to accommodate charges flowing through them, which means they need to be fairly big.

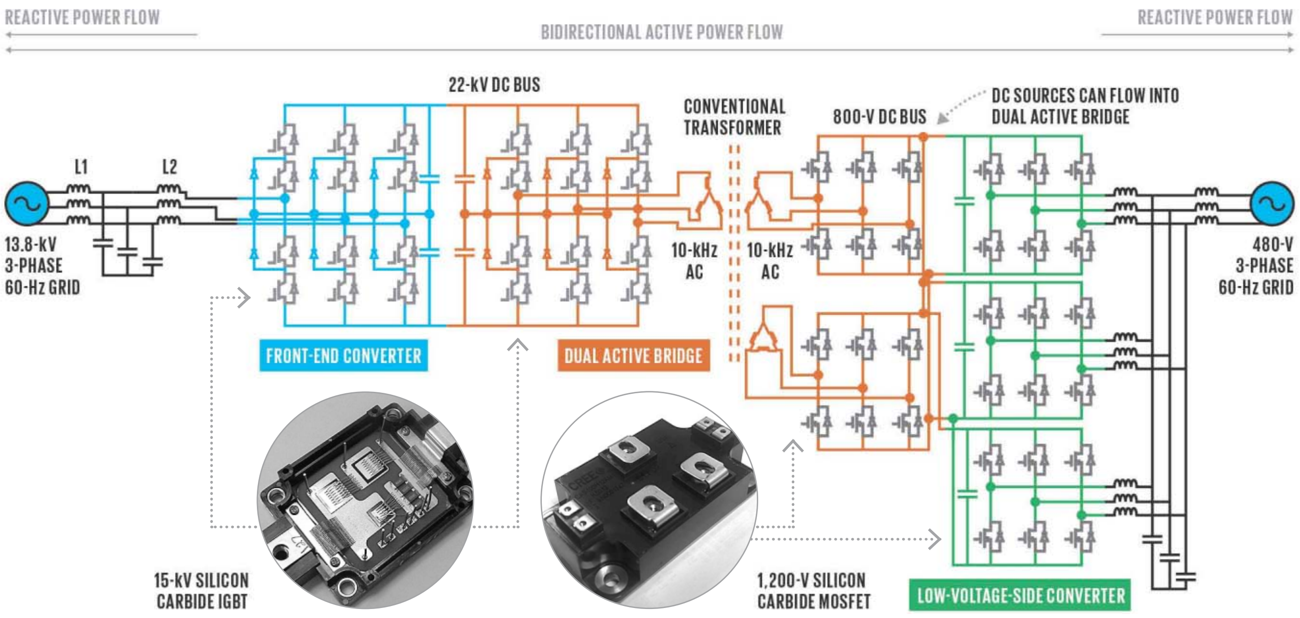
The workhorse switch of power electronics, the silicon-based insulated-gate bipolar transistor (IGBT) is a better fit. These devices have been used to build SSTs for rail applications in Europe. And they are certainly faster. But the most rigorous commercial devices can withstand voltages up to only about 6.5 kilovolts. While this breakdown voltage is perfectly fine for a range of power applications, it isn't sufficient to handle the electricity that flows through distribution transformers; in the United States, a typical voltage at the low end of the spectrum is 7.2 kV.

Of course, if a few of those IGBTs were connected in series, they could be used to create an SST that can handle the voltage. But small manufacturing variations mean each IGBT will switch at a slightly different voltage, and that means some transistors will switch earlier than others, bearing more of the load. Capacitors can help equalize the voltages, but the result would be bulky, inefficient, less reliable, and more expensive.

Fortunately, silicon is not the only option. In the last 10 years, great strides have been made in the development of switches based on compound semiconductors—silicon carbide in particular. Silicon carbide has a range of attractive properties that stem from its large bandgap—the energy hurdle that must be overcome to switch from insulator to conductor. Silicon carbide's bandgap is 3.26 electron volts to silicon's 1.1 eV, which means the material can be exposed to significantly higher electric fields and temperatures than silicon can without breaking down. And because this compound semiconductor can withstand much higher voltages, power transistors built from it can be made more compact, which in turn allows them to switch much faster than their silicon-based counterparts. A faster switching speed also cuts down on energy loss, so silicon carbide transistors can carry more current for a given thermal budget.

Inspired by developments in silicon carbide devices and by related research funded by the U.S.-based Electric Power Research Institute, a group of us at North Carolina State University applied in 2007 for a grant from the U.S. National Science Foundation. We used the grant to start the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center, with the aim of advancing the technologies we'll need to modernize the electrical grid, making it more secure, reliable, and environmentally sustainable.

SSTs were a big priority for the center, and we aimed to tackle both single-phase and three-phase distribution transformers. To understand the difference, here's a little background. The energy that flows out of substations is generally carried by three wires, each carrying an alternating current that is 120 degrees out of phase with respect to the other two. These lines can be separated and passed individually (along with a neutral line) through a single-phase transformer to supply fairly low-voltage electricity to residential neighborhoods, for example. Or the lines can be carried together in a three-phase feeder to places that have bigger energy demands, such as data centers, factories, commercial buildings, and retail complexes.



CONVERSION IN THREE PARTS: TIPS (Transformerless Intelligent Power Substation) was finished in 2015 and was the first three-phase transformer made with solid-state devices. The transformer consists of three modules and includes small, conventional single-phase transformers operating at high frequency.

At FREEDM, we started by working on SSTs designed to handle that lower-voltage, single-phase service. The transformers are similar in some respects to switched-mode power supplies, which are now ubiquitous as power sources for laptop computers and other appliances.

Our approach has been to build the SSTs from three modules. The first, called a front-end converter, takes incoming alternating current at, say, 7.2 kV and converts it to direct current (because of the particulars of our design, that DC current has a somewhat higher voltage). The AC-to-DC conversion is done using a set of power transistors. In the first incarnation, this was done with silicon IGBTs, and in our second SST, we did it with an early silicon carbide switch: the silicon carbide metal-oxide-semiconductor field-effect transistor, or MOSFET.

To convert the incoming electricity–which oscillates at 60 hertz in the United States–into a DC current requires two complementary sets of transistors. One set is in operation when the incoming AC electricity has a positive voltage, and the other set is in operation when it has a negative voltage. Thanks to the way the transistors are wired up, regardless of the voltage of the incoming electricity, charge piles up on a capacitor, which is steadily discharged to create DC current. We use transistors to perform this rectification process instead of traditional diodes because we can run them at many times the incoming frequency. This lets us chop up the sinusoidal incoming current very finely so that we don't inject noise and unwanted harmonics upstream. That would create deviations from clear sine waves in voltage and current, and thus unusable energy that would be lost to heat.

In the second module, another set of transistors converts incoming DC current into an AC current with a frequency measured in kilohertz. This current is then passed through a conventional–though high-frequency–transformer to convert the voltage down to, say, 800 V.

Why the high frequency? Basically, the size of a transformer is inversely related to the frequency of the voltage it must transform. The higher the frequency, the smaller the transformer–and, as a bonus, the more efficient it will be. After the voltage is reduced, a set of lower-voltage devices converts this still-high-frequency AC current back to a direct current.

The third module is an inverter, which uses yet another set of transistors to convert the DC electricity back to AC with a mains frequency, at which point it can then be safely supplied to end users.

The first single-phase SST we built was designed to explore silicon's limits; the second allowed us to put silicon carbide devices through their paces. And if there was any doubt about the benefits of silicon carbide over silicon, it could be resolved by comparing those two SSTs. Our silicon-based transformer needed three sets of silicon IGBTs arranged in series to convert incoming 7.2-kV electricity down to the standard 120- and 240-V output, and could operate only up to 3 kHz. At that frequency, the conventional transformer was smaller, but we needed three of them. The silicon carbide version could accomplish the same task with one set of transistors, and it could operate at 20 kHz–a frequency that enabled us to use a transformer in the second module that was just 20 percent the size of a conventional 60-Hz transformer. All told, our single-phase silicon carbide SST was a third the size of its conventional counterpart.

So, in the end, did we simply take one big transformer and replace it with a smaller one with a lot of costly elec-

PHOTOS: CREE (2)

tronics? Not exactly. Like the hybrid transformer, the transformer we created can automatically and quickly adjust to shifts in voltage over a wide range, eliminating the need for mechanical tap changers. But it is also a smart energy-management device that can handle a wide range of loads and sources, providing much better flexibility and resilience than a conventional or hybrid transformer.

With the three-module approach, batteries and renewable energy sources can connect directly to one side of the SST's central module. As a result, those energy sources can have a direct DC interface with the grid. This arrangement will significantly decrease how much energy is lost when solar panels, wind turbines, and the like pump energy back on the grid, as the electricity they generate won't need to be converted into an alternating current in order to pass through nearby transformers.

Our work on single-phase SSTs motivated us to extend our efforts to build a three-phase SST. This would mean creating a transformer that can handle all three of the lines that are leaving the substation or are carried along a distribution feeder circuit. A common input voltage there is 13.8 kV, which is converted down to 480 V for industrial and commercial uses.

Here, at this relatively high voltage, silicon carbide MOSFETs weren't the best choice; they lose a lot of energy when current is flowing through them, and the loss gets worse the higher the voltage and temperature. Fortunately, a corporate partner near the university, Cree, had been working on silicon carbide IGBTs. These lose more energy than MOSFETs do when they're switching, but they can carry more current through the same area and so be even more compact.

In 2010, the U.S. Department of Energy's Advanced Research Projects Agency-Energy awarded our team US $4.2 million to build a three-phase SST from these devices. We called the project the Transformerless Intelligent Power Substation, or TIPS. I'll admit it is a somewhat odd moniker: TIPS is not a substation, nor does it lack a transformer. But the "substation" part of the name came about because we wanted to emphasize how smart and capable an SST could be. And "transformerless" really refers to the idea of using less of the conventional transformer technology by operating at a fairly high frequency.

With so many different conversion steps, you might think that SSTs such as TIPS are significantly less efficient than conventional transformers. But they actually perform quite well. Transformers today have an efficiency of more than 99 percent when they're operated at full capacity, with less than 1 percent of the electricity lost to heat. But the efficiency drops down to 95 percent for a transformer operating at 30 to 50 percent of capacity. For contrast, we expect SSTs such as TIPS to have an efficiency of 98 percent, regardless of load. What's more, by fluidly adjusting voltage, an SST can reduce the reliance on boosting current–a highly inefficient remedy that is used today to make sure enough power reaches a user even if the voltage drops on a line.

Ours is not the only team that has built SSTs. But with TIPS we were able to demonstrate what silicon carbide IGBTs have to offer: a new class of three-phase transformers that are simultaneously compact and ultracapable.

There are still obstacles to widespread adoption. One is the ability to withstand extreme conditions. Traditional transformers can handle lightning strikes and surges, overheating without failing. But power electronics are significantly less forgiving; the transistors are small and have little thermal inertia, which means they heat up almost instantaneously. Voltage-dependent resistors and surge arresters, installed at the high-voltage side of an SST, could help compensate for this limitation.

Another obstacle is cost. The silicon carbide IGBTs that we used to make TIPS were experimental devices not available commercially. Companies such as Cree, General Electric, Infineon, Mitsubishi, and Rohm are continuing to develop these devices. And Cree has since gone on to build 20-kV and 24-kV versions. These higher-voltage ratings could lead to SSTs that require significantly fewer devices, saving on cost and space. But silicon carbide IGBTs are still at an early stage of development, and their commercialization will depend in part on practicalities like the ability to manufacture them with fewer defects. It may be some years before silicon carbide IGBTs will be mature and thus inexpensive enough to produce an SST that could be offered at a competitive price.

In the meantime, our team has received significant support to investigate building SSTs using more mature 10-kV silicon carbide MOSFETs. These transistors must be connected in series to be able to withstand three-phase distribution voltages, and they won't be as efficient as IGBTs. But they could still offer a path toward creating smaller transformers than we have today, with all the SST smarts and functionality we've demonstrated.

You may have noticed that if you lop off the outer modules of TIPS, you wind up with a DC-DC converter. If we had such converters in the early days of electricity, we may well have seen Thomas Edison's DC distribution scheme contending with Nikola Tesla's AC approach to this day. In the past few years, this old rivalry has again come to the fore. DC transmission promises fewer losses over long distances. And engineers are contemplating DC microgrids, to more efficiently power our DC-dependent appliances and everyday gadgets. We can now make DC-DC converters out of silicon power electronics that are efficient enough to be used for such microgrids; silicon carbide versions could have higher efficiency and even wider applications.

Few of these ideas are new. But they are taking on new urgency as we strive to make the most of our energy resources. SSTs offer a way to dramatically change how power makes its way to us. The changes they'll effect won't be as glamorous or as visible as the great leaps in electronics that have, in the last 50 years, revolutionized our daily lives. But they will have a profound impact on the stability and efficiency of our electrical infrastructure, finally bringing it–at long last–into the electronics age. ■

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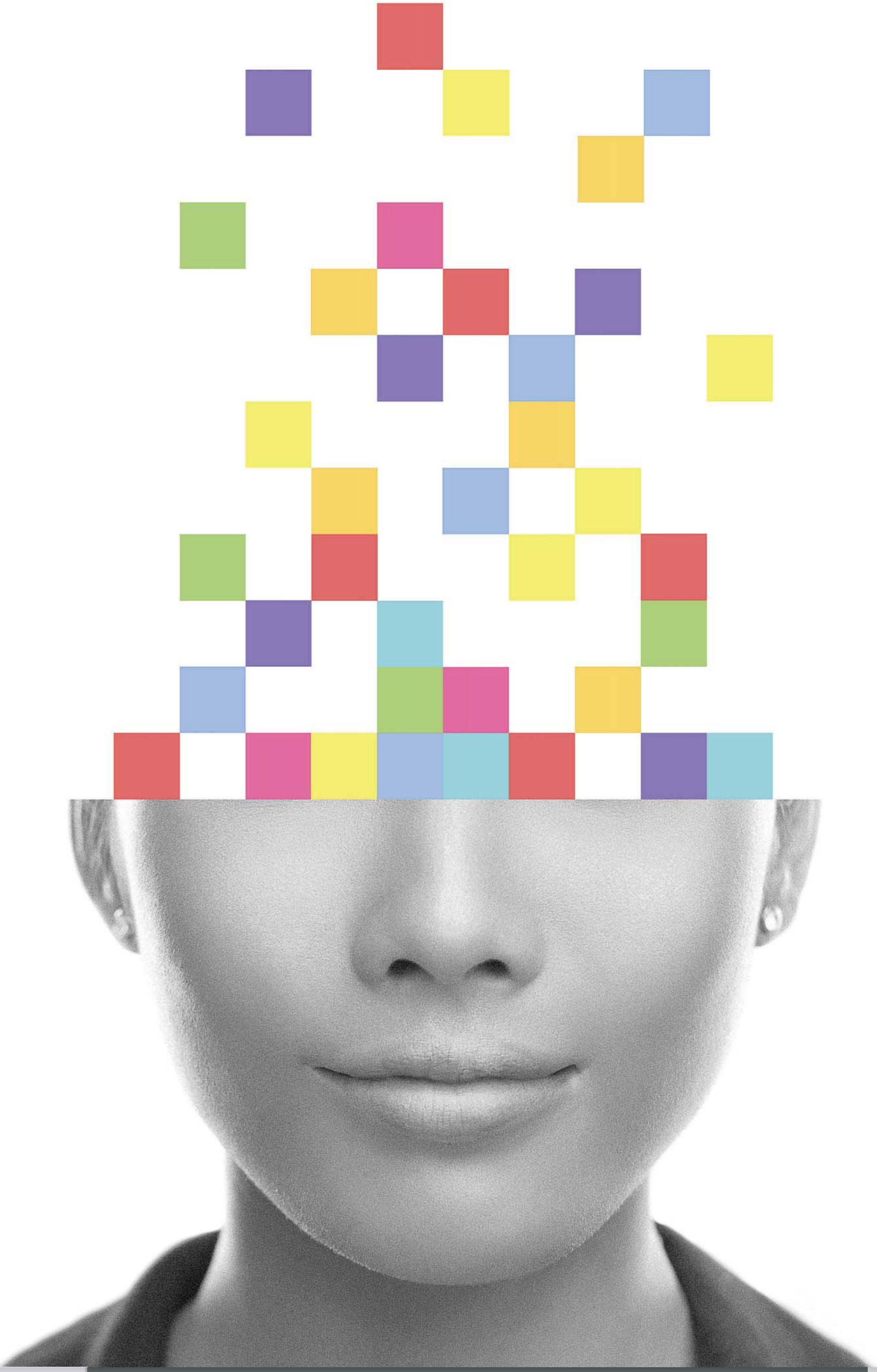


THE CASE FOR DIGITAL PSYCHIATRY

Data is about to revolutionize the treatment of depression, schizophrenia, and many other disorders

By John Torous

PHOTO-ILLUSTRATION BY Edmon de Haro

Zach has been having trouble at work, and when he comes home he's exhausted, yet he struggles to sleep. Everything seems difficult, even walking—he feels like he's made of lead. He knows something is wrong and probably should call the doctor, but that just seems like too much trouble. Maybe next week.

Meanwhile, software on his phone has detected changes in Zach, including subtle differences in the language he uses, decreased activity levels, worsening sleep, and cutbacks in social activities. Unlike Zach, the software acts quickly, pushing him to answer a customized set of questions. Since he doesn't have to get out of bed to do so, he doesn't mind.

Zach's symptoms and responses suggest that he may be clinically depressed. The app offers to set up a video call with a psychiatrist, who confirms the diagnosis. Based on her expertise, Zach's answers to the survey questions, and sensor data that suggests an unusual type of depression, the psychiatrist devises a treatment plan that includes medication, video therapy sessions, exercise, and regular check-ins with her. The app continues to monitor Zach's behavior and helps keep his treatment on track by guiding him through exercise routines, noting whether or not he's taking his medication, and reminding him about upcoming appointments.

While Zach isn't a real person, everything mentioned in this scenario is feasible today and will likely become increasingly routine around the world in only a few years' time. My prediction may come as a surprise to many in the health-care profession, for over the years there have been claims that mental health patients wouldn't want to use technology to treat their conditions, unlike, say, those with asthma or heart disease. Some have also insisted that to be effective, all assessment and treatment must be done face to face, and that technology might frighten patients or worsen their paranoia.

However, recent research results from a number of prestigious institutions, including Harvard, the National Alliance on Mental Illness, King's College London, and the Black Dog Institute, in Australia, refute these claims. Studies show that psychiatric patients, even those with severe illnesses like schizophrenia, can successfully manage their conditions with smartphones, computers, and wearable sensors. And these tools are just the beginning. Within a few years, a new generation of technologies promises to revolutionize the practice of psychiatry.

TO UNDERSTAND THE POTENTIAL of digital psychiatry, consider how someone with depression is usually treated today.

Depression can begin so subtly that up to two-thirds of those who have it don't even realize they're depressed. And even if they realize something's wrong, those who are physically disabled, elderly, living in rural areas, or suffering from additional mental illnesses like anxiety disorders may find it difficult to get to a doctor's office.

Once a patient does see a psychiatrist or therapist, much of the initial visit will be spent reviewing the patient's symptoms, such

Diagnosis by Smartphone

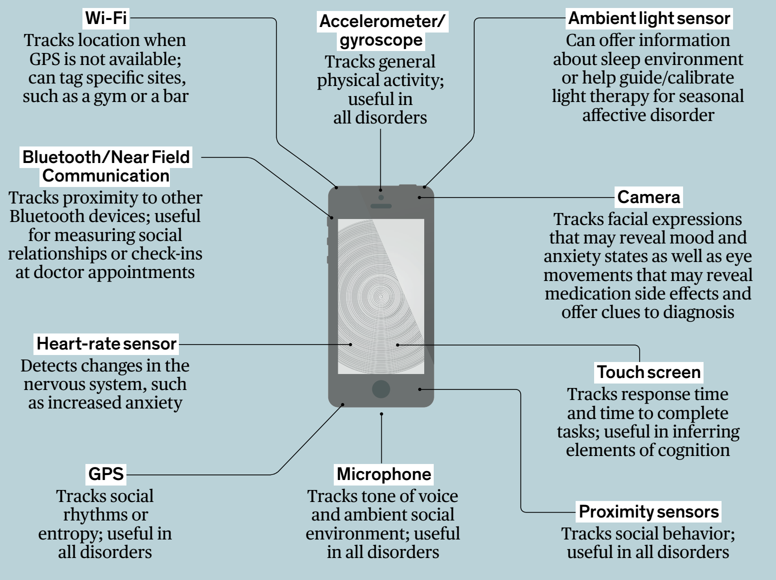


ILLUSTRATION: RICH MORGAN; SOURCE: JOHN TOROUS

FIGHTING FEARS: Virtually Better's simulations are designed to help people undergoing therapy for phobias—such as a fear of heights [top] or flying [bottom]—to face their fears in a safe environment.

VIRTUALLY BETTER

as sleep patterns, energy levels, appetite, and ability to focus. That too can be difficult; depression, like many other psychiatric illnesses, affects a person's ability to think and remember.

The patient will likely leave with some handouts about exercise and a prescription for medication. There's a fair chance that the medication won't be effective at least for many weeks, the exercise plan will be ignored, and the patient will have a bumpy course of progress. Unfortunately, the psychiatrist won't know until a follow-up appointment sometime later.

Technology can improve this outcome, by bringing objective information into the psychiatrist's office and allowing real-time monitoring and intervention outside the office. Instead of relying on just the patient's recollection of his symptoms, the doctor can look at behavioral data from the person's smartphone and wearable sensors. The psychiatrist may even recommend that the patient start using such tools before the first visit.

It's astonishing how much useful information a doctor can glean from data that may seem to have little to do with a person's mental condition. GPS data from a smartphone, for example, can reveal the person's movements, which in turn reflects the person's mental health. By correlating patients' smartphone-derived GPS measurements with their symptoms of depression, a 2016 study by the Center for Behavioral Intervention Technologies at Northwestern University, in Chicago, found that when people are depressed they tend to stay at home more than when they're feeling well. Similarly, someone entering a manic episode of bipolar disorder may be more active and on the move. The Monitoring, Treatment, and Prediction of Bipolar Disorder Episodes (Monarca) consortium, a partnership of European universities, has conducted numerous studies demonstrating that this kind of data can be used to predict the course of bipolar disorder.

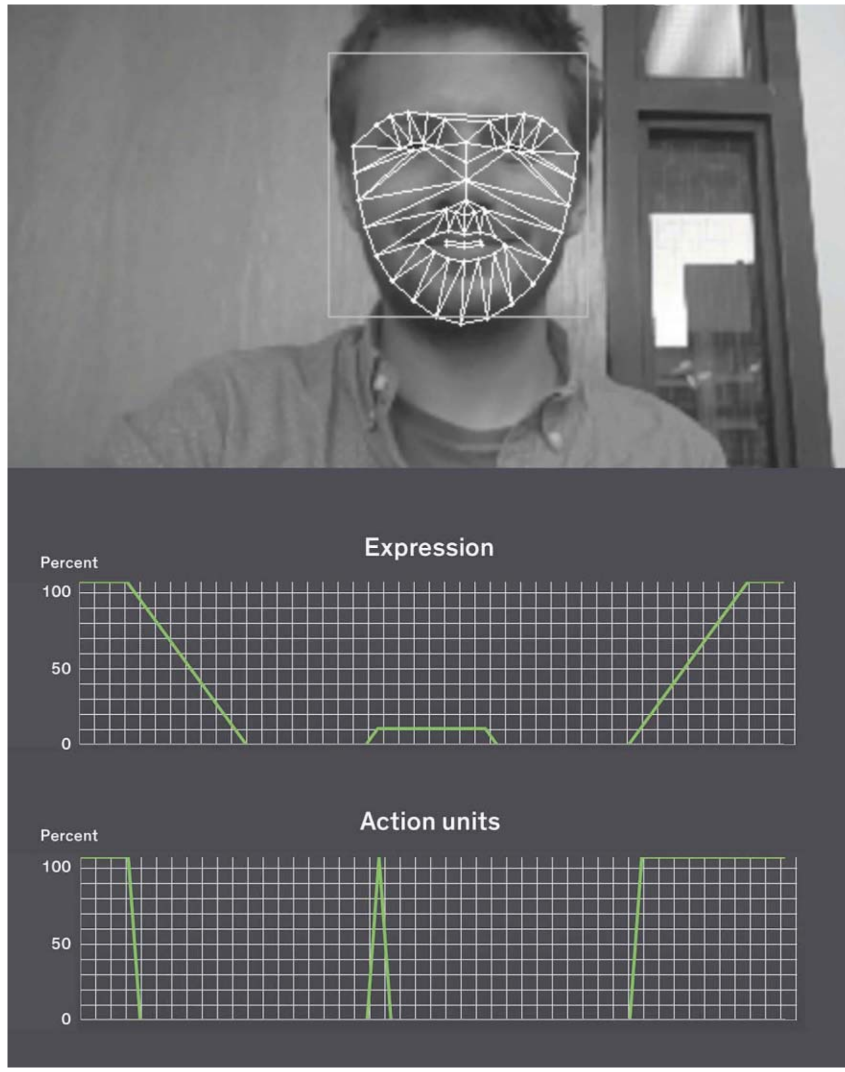
Where GPS is unavailable, Bluetooth and Wi-Fi can fill in. Research by Dror Ben-Zeev, of the University of Washington, in Seattle, demonstrated that Bluetooth radios on smartphones can be used to monitor the locations of people with schizophrenia within a hospital. Data collected through Wi-Fi networks could likewise reveal whether a patient who's addicted to alcohol is avoiding bars and attending support-group meetings.

Accelerometer data from a smartphone or fitness tracker can provide more fine-grained details about a person's movements, detect tremors that may be drug side effects, and capture exercise patterns. A test of an app called CrossCheck recently demonstrated how this kind of data, in combination with other information collected by a phone, can contribute to symptom prediction in schizophrenia by providing clues on sleep and activity patterns. A report in the *American Journal of Psychiatry* by Ipsit Vahia and Daniel Sewell describes how they were able to treat a patient with an especially challenging case of depression using accelerometer data. The patient had reported that he was physically active and spending little time in bed, but data from his fitness tracker showed that his recollection was faulty; the doctors thus correctly diagnosed his condition as depression rather than, say, a sleep disorder.

Tracking the frequency of phone calls and text messages can suggest how social a person is and indicate any mental change. When one of Monarca's research groups looked at logs of incoming and outgoing text messages and phone calls, they concluded that changes in these logs could be useful for tracking depression as well as mania in bipolar disorder.

COMBINING ALL THESE data streams will amplify the power of digital psychiatry. Today, studies are under way using apps and sensors to explore nearly every subtype of mental illness. I am part of a collaboration between Beth Israel Deaconess Medical Center's Digital Psy-

GLASS ACT: The Autism Glass Project at Stanford University is using smart glasses to read facial expressions and provide social cues for children with autism.



HAPPY FACE: Wearable cameras combined with analytic software, like this program used in Stanford University's Autism Glass Project, can detect emotions in order to give social cues in real time or to track responses for later analysis by a psychiatrist or behavioral therapist.

chiatry Program and the Onnela Lab at the Harvard T.H. Chan School of Public Health, both in Boston, that is studying how the various types of sensor data described above can help predict relapses in schizophrenia, as well as better understand what patients with schizophrenia experience when they relapse.

It's not just behavioral data that is valuable. Physiological data such as heart rate, temperature, and galvanic skin response can also shed light on a person's mental well-being. Such data is already collected by some wearable devices. Numerous studies have shown that heart rate variability can be used to track the severity of bipolar disorder and schizophrenia. Galvanic skin response, a measurement of the electrical conductance of the skin that varies with the state of sweat glands and is controlled by the "fight or flight" component of the nervous system, can offer clues into the biological activity that may be overactive in anxiety disorders.

Ultimately, psychiatric disorders are brain disorders, and using electroencephalography (EEG) to monitor brain activity has long been an accepted practice in psychiatric research and biofeedback treatments. Newer, consumer-grade EEG gadgets are now on the market, but it's still unclear how effective they are. In time, though, as the technology improves and expands–3D-printed EEG headsets and less cumbersome electrodes may be promising–these devices will likely prove more useful.

BEYOND JUST DIAGNOSING and monitoring mental illness, digital psychiatry can also help treat certain conditions. Without knowing whether or not a patient is taking his medication, for example, a doctor can't identify the cause of any continued problems. It could be that the drug isn't effective, or the patient isn't taking the medication as prescribed.

Sensors embedded in pills can help. In the case of aripiprazole, an antipsychotic drug, researchers added an ingestible sensor that detects stomach acid and then sends a signal to a wearable patch to confirm that the medication has been taken. The patch, in turn, forwards the information via Bluetooth to a smartphone. This intervention proved both technically feasible and acceptable to patients with schizophrenia. For such patients, systems backed by artificial intelligence, simulations run in virtual reality, and even cheaper and simpler solutions, like those based on text messaging, may likewise help patients adhere to medication schedules.

Many psychiatric treatments aren't medications, of course. Studies show that therapy sessions can also benefit from a digital psychiatry approach. Today, therapy requires visiting an office, but it can be just as effective to conduct the session via

STANFORD UNIVERSITY (2)

computer or smartphone, and it's more convenient for the average patient. Computers and smartphones can even deliver specialized therapy involving virtual reality technology. Doctors now use VR therapy, in the office or at home, to help patients overcome phobias, such as a fear of heights or spiders, as well as to help soldiers suffering from post-traumatic stress disorder. And a pilot study at the University of Oxford, in England, recently demonstrated that VR tools may reduce the delusional beliefs that come with schizophrenia, while researchers at Stanford University are exploring augmented reality glasses to help children with autism.

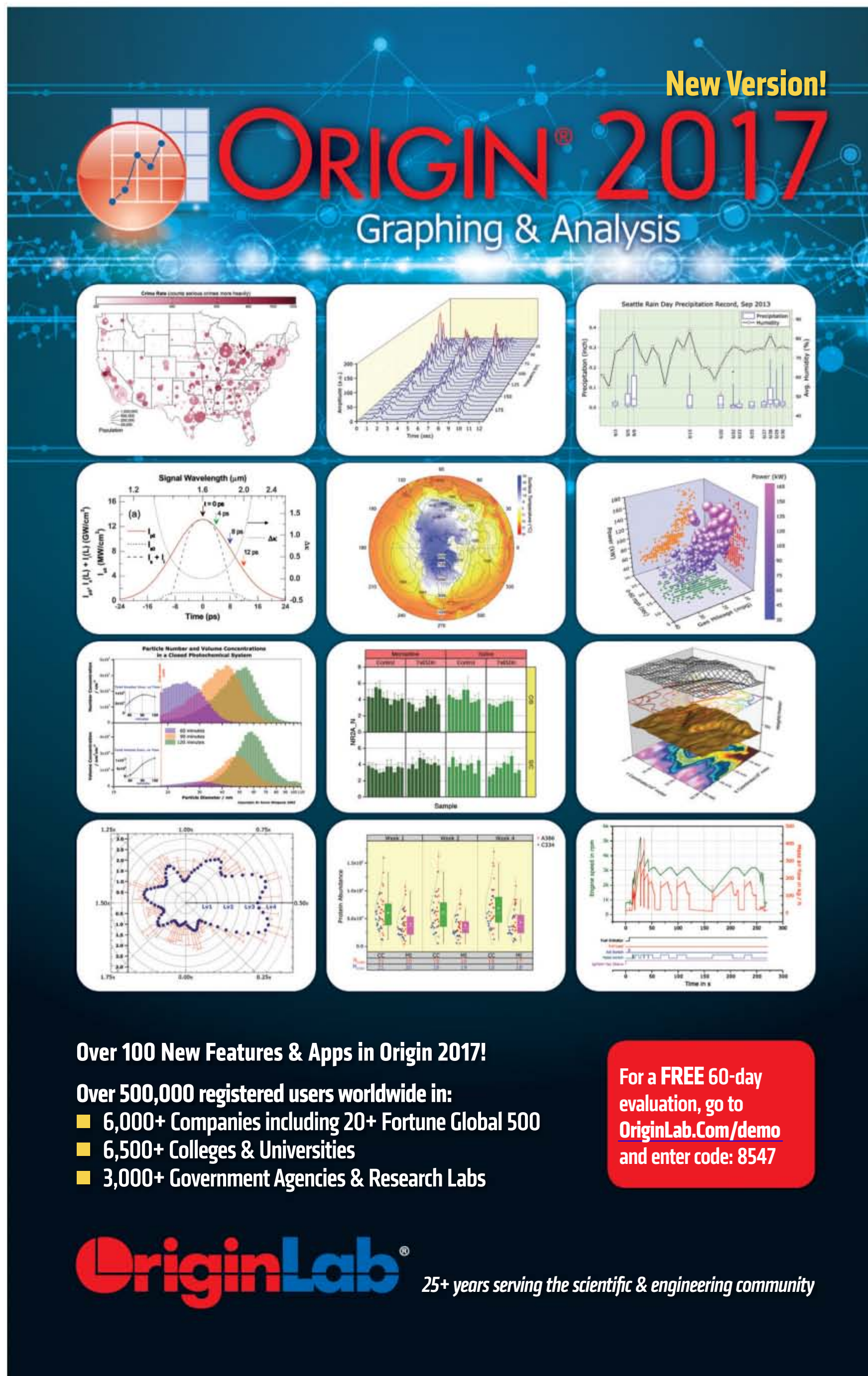
THE ULTIMATE PROMISE of digital psychiatry is that it could help improve everyone's mental health. It shouldn't be too difficult to use the Internet of Things to encourage healthy behaviors—for instance, automatically dimming the lights in the home at a recommended bedtime or turning off the TV to encourage exercise. Relaxing music could be cued to ease stress, and window shades could be programmed to let in the maximum amount of natural light.

To be sure, there is much that digital psychiatry's tools cannot yet do or that researchers have not yet proven they can do. Any new health-care technology must be validated clinically before it can become mainstream. While many of the tools discussed already exist, few have been well studied for use in psychiatric disease.

Taking therapies that work well when delivered in person and translating them into digital or mobile versions isn't always straightforward. For example, one study looked at an app designed to help people quit smoking; it was based on an effective in-person smoking-cessation treatment. But the study found that only some elements of the therapy were successful in app form. What's more, the app features that users liked most, like tracking how often they smoked or sharing progress with friends, weren't actually the most effective at changing behavior, while more effective techniques, like practicing resistance to an urge to smoke until it passes, were less popular on the app.

Plenty of technical challenges also remain. On the diagnostic side, the biggest one is emotion sensing. We can now capture a tremendous amount of behavioral and physiological data on the go and in real time, but we don't fully understand how to connect this information with how someone is feeling. Many companies have proposed various big-data analytical methods to synthesize sensor data in order to draw conclusions about mental health, but transforming these promising ideas into scalable and reproducible results that give doctors and patients useful information remains a challenge.

A different kind of challenge is patient adherence to technology-driven programs. Many researchers and clini-



cians worry that patients will stop using their apps or wearing their sensors once the novelty wears off. Mental illnesses tend to be chronic, and nearly all require treatment or monitoring for at least several months, so a technology that gets abandoned after a few weeks won't be too helpful.

But assuming we can get patients to use their digital psychiatry tools, we still have to address the basic issues of battery life and data security. Constantly running the GPS on a phone, for example to monitor a patient's location, quickly depletes the battery. Until longer-lived smartphone batteries come along, it will remain impractical to collect huge amounts of behavioral data that way. Researchers also worry about security flaws in specific apps as well as in data transmission and storage, which could reveal confidential patient data to others. Given the stigma associated with mental illness, security has to be a top concern for anyone thinking of developing or using digital psychiatry tools. Ethical concerns about how apps respect privacy and use patient data remain rife, with many mental health apps still lacking even basic privacy policies or covertly selling users' mental health information to data brokers. Efforts like the Connected and Open Research Ethics project are trying to bring more trust and transparency to the field and to advocate for patients and consumers.

↗ POST YOUR COMMENTS at http://spectrum.ieee.org/digitalpsychiatry0717

DESPITE THESE CHALLENGES, the digital future of psychiatry may be much closer than we realize. The smartphone-based treatment scenario described at the start of this article is already within sight, and all of the individual elements exist today. Meanwhile, various groups are working on algorithms to extract meaningful information from the sea of behavioral data generated by phones and sensors. And in general, mental health apps are becoming more usable and engaging; some, like the smoking-cessation app, even have social or game features.

I predict that this technology will have an enormous impact on psychiatry. It cannot happen soon enough. One in five people around the world will suffer from a psychiatric illness over the course of a lifetime, but far fewer will seek or receive professional help. According to the World Health Organization, this year depression moved past hearing loss and vision problems to become the leading cause of ill health and disability worldwide.

But the technology to help those with psychiatric illnesses can reverse this trend. Such technology can be modified, scaled, and culturally adapted to serve the global population—but only if we, members of the engineering and mental health professions, work together to make that happen. ■

FREE PDF BOOK

THEORY vs PRACTICE

Those who took a course on **Signals and Systems** in college are invited to read the book:

Signals and Systems: A Fresh Look

by Chi-Tsong Chen, IEEE Fellow and Author of a Standard Graduate Text Linear System Theory and Design.

The book strives to close the gap between theory and practice. It downplays some conventional topics such as Fourier series and introduces many concepts which are basic and relevant to engineering. Some unique features of the book include: The frequency spectra of a tuning fork and a piano key are computed and compared with their specified frequencies. The operational amplifier (op amp) is used to introduce basic system concepts and its graphical description is then extended to four types of linear equations (convolutions, differential equations, state-space equations, and transfer functions) to describe general systems. We downplay the first two types, use the third type in real-time computation and in op-amp circuit implementation, and the last type in qualitative analysis and system design. Seismometers and accelerometers are designed after introducing the concepts of stability, model reduction, and operational frequency range. Complete MATLAB examples are provided throughout.

Whether the book has succeeded in closing the gap between theory and practice is best judged by practicing engineers. It is hoped that those teaching such a course will also read the book. To download a free PDF copy (5MB), visit **http://ctchen.me**. A 405-page hardcopy can be ordered from Amazon for $22.

Lawrence Technological University

Electrical and Computer Engineering Department Chair and Professor

Lawrence Technological University seeks a Professor and Chair of the Department of Electrical and Computer Engineering. The department enrolls some 180 undergraduate and 40 graduate students. It offers accredited B.S. degrees in Electrical Engineering, Computer Engineering, and Embedded Software Engineering and an M.S. in Electrical and Computer Engineering. The department's faculty is primarily dedicated to high quality teaching and learning, and it has a commendable scholarship program.

Qualified applicants for the chair position will have strong leadership and administrative skills, an interest in advanced teaching methodologies, a vision for growing the research enterprise, and the ability to build strong relationships with academic departments, potential students, and corporations. A Ph.D. in electrical or computer engineering or a closely related field is required and credentials commensurate with appointment as a full professor with tenure. Past experience in formal academic leadership and in the ABET accreditation process is preferred. Salary is competitive and commensurate with qualifications and experience.

Lawrence Tech is a private university. The College of Engineering is the oldest and largest, enrolling more than 1,000 undergraduate and 400 graduate students. The College includes five departments: Civil and Architectural; Biomedical; Electrical and Computer; Mechanical; and Technology. Over a third of the students enroll in evening programs, and the College serves both full-time and working adult students. The University enjoys strong ties with many industries headquartered in the region and is expanding academic, service, and applied research programs.

PayScale lists Lawrence Tech among the nation's top 100 universities for the salaries of its graduates, and U.S. News and World Report lists it in the top tier of best Midwestern universities. LTU's College of Engineering also fares well in the best undergraduate engineering programs category, ranking 23rd of 46.

Lawrence Technological University conducts pre-employment screening on initial candidates for all positions, which may include but is not limited to, a criminal background check, verification of academic credentials, license, certifications, and/or verification of work history.

Lawrence Tech welcomes applications from minorities and women. Applications will be reviewed on a rolling basis and will be accepted until the position is filled. Interested candidates should send resume and references to: Dr. Nabil Grace, Dean, College of Engineering, Lawrence Technological University, 21000 W. Ten Mile Rd., Southfield, MI 48075-1058 or engrdean@ltu.edu. EOE

National Sun Yat-Sen University

Department of Electrical Engineering
& Institute of Communications Engineering

FACULTY RECRUITMENT

Department of Electrical Engineering and Institute of Communications Engineering at National Sun Yat-Sen University (NSYSU) invite applications from outstanding candidates for faculty positions (Assistant Professor, Associate Professor, or Full Professor). Applicants of all disciplines in the electrical engineering and computer science are welcome, but those in the following areas will be given priority.

(1) computer graphics, virtual reality, augmented reality;
(2) big data analysis, cloud computing, data mining;
(3) electromagnetics and communications systems.

Applicants should have a Ph.D. degree in electrical engineering, computer science, computer engineering, or other related fields. Responsibilities include effective teaching at the undergraduate and graduate levels, and establish a strong research program that involves supervision of graduate students and acquisition of research grants.

Applicants should arrange the following documents be sent (hard copy by mail or the corresponding PDF files by e-mail), before **August 21, 2017**, to:

Faculty Search Committee
Department of Electrical Engineering
National Sun Yat-Sen University
Kaohsiung, 80424 Taiwan
E-mail: chiaying@mail.ee.nsysu.edu.tw
Phone: +886-7-5252000 ext. 4103 Fax: +886-7-5254199
URL: **http://www.ee.nsysu.edu.tw**

1. *a curriculum vitae and a copy of Ph.D. diploma;*
2. *one representative publication within the last five years and no more than three reference publications within the last seven years;*
3. *transcript (for fresh Ph.D. applicants only);*
4. *a statement of teaching and research plans;*
5. *three recommendation letters;*
6. *other supporting material.* ***items 1 to 5 are required.**

BINGHAMTON UNIVERSITY
STATE UNIVERSITY OF NEW YORK

The Thomas J. Watson School of Engineering and Applied Science at Binghamton University is seeking nominations and applications for the George J. Klir Endowed Professor in Systems Science. This is a newly-created position made possible by a gift to honor the memory and work of the late George J. Klir, a Distinguished Professor Emeritus of Systems Science at Binghamton University. The candidate should demonstrate leading academic fortitude in the fields inspired by Dr. Klir's work including, but not limited to: complex systems; cybernetics; fuzzy set theory, fuzzy logic and fuzzy systems; general systems concepts and theory; generalized information theory; probabilistic and possibilistic theory; soft computing; systems problem solving; uncertainty theory; and fields and disciplines that develop from this work. The position will carry the rank of full professor in the Department of Systems Science and Industrial Engineering (SSIE). Other attributes of the desired candidate include international stature and visibility; a history of recognized teaching and scholarship; and a reputation as a respected leader and mentor for graduate students and post-doctoral researchers. The Watson School is dedicated to the goal of building a diverse and inclusive teaching, research, and working environment. Potential applicants who share this goal, especially underrepresented minorities, women and persons with disabilities, are strongly encouraged to apply. Applications and nominations should include full contact information, a complete CV, cover letter, research and teaching statements, and the names of three professional references. Review of applications will begin on **August 1st**, but the position will remain open until filled. Application materials or nominations may be sent to Dr. John S. Bay, Associate Dean for Research and Graduate Studies, bayj@binghamton.edu.

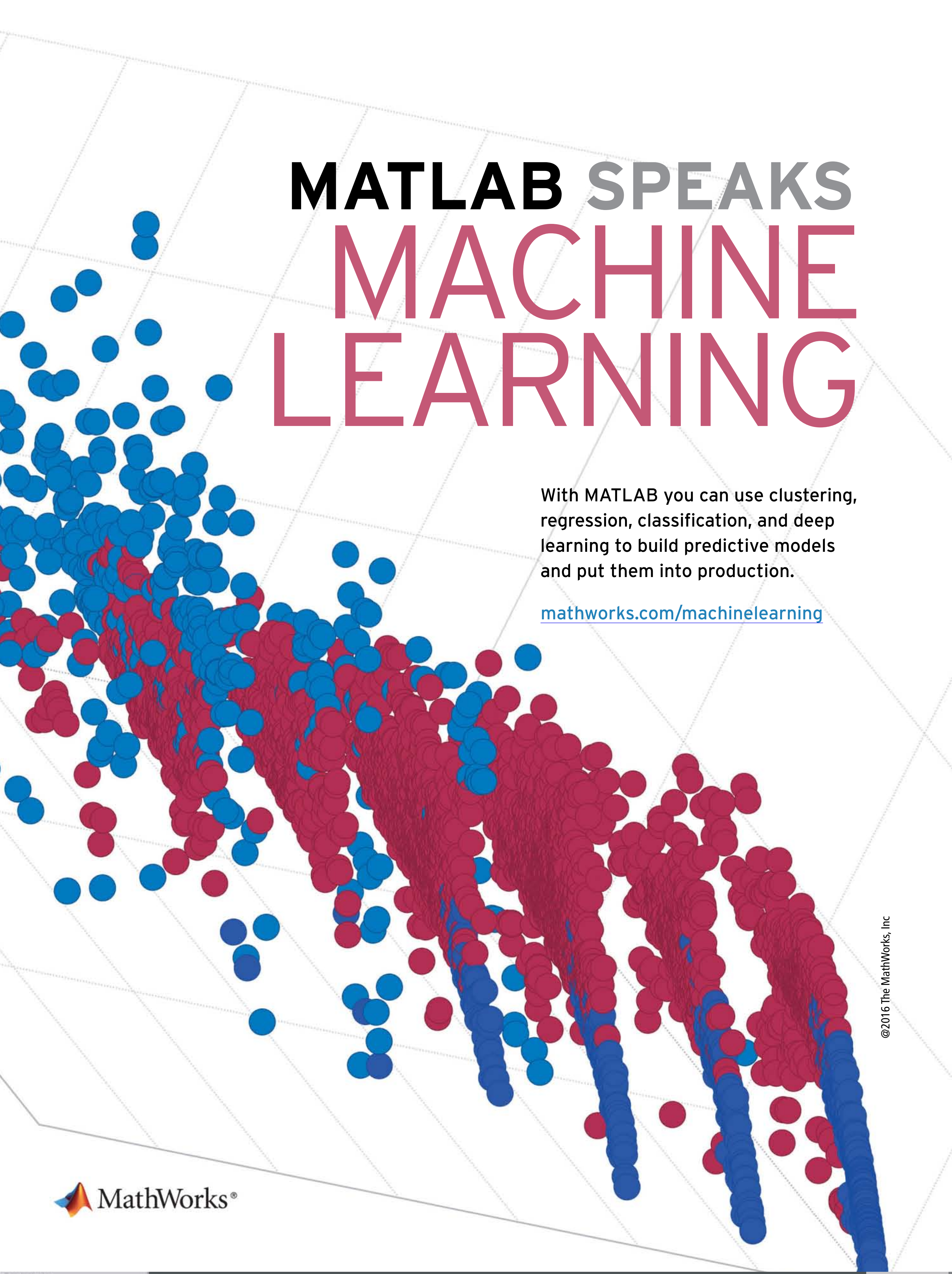
PAST FORWARD_BY DAVID C. BROCK

THE COIN-OP COMPUTER

In 1973, a group of computer enthusiasts called Loving Grace Cybernetics began setting up terminals like this one in Berkeley, Calif. Each terminal connected by modem to a remote computer that hosted an electronic bulletin board, which members of the public were invited to use as a "community memory." Reading the bulletin board was free, but posting a listing cost a quarter. Listings covered a range of practical matters: apartment rentals, music lessons, and where to find a decent bagel. ■

↗ FOR MORE ON THE COMPUTER MEMORY PROJECT, go to http://spectrum.ieee.org/pastforward0717

MARK RICHARDS/COMPUTER HISTORY MUSEUM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