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A new kind of brain-machine interface will revolutionize prosthetics P. 36

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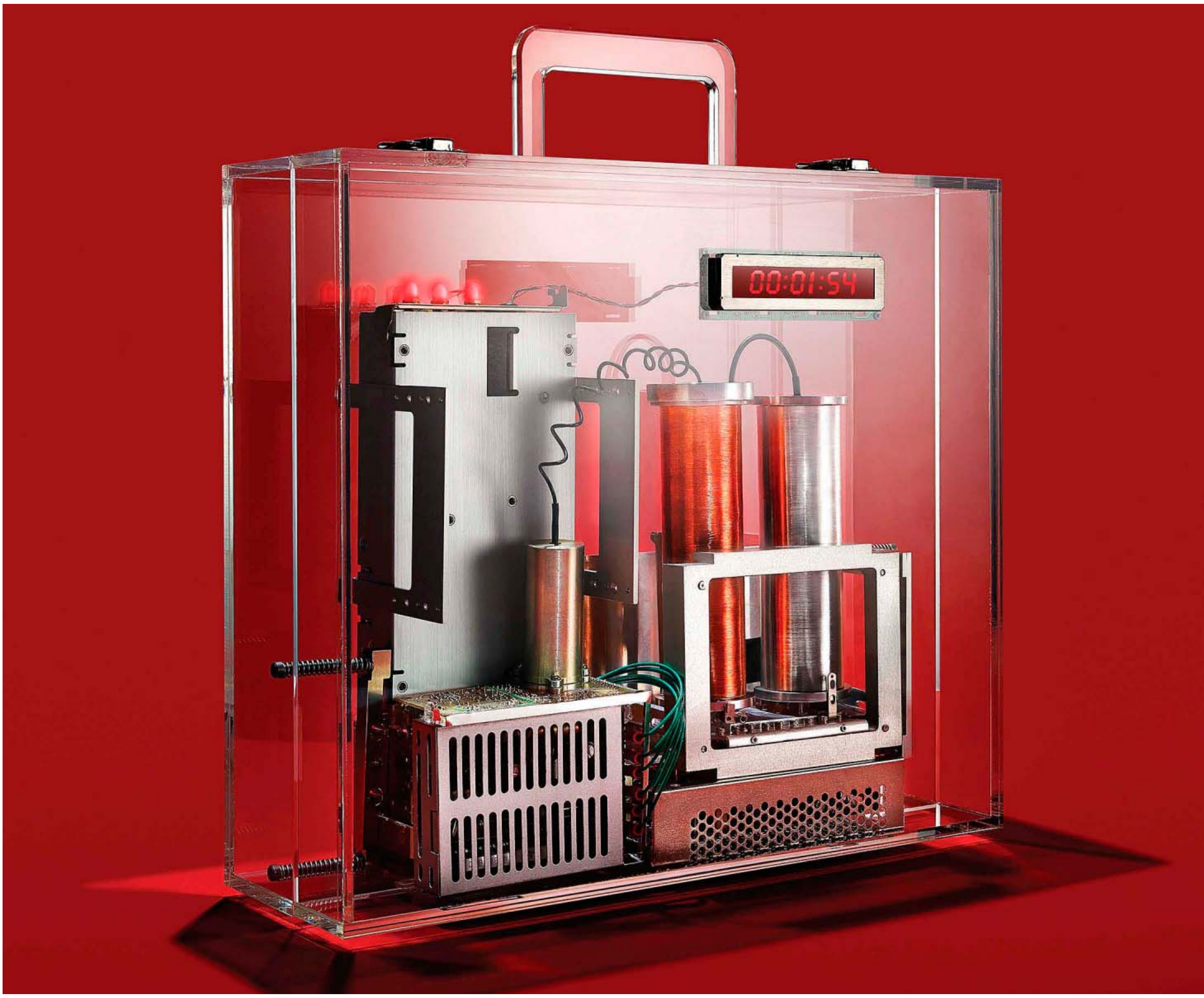

PROP STYLIST: BIRTE VON KAMPEN

On the Cover **Illustration for *IEEE Spectrum* by Guyco**

PHOTOGRAPH BY Dan Saelinger

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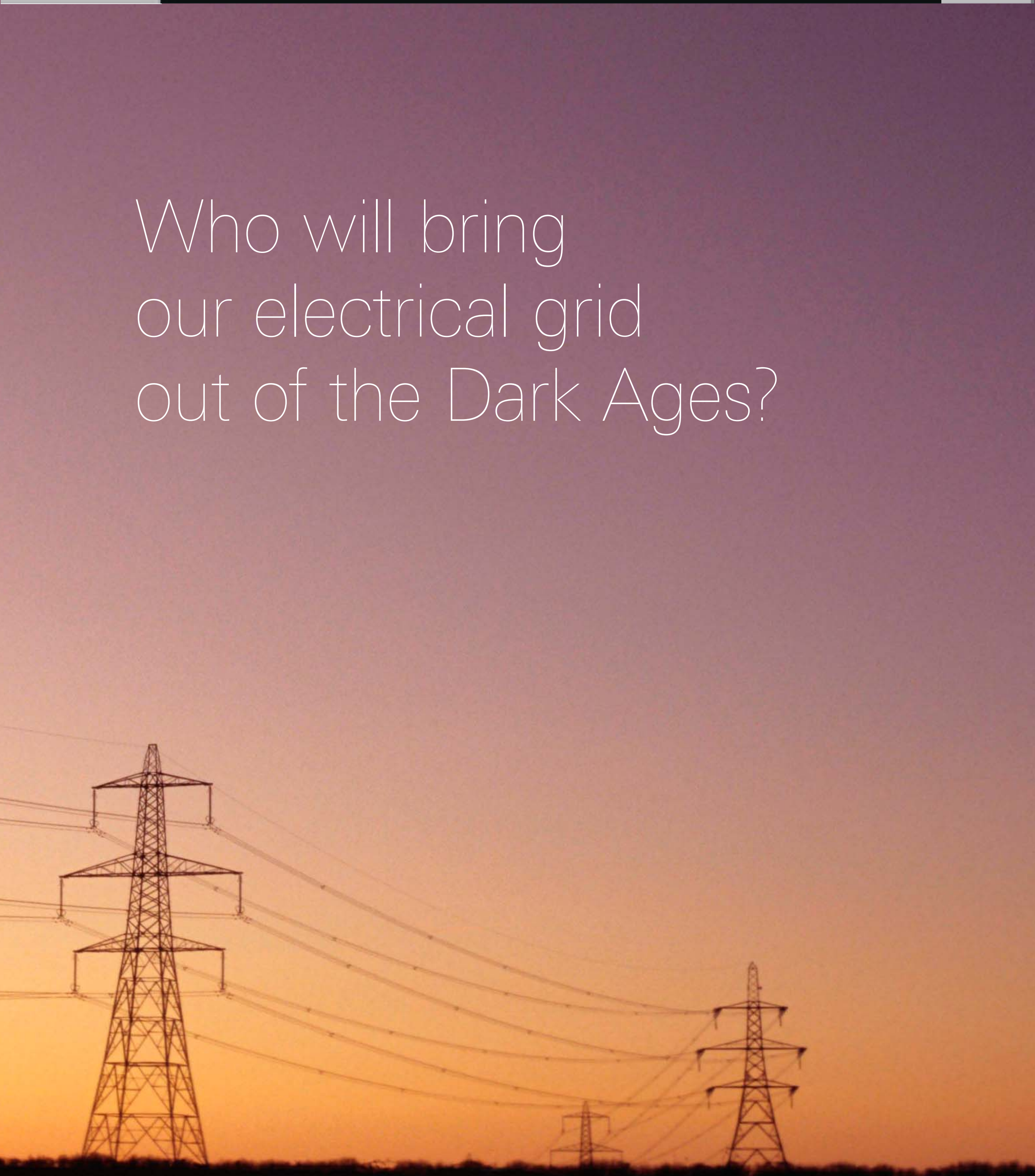

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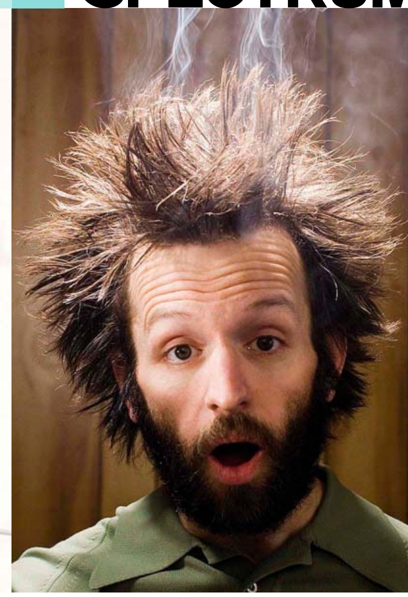

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FROM LEFT: BRAD RICKERBY/GETTY IMAGES; RANDI KLETT; MIKE KEMP/GETTY IMAGES

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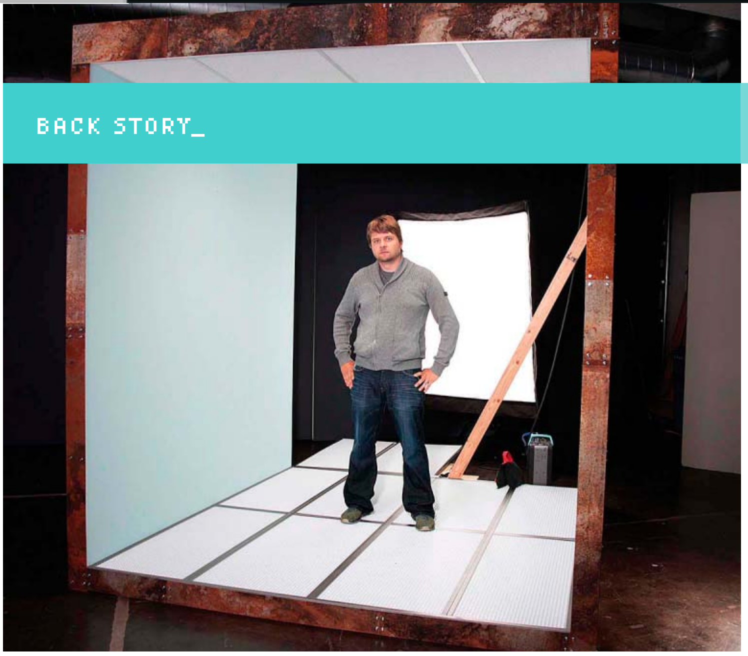

Is It Real, or Is It Photoshop?

NOWADAYS, A STRIKING IMAGE can provoke wonder–you wonder whether it was simply created in a computer. Take the opening illustration for the article “Fear of Frying,” in this issue, which explains how best to protect your computers from electromagnetic attack. It shows a bank of servers in a room clad in metal, to shield against a briefcase e-bomb pictured just outside the room.

That’s no shoe-box diorama. To make that image, photographer Dan Saelinger [above] and his assistants built a life-size set in his Portland, Ore., studio. It took three days to construct, using materials sourced by stylist Birte Von Kampen. And it was 3 meters high.

“I just felt it would have more authenticity,” Saelinger says.

Then came hours of shooting the room and the model, Paige Hendrix, followed by postproduction. All told, he and his troupe put in at least 120 person-hours of work to create that one image, Saelinger estimates.

“It was a lot about getting the lighting right,” he says. “We lit it from the back, to make it seem as if light is glowing through the room, and we had spotlights in front. Then we shot the model and the electromagnetic device, which the stylist built out of transparent plastic and a lot of electronic components.”

Only then, he says, did the digital fakery come in, beginning with a CGI rendering of a rack of servers and followed by hours of aligning light and shadow. “The goal is to make it look photographic,” says Saelinger, who is 35.

A day after the shoot, he had the room dismantled. “It’s torn down, then you move on to the next thing,” he says, wistfully.

What about the briefcase? Could we add it to *Spectrum*’s collection of curiosities? “Well, it’s built to last just for the shoot,” says Saelinger. “Put together with glue. Maybe too fragile to be shipped.” More wistfulness.

Fragile, yes, but a thing of beauty. And ready for a close-up, we suspect, if another of Saelinger’s shots needs an ominous-looking briefcase. ■

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PHOTOGRAPH BY **Josh Elliott**

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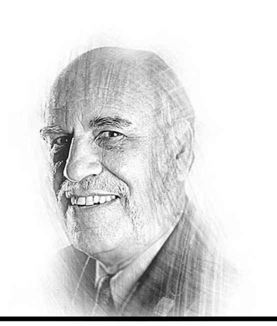
Dustin Mulvaney

Mulvaney is an assistant professor of environmental studies at San Jose State University, in California, where he studies the solar-energy, biofuel, and natural-gas industries. Although he identifies himself as both a solar advocate and a solar user—he has a photovoltaic array in his yard—his research has made him mindful of the significant health risks and environmental costs of manufacturing PV panels, which he writes about in "Solar's Green Dilemma" [p. 26].

Alfred Poor

A senior member of the Society for Information Display, Poor has written for *PC Magazine, PC World,* and *Bloomberg Businessweek*. This month he reports on the rise of quantum-dot-based displays at the annual Display Week conference [p. 22]. "It is the one display conference where you get to meet directly with the engineers and others who make the magic happen, and where you get to peek over the horizon to see what's coming," says Poor.



William A. Radasky

Radasky, an IEEE Life Fellow, has been interested in the risks from electromagnetic transients since 1968. At the time he was at the U.S. Air Force Weapons Laboratory, studying pulses from nuclear explosions. More recently, he says, when his lab at Metatech Corp. tested commercial electronics against EM weapon threats, "we were startled to find out that some chips melted and other components exploded." He writes about the growing threat of EM attacks in this issue [p. 42].

Theodore S. Rappaport

Rappaport is the founding director of New York University's wireless research center. With coauthors Wonil Roh and Kyungwhoon Cheun, vice presidents at Samsung Electronics, he is helping to realize future 5G networks. In "Mobile's Millimeter-Wave Makeover" [p. 30], the trio describes how recent breakthroughs could revolutionize cellular systems. "I haven't been this excited about cellular technology since I got my Ph.D. in 1987, when the industry was just getting started," Rappaport says.

Nitish V. Thakor

Thakor, director of the Laboratory for Neuro-engineering at Johns Hopkins University, in Baltimore, embraces the scientific challenge of mapping electrical activity in the human brain. But what gets him out of bed in the morning, he says, are the clinical problems. In this issue, he describes the brain-machine interfaces he's developing with colleagues at the Hopkins School of Medicine [p. 36], which may one day let paralyzed patients control robotic limbs with their brain waves.

09.14

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PHOTO-ILLUSTRATIONS BY **Gluekit**

AGING WELL: Senior Art Director Mark Montgomery [left], Digital Editorial Director Harry Goldstein [center], and Senior Interactive Editor Joshua J. Romero show how far the *IEEE Spectrum* website has come since its birth in 1996 [onscreen, left].

A Ride on the Not-So-Wayback Machine

Technologies change, people change, and so must the websites they create

WEBSITES ARE ABOUT THE CONTENT they feature, the technology they're built on, and the people who make them. And all three of those elements are always changing. If you take a ride in Brewster Kahle's Wayback Machine, as I did recently, you'll find six distinct *IEEE Spectrum* websites spanning 17 years. There were three radically different designs in the last 7 years alone.

It all started in 1996, with a lot of hand coding and head scratching. Richard Comerford, then a senior editor at *Spectrum*, and Craig Engler, electronic publishing editor, led the effort that created our first site by writing its code in HTML, line by line. A typical coding session would have Comerford or Engler at the keyboard and Mark Montgomery, now our senior art director, offering design guidance over their shoulders.

IEEE SPECTRUM 1964 / 2014

I took charge of the site a decade later, in 2007. I was not a newbie—I'd written for first-generation websites like Utne Lens and Tripod in the mid-1990s and I had crudely coded some HTML for a hypertext novel I put up on the Web around the same time—but I was basically thrown into the deep end of the pool. Fortunately, I had company: an intern named Joshua J. Romero, who would eventually become *Spectrum*'s first senior interactive editor.

The site we inherited was hard to read, difficult to navigate, and, in general, outdated. So we soon set about planning the one that would replace it. Like many publications, we were feeling our way into this burgeoning world of online journalism, and there were bumps, false starts, dead ends, and crashes. But it was a great opportunity to learn the nuances of website engineering.

After sketching out the basic structure of the site with the usability experts at Interface Guru, we assigned the task of building it to Agile Partners. Agile practices the iterative software development methodology known as *scrum* to prioritize and manage its programmers' daily tasks. I'd written about complex software projects, but I had not been involved in one myself, and I was quickly plunged into an intense routine of daily stand-up meetings and perpetual iteration. I would often have a phone pressed to each ear, with a project manager on one and the lead developer on the other. I'd be clarifying requirements for the content management system and the website's front end, which is what users see when they visit the site. After six months, the code was finished.

We'd taken the prototype for a few test drives, but there was no formal beta-test period. We were going to cut over from the old site to the new one and, at the same time, migrate the thousands of pages from the old site to the new one. It was, to put it mildly, a high-risk maneuver.

We started that migration on a Friday night at the end of May 2009 so everything would be live on Monday morning. Yes, there were pizza boxes and cans of Red Bull scattered around our office in New York City, and the 12-hour sessions staring at our screens left us all bleary-eyed. Lead developer Franqueli Mendez, a black-bearded giant, enveloped his laptop like a serenely calm, code-cranking Buddha. Josh and I sat next to each other, frantically tagging content from the old site with

Editor's note: In this 50th anniversary year of IEEE Spectrum, *we are using each month's Spectral Lines to recount some pivotal moments of the magazine's history. Here, Digital Editorial Director Harry Goldstein describes the origins and evolution of* Spectrum'*s website.*

PHOTOGRAPH BY Randi Klett

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our production team of Jacqueline Parker and Michael Spector at their cubes in Piscataway, N.J., and in the virtual trenches with us.

At the heart of a publication's website is a content management system (CMS), which we use to produce and track all the articles, videos, audio segments, still photographs, and other items that constitute the entire site. During that cutover weekend, our group became intimately acquainted with our new CMS, the four of us slotting old articles and blog entries into topical channels and loading visually exciting stories onto the home page. Meanwhile, Franqueli's fingers danced across the keyboard, fixing bugs on the fly.

When the site launched, we high-fived and hugged each other like we'd just won the World Cup. We took a few moments to appreciate the magnitude of the change. Visually, our site had been instantly transmogrified from a dull blue smudge that you had to squint to read to a (maybe too) vibrant green-and-orange frame for the best tech journalism on the planet. And then we got to work fixing the bugs Franqueli hadn't gotten to.

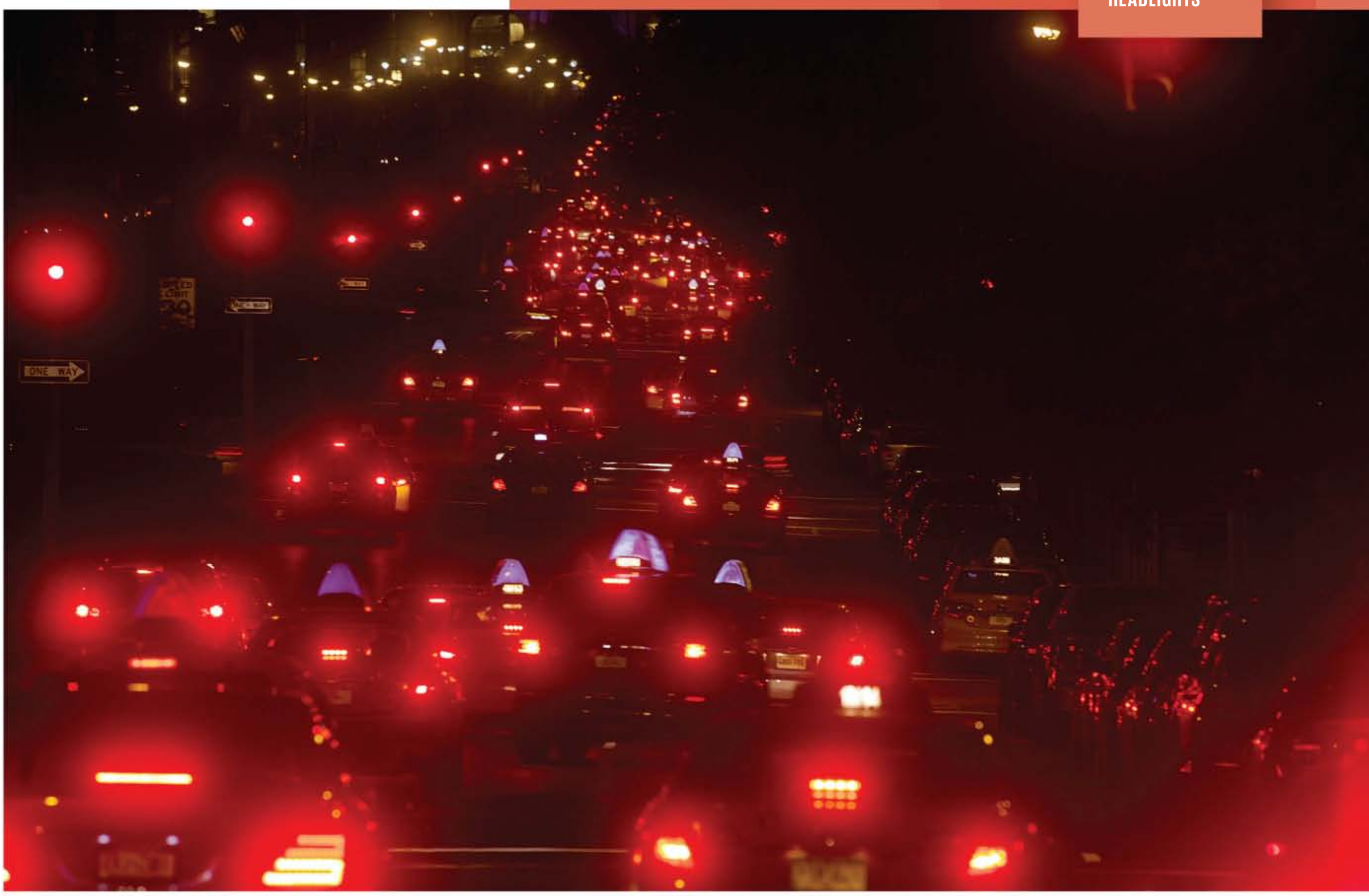
In comparison with the rough-and-tumble of that fifth-generation launch, the design and implementation last year of our sixth-gen site, the one you are probably viewing right now, was downright dull. Josh, Kenneth Liu (our lead developer), and I had learned much in the intervening four years. The site redesign had a clear goal: to provide a great experience for people viewing it on anything from a smartphone to an HDTV screen. Our scrum planning meetings were tightly structured, our requirements very clearly defined, our sprints more efficient. Testing happened in concert with development. Our design partners at Method delivered detailed, documented specs and front-end code. A five-month-long beta period gave us time to migrate all our existing content to the new formats and also to elicit user feedback that we incorporated before launch. When the site went live in May 2013, it did so with little fuss and no glitches.

Our site now has the flexibility to feature new kinds of content, such as the interactive Top Programming Languages app, and new blogs, such as Cars That Think and View From the Valley, which both debuted in May. And we're not done. Like organisms, the only websites that don't change are the dead ones. The Wayback Machine is littered with them. —HARRY GOLDSTEIN

HAND CODED: The 28 June 1996 *Spectrum* website was crafted by editors Richard Comerford and Craig Engler.

NEWS

2.1 g/km: REDUCTION IN CO_2 EMISSIONS BY USING LED HEADLIGHTS



IF TAILLIGHTS TALKED: All these cars could be communicating by modulating their LEDs.

BRAD RICKERBY/GETTY IMAGES

HIDDEN MESSAGES IN HEADLIGHTS

Signals transmitted by LEDs will help vehicles cooperate and avoid crashes

Drive on a city's streets at night and you're guided by artificial lights: glowing traffic signals beckoning you forward, the headlights of a car trailing you, a sign warning of work ahead.

Artificial lights may soon guide your car, too: In the quest for cars that understand the world around them and respond intelligently, a growing number of research engineers are exploring systems that encode signals in LED light.

"We envision car lights transmitting messages that your eyes can't see," says Richard Roberts, a research scientist at Intel. "They're blinking out messages to be used by other automobiles for safety reasons: positioning, collision avoidance, cooperative driving—maybe even someday for autonomous driving."

Roberts has been a part of this work since Intel started looking into visible light communication (VLC) in 2008, and he's seen it go from the "next Wi-Fi" to a research topic on hold—at least at Intel. While companies have tried using visible light to send extra information from a sign when scanned, as with a QR code, to pinpoint locations within a store, and even as a high-bandwidth Wi-Fi substitute—called Li-Fi—it just hasn't caught on in the mainstream. »

Now Roberts and other researchers think they've found its killer app: car-to-car communications.

VLC is based on the idea that while humans can't pick up on fast modulations in light, cameras can. Unlike Li-Fi, which uses special receivers, versions of VLC for cars rely on data rates low enough for ordinary cameras and would use the car's existing lights, making such a system inherently inexpensive. The lack of purpose-built equipment also distinguishes the effort from today's radio-frequency communication standard for vehicles.

"Adding more hardware onto a device is always an issue," says Roberts. "But cars are becoming full of cameras." In fact, the United States will require back-up cameras to be installed in new cars beginning in 2018. And many cars already have LED headlights that can be used for transmitting. "So we said, pragmatically, what can you do with that? It turns out you can do quite a bit."

Roberts and others are working on ways to communicate details about a vehicle's size, speed, and actions on the road so that the cars around it can calculate its exact location and be aware of its behavior. Such systems could warn of impending collisions, help judge whether lane changes are possible, and help coordinate cooperative adaptive cruise control, where the cars signal to one another so they can respond quickly to upcoming changes in traffic flow.

Hsin-Mu Tsai, a computer scientist at National Taiwan University, has been working on a prototype VLC device to increase the safety of the cheap motor scooters that are common on the streets of Taiwan. Apart from its affordability, Tsai says that one of VLC's greatest advantages is something that initially sounds like a problem: the fact that it works only over line of sight.

"Radio-frequency communication is usually omnidirectional," says Tsai, "and it covers a lot more than you need." Such signals can interfere with each other when it gets too crowded and can lead to confusion over where the signals are coming from. With VLC, the only transmissions your car picks up are the ones adjacent to it–the ones it needs to know about most for safety.

Another bonus is that a camera measures an entire scene, so it can receive several signals at once and distinguish among them. And the location information helps assign objects to signals, according to Tsai: "The beautiful thing about VLC, when we're using a camera as a receiver, is that the actual pixels are transmitting information to you."

Of course, cars are rarely cruising around in a perfectly clear and dark environment. In order for such a communication system to work, it has to withstand all the variations of weather and sunlight a driver could encounter.

"Due to the sunlight noise, the operation of VLC at daytime is the biggest challenge in vehicle-to-vehicle VLC development," says Sung-Yoon Jung, an assistant professor in the electronics engineering department at Yeungnam University, in South Korea. Jung has been modeling and testing VLC protocols to identify their flexibility and performance. Some protocols allow signals to be received from as far as 30 meters, even in daylight. And a 2013 study showed that VLC receivers are more sensitive than human eyes.

VLC's proponents say that their next mission is to get the technology incorporated into cars. Roberts and others are working now to develop a series of IEEE standards for the technology to coordinate communication efforts and help convince automakers to pick it up. If adapted widely enough, VLC could be incorporated into infrastructure such as traffic lights as well.

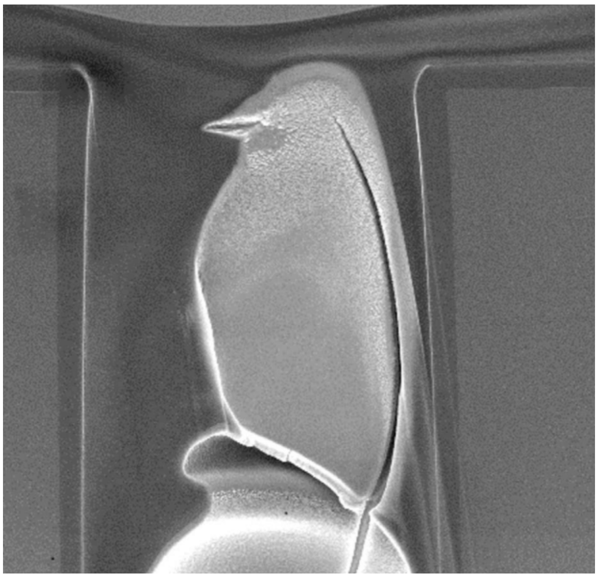
According to Tsai, about 10 percent of cars need to be transmitting for any vehicle-to-vehicle system to be effective, which would take around two years if every new car included the technology. But it's a saturation nobody has begun to reach–even the dedicated short-range RF standard for automobiles is not yet in use.

Sven Beiker, the executive director of Stanford's Center for Automotive Research, says it's clear that many technologies, including VLC, would work in car-to-car communications. "It does not seem to be a technology question," says Beiker. "It's this infrastructure, this standardization, and this monetary question. It's tough to find a business case for vehicle-to-vehicle communication." Beiker believes that business case might be to enable self-driving cars. The two technologies are complementary, he says. –SARAH LEWIN

BIRDIE IN THE HOLE

This little bird sits contentedly under the microscope's gaze, but it didn't fly there on its own. According to Lew Li Lian from GlobalFoundries, in Singapore, it formed from a stray particle that caused a hole in the chip's coating. The image won first prize at the 2014 IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA) Art of Failure Analysis contest.

For more startling images from the contest, see http://spectrum.ieee.org/the-art-of-failure-2014



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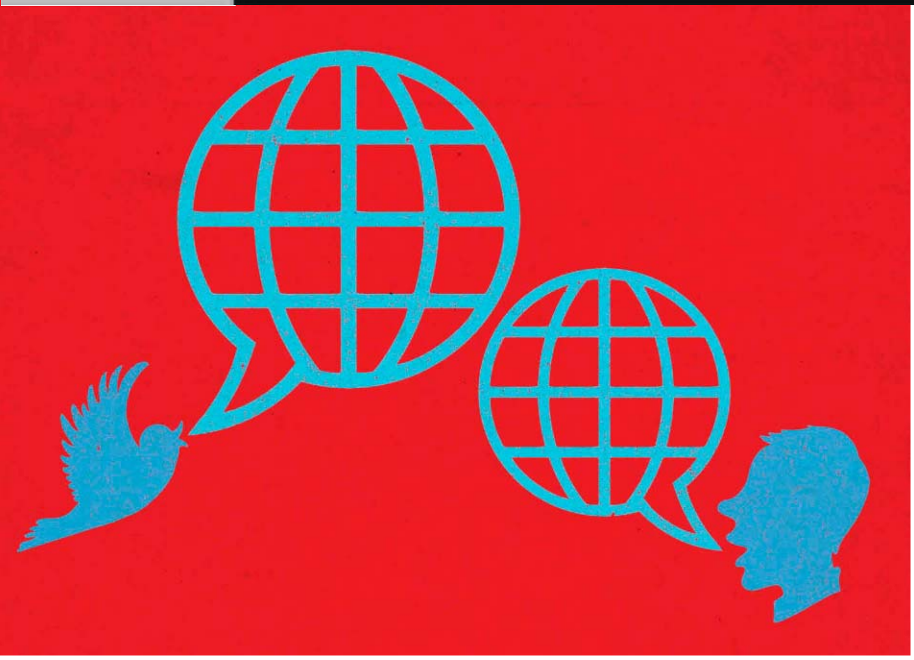

HOW SOCIAL MEDIA TEACHES SKYPE TO SPEAK

The quirky cant of Twitter and Facebook helped Microsoft build the tools for its real-time translator

Think you have trouble deciphering social media slang? Try translating it. Microsoft researchers have been studying how to translate social media, and in their efforts they came across a way to teach the company's upcoming Skype Translator how to speak more like us.

Some researchers think social media could be key to getting computers to better understand humans. Social media experiments are "important examples of a new line of research in computational social science, showing that subtle social meaning can be automatically extracted from speech and text in a complex natural task," says Dan Jurafsky, an expert in computational linguistics at Stanford, who recently led work on teaching computers about human interactions by listening to speed dating.

The Skype Translator app, set for beta release later this year, translates multilingual conversations over the service as they're happening. In May, Gurdeep Singh Pall, corporate vice president of Skype and Lync at Microsoft, and a German-speaking colleague demoed the app at the Code Conference, in Rancho Palos Verdes, Calif. As Pall spoke in English, both German and English subtitles scrolled along the bottom of the screen while real-time audio translation accompanied the subtitles.

The software system is a synthesis of several technologies, including speech recognition, machine translation, and speech synthesis. But Vikram Dendi, technical and strategy advisor at Microsoft Research, in Redmond, Wash., says past attempts to simply daisy-chain the technologies were unsuccessful because developers had failed to consider the drastic difference between the way we speak and the way we write.

For starters, real speech is peppered with vocalized "ums" and "ahs," awkward pauses, varying intonations, and vocal stresses, which are all absent in text. Consider what would happen if a speech translation system misinterpreted the subtle difference between these two statements:

"You're picking up the kids?"

And "You're picking up the kids!"

Suffice it to say, grumpy offspring would be the end product.

The gap exists between translating text and translating speech because some of the best machine translation systems today are taught using large volumes of high-quality text, which does not include the awkwardness that speech recognition systems deal with. So Microsoft Research set about searching for techniques to help close that gap. Among them was a software system the company developed to translate social media musings.

Before turning to social media, Microsoft's translation system extracted text from published books and Web sources that had been translated from one language to another. The data was then fed into a machine-learning pipeline that Microsoft calls phrasal statistical machine translation (phrasal SMT). The system chops up the text into a collection of small phrases called an *n*-gram, where *n* denotes the number of phrases. If the system is trying to translate, say, English to German, then the *n*-gram from a text in English is mapped to the *n*-gram of the equivalent text in German. This process teaches the computer what each phrase translates to.

Once it has learned its fill from the *n*-gram alignment, the software is ready to encounter new, untranslated text. When the machine is asked to translate a new phrase in English, the algorithm calculates the probability that the new English segment of text maps to one of the phrases it knows in German. The system then spits out the most probable translation.

Phrasal SMT excels at memorizing and matching data. For common phrases it can translate that exact phrase across several languages, and even if the words in the phrase are slightly reordered, it still works. But if the words in an uncommon phrase are reordered, the system gets confused. Some of the confusion arises because SMT doesn't really understand grammar and so can't shift from the rules of one language to those of another. For example, an English sentence usually runs subject, verb, object. But the same sentence in Japanese would be subject, object, verb.

This is why the Microsoft Research team pioneered a system known as syntactically

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ILLUSTRATION BY Dan Page

informed phrasal statistical machine translation (syntactic SMT). It builds on the phrasal SMT foundation but also understands syntax. Instead of just matching common phrases, syntactic SMT breaks up a phrase into individual words and then maps each word over to the other language.

Cutting up phrases and connecting individual words may sound like a primitive approach, but it's not. "That's pretty much the best method," says Chris Manning, professor of linguistics and computer science at Stanford. "Microsoft's machine translation team has been one of the prominent developers in this area, and basically, that is the state of the art in machine translation at the moment."

Syntactic SMT was a big step, but there was room for improvement, particularly in the fast-growing universe of social media. The Microsoft Research team began studying communications on Facebook, by Short Message Service (SMS), and on Twitter to figure out the best way to manage conversational text.

But that came with a new set of problems. Each social media platform has its own distinct characteristics–Facebook posts incorporate more emotional expressions, SMS users type shorter messages, and tweets are something in between. So researchers had to first develop a social media text normalization system, software that could automatically adapt to these variations in style to produce something that syntactic SMT can process. Adding the normalizer system to the translator's training protocol helped increase the accuracy of social-media text translation by 6 percent, according to Microsoft's Dendi. "That significantly improved the quality," he says. "Of course, there's still a lot of work to do, but when we did this, it really did move the needle on understanding and translating that type of data better." What's more, the techniques developed to improve social media translation are very similar to what was needed to bridge the gap between speech recognition and translation.

Skype Translator isn't the only speech translation system on the scene, though. According to Macduff Hughes, engineering director of Google Translate, many people use his company's software to test their own ability to speak a foreign language. He also says that in the past year, Google has added new features on its mobile apps that allow people to use Translate in more scenarios. But the system doesn't yet translate in real time and is not integrated into a video telephony application, which means multilingual speakers need to be in the same location and speak into the same app.

Google might be one of the only other companies with a shot at making a comparable system. Dendi says Microsoft's Skype work required deep knowledge of the company's Bing Web index to build the translation system, and a company would need similar assets to build another. "That's why there are only a few places in the world that can build a system of this kind and scale that can serve millions and millions of customers in this fashion across a range of scenarios," Dendi says. –THERESA CHONG

WORLD WAR I: THE WAR OF THE INVENTORS

World War I, which began 100 years ago, became known in certain circles as an "inventor's war." True, many of the inventions now associated with the conflict had actually been conceived earlier, but the pressures of war propelled them forward. The IEEE History Center's Robert Colburn identified sonar, the superheterodyne receiver, air-to-ground communications [above], and analog fire-control computers as some of the inventions that had the most lasting impact.

See the full story at http://spectrum.ieee.org/wwone0914

MAKING A HUMAN MEMORY CHIP

DARPA project could lead to implanted devices within four years

"They're trying to do 20 years of research in 4 years," says Michael Kahana in a tone that's a mixture of excitement and disbelief. Kahana, director of the Computational Memory Lab at the University of Pennsylvania, is mulling over the tall order from the U.S. Defense Advanced Research Projects Agency (DARPA). In the next four years, he and other researchers are charged with understanding the neuroscience of memory and then building a prosthetic memory device that's ready for implantation in a human brain.

DARPA's first contracts under its Restoring Active Memory (RAM) program challenge two research groups to construct implants for veterans with traumatic brain injuries that have impaired their memories. Over 270,000 U.S. military service members have suffered such injuries since 2000, according to DARPA, and there are no truly effective drug treatments. This program builds on an earlier DARPA initiative focused on building a memory prosthesis, under which a different group of researchers had dramatic success in improving recall in mice and monkeys.

Kahana's team will start by searching for biological markers of memory formation and retrieval. For this early research, the test subjects will be hospitalized epilepsy patients who have already had electrodes implanted to allow doctors to study their seizures. Kahana will record the electrical activity in these patients' brains while they take memory tests.

"The memory is like a search engine," Kahana says. "In the initial memory encoding, each event has to be tagged. Then in retrieval, you need to be able to search effectively using those tags." He hopes to find the electric signals associated with these two operations.

Once they've found the signals, researchers will try amplifying them using sophisticated neural stimulation devices. Here Kahana is working with

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REMEMBER THIS? Lawrence Livermore engineer Vanessa Tolosa holds up a silicon wafer containing micromachined implantable neural devices for use in experimental memory prostheses.

LAWRENCE LIVERMORE NATIONAL LABORATORY

the medical device maker Medtronic, in Minneapolis, which has already developed one experimental implant that can both record neural activity and stimulate the brain. Researchers have long wanted such a "closed-loop" device, as it can use real-time signals from the brain to define the stimulation parameters.

Kahana notes that designing such closed-loop systems poses a major engineering challenge. Recording natural neural activity is difficult when stimulation introduces new electrical signals, so the device must have special circuitry that allows it to quickly switch between the two functions. What's more, the recorded information must be interpreted with blistering speed so it can be translated into a stimulation command. "We need to take analyses that used to occupy a personal computer for several hours and boil them down to a 10-millisecond algorithm," he says.

In four years' time, Kahana hopes his team can show that such systems reliably improve memory in patients who are already undergoing brain surgery for epilepsy or Parkinson's. That will lay the groundwork for future experiments, he says, in which medical researchers can try out the hardware in people with traumatic brain injuries, who would not normally receive invasive neurosurgery.

The second research team is led by Itzhak Fried, director of the Cognitive Neurophysiology Laboratory at the University of California, Los Angeles. Fried's team will focus on a part of the brain called the entorhinal cortex, which is the gateway to the hippocampus, the primary brain region associated with memory formation and storage. "Our approach to the RAM program is homing in on this circuit, which is really the golden circuit of memory," Fried says. In a 2012 experiment, he showed that stimulating the entorhinal regions of patients while they were learning memory tasks improved their performance.

Fried's group is working with Lawrence Livermore National Laboratory, in California, to develop more closed-loop hardware. At Livermore's Center for Bioengineering, researchers are leveraging semiconductor manufacturing techniques to make tiny implantable systems. They first print microelectrodes on a polymer that sits atop a silicon wafer, then peel the polymer off and mold it into flexible cylinders about 1 millimeter in diameter. The memory prosthesis will have two of these cylindrical arrays, each studded with up to 64 hair-thin electrodes, which will be capable of both recording the activity of individual neurons and stimulating them. Fried believes his team's device will be ready for tryout in patients with traumatic brain injuries within the four-year span of the RAM program.

Outside observers say the program's goals are remarkably ambitious. Yet Steven Hyman, director of psychiatric research at the Broad Institute of MIT and Harvard, applauds its reach. "The kind of hardware that DARPA is interested in developing would be an extraordinary advance for the whole field," he says. Hyman says DARPA's funding for device development fills a gap in existing research. Pharmaceutical companies have found few new approaches to treating psychiatric and neurodegenerative disorders in recent years, he notes, and have therefore scaled back drug discovery efforts. "I think that approaches that involve devices and neuromodulation have greater near-term promise," he says.
—ELIZA STRICKLAND

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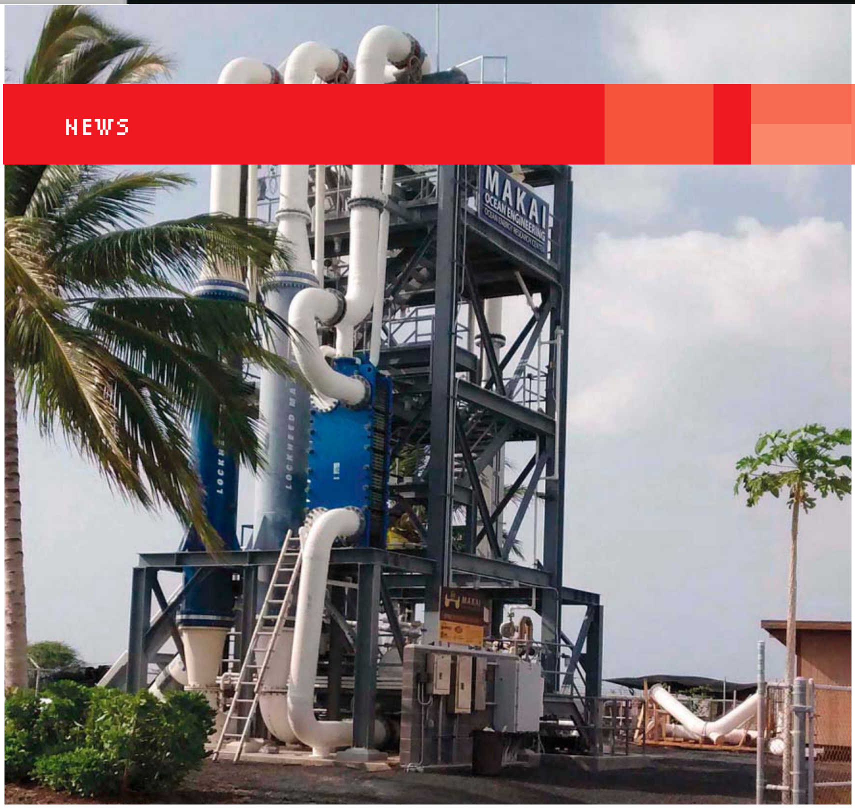

TOWER OF POWER: A system in Hawaii generates electricity by exploiting the temperature difference between the ocean's cold depths and warm surface.

OCEAN THERMAL ENERGY: BACK FROM THE DEEP

Makai Ocean Engineering preps a 100-kilowatt test facility on the Hawaiian coast, while others look offshore

This month, the Hawaii-based firm Makai Ocean Engineering will prepare to hoist a small turbine up a spare steel structure with a commanding view of the Pacific Ocean. There, with a flood of near-freezing water piped up from 1,000 meters below the surface, the company will put what will be the largest experimental ocean thermal energy plant through its paces.

Ocean thermal energy conversion, or OTEC, is an approach to energy generation that harnesses the temperature difference between surface and deep-sea waters. It's an energy dream that made inroads in the late 1970s and early 1980s, only to fizzle once oil prices fell. But there are some suggestions that it is again gaining momentum.

Among OTEC's attractions is that unlike other renewable energy sources, it should be capable of generating a steady stream of energy 24-7. "The utilities are excited about it because they don't have to worry about variability," says mechanical engineer Michael Eldred, who manages Makai's test facility. "But the reality is that it is quite expensive, and it is a technical challenge."

Makai's plant uses an approach common in OTEC research today. Warm ocean water is pulled from the surface and fed into a heat exchanger, where it vaporizes a low-boiling-point liquid such as ammonia. This vapor drives a turbine to create electricity. Cold ocean water, drawn from the deep, is then used to condense the ammonia back into liquid to complete the loop.

The finished facility, which will be only a bit higher in capacity than existing test plants in Japan and South Korea, is quite modest by energy production standards. The plant will be able to produce at most 100 kilowatts of power—enough, when operating continuously, to supply electricity to about 80 average American homes.

The plant and its pumps will consume most of the energy produced. But Makai's plant is geared toward research, Eldred notes, not energy generation. The facility was built primarily to design and test heat exchangers, which are among the most expensive components of an OTEC plant. With the addition of a turbine, Eldred says, Makai will be able to design an automatic control system and improve both performance and cost predictions for its commercial plant designs. The company also hopes to get a sense of how fluctuations in the temperature and pressure of ocean water will alter power output, a factor that might prove significant for wave-tossed offshore plants.

That's likely to be where OTEC energy production winds up. A 10-megawatt plant, such as one that Lockheed Martin aims to build for China's Reignwood Group, will require a cold-water pipe that is several meters wide. A plant floating in open water could send a pipe straight to the depth required instead of diagonally, down a long slope extending out from shore. That would make for a shorter and less expensive pipe, reduce the impact on the landscape, and cut down on the energy required to pump the cold water.

The first large-scale plant to make the leap could be New Energy for Martinique and Overseas (NEMO), says Luis Vega of the University of Hawaii's National Marine Renewable Energy Center. The project, which is a collaboration between renewable energy firm Akuo Energy and naval defense company DCNS, both based in Paris, plans to construct a 16-MW plant about 5 kilometers off the shore of the island of Martinique.

Construction is set to start next year, and the team aims to have the plant operational in four years. When complete, NEMO should be able to supply some 11 MW of energy to the Caribbean island.

NEMO will be the "first industrial-scale, turnkey" OTEC plant to go into operation, says Emmanuel Brochard, who leads the OTEC effort at DCNS. And it will get some help. In July, the European Commission awarded up to €72.1 million to help subsidize the first five years of the plant's operation. This is a vote of confidence in the technology, Brochard says. "OTEC is no longer R&D," he says. "It is a real, new source of renewable energy." —RACHEL COURTLAND

RACHEL COURTLAND

PHOTOGRAPH BY The Asahi Shimbun/Getty Images

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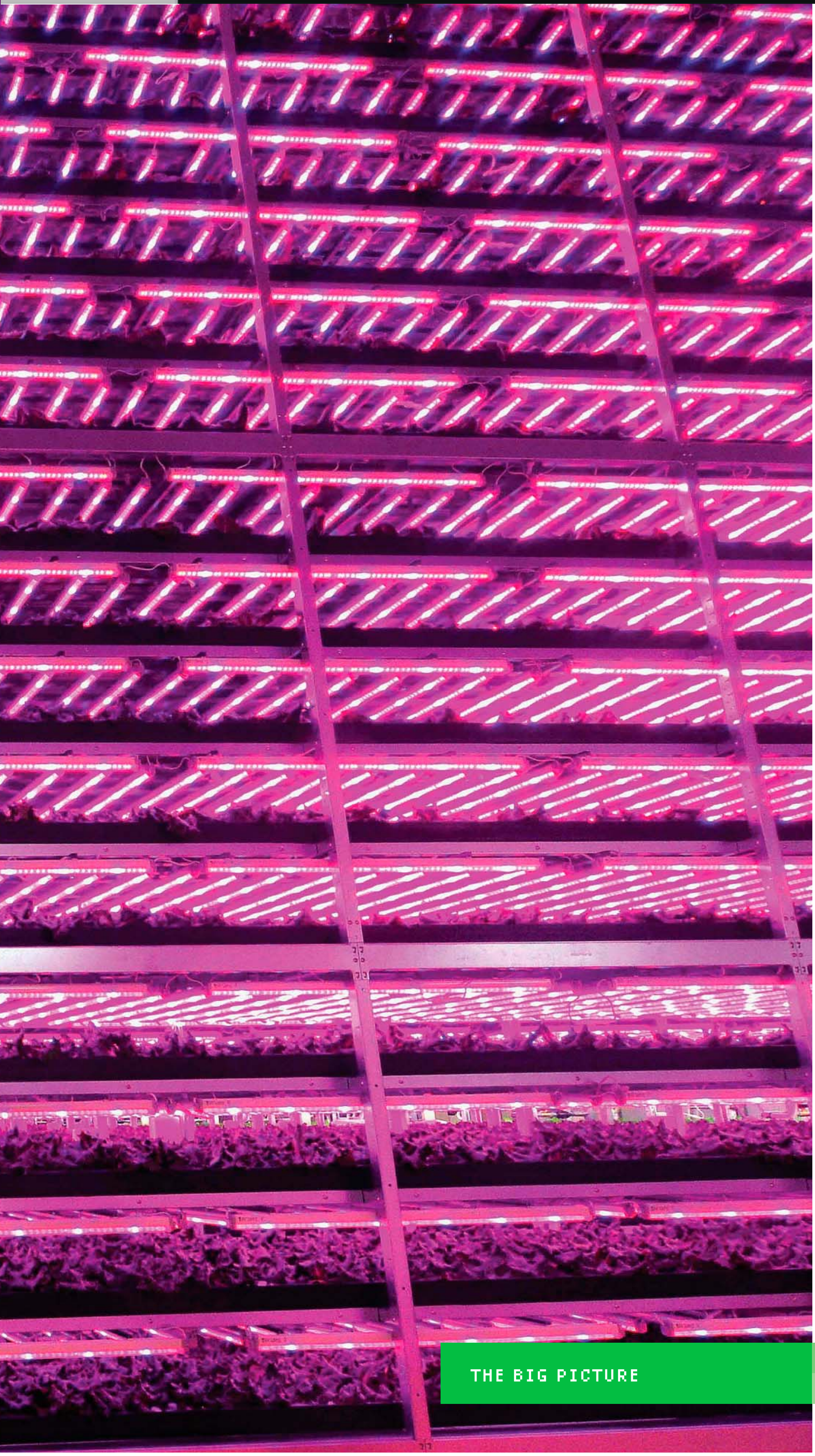

FARM IN A BOX

THE NEWEST wrinkle in industrialization doesn't involve computer chips or car parts but the manufacturing of... lettuce. In place of open fields of green, plant physiologist Shigeharu Shimamura has turned a former Sony Corp. semiconductor plant in Tagajo, Japan, into a roughly 2,300-square-meter indoor garden plot. The crop is grown under 17,500 specially made LED lights on racks that reach to the ceiling. Purple LEDs stand in for night, and white lights are adjusted over the course of the day to mimic the rising and setting of the sun. Shimamura's high-tech horticultural fab, which opened in July, can grow lettuce at more than twice the rate of outdoor farms. Meanwhile, control over the "weather" at the indoor facility lets the plants thrive on 1 percent of the amount of water that a typical farm uses.

THE BIG PICTURE NEWS

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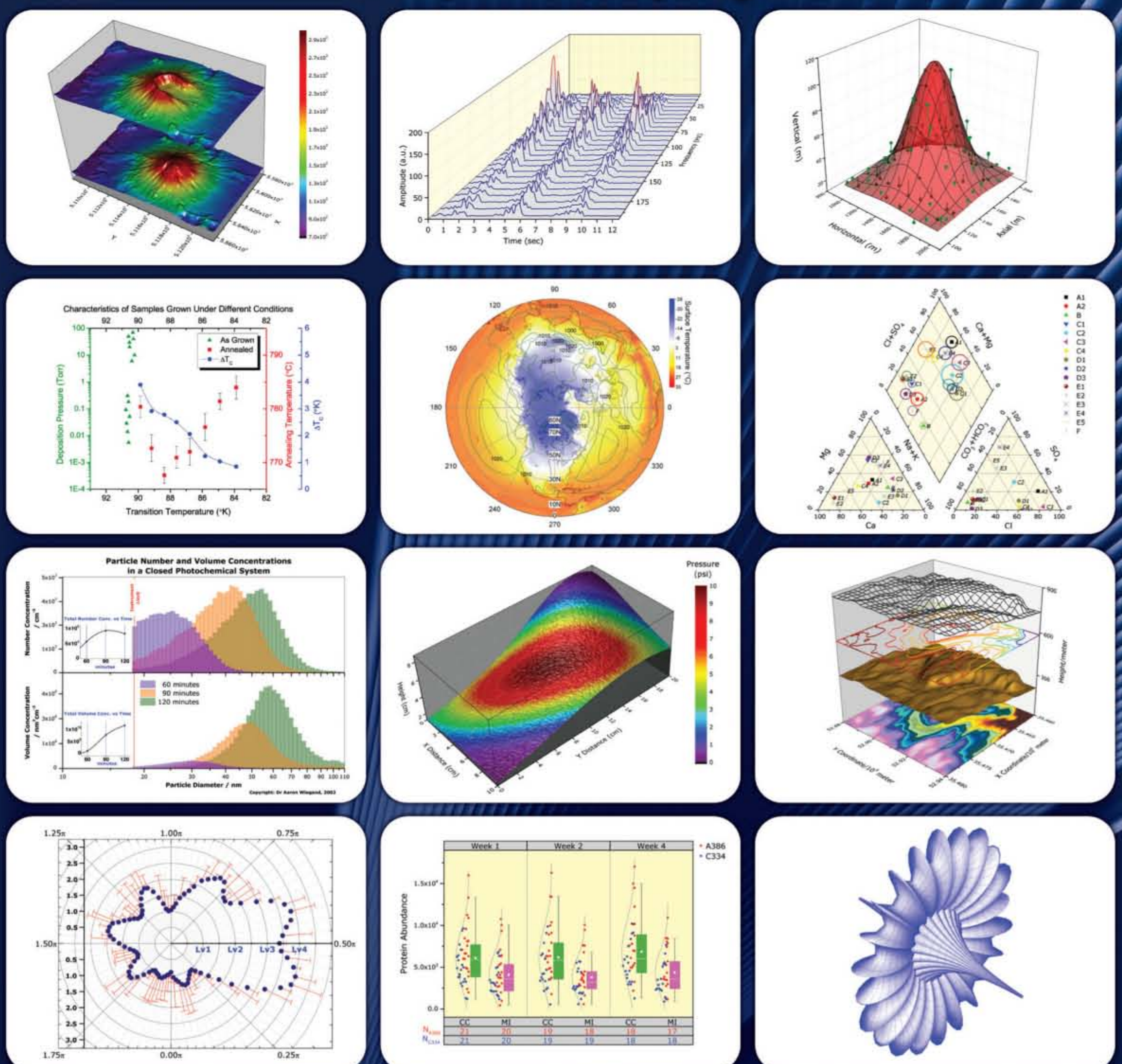

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RESOURCES

1878: THE YEAR THE FIRST QWERTY KEYBOARD APPEARED, FOLLOWING SEVERAL TRIAL DESIGNS

RESOURCES_HANDS ON

MUSCLE-MEMORY PROGRAMMER

THESE VIBRATING GLOVES TEACH FINGERS TO TOUCH-TYPE

RANDI KLETT

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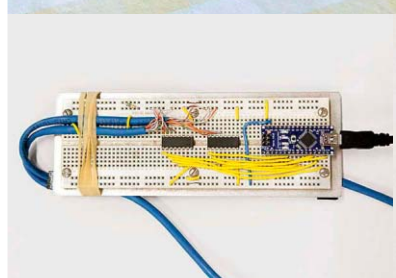


MOTOR CONTROL: Software running on a laptop computer [top] displays common English words. Depending on the letters in each word, the software sends codes corresponding to different fingers to an Arduino Nano [center, left], which activates vibration motors [center, right] sewn into a glove [bottom].

TOP AND BOTTOM: DAVID SCHNEIDER; MIDDLE: RANDI KLETT (2)

For *IEEE Spectrum*'s special issue this past June, my colleague Ariel Bleicher visited Tad Starner's lab at Georgia Tech and tried out an intriguing kind of wearable technology: a computerized glove equipped with five vibration motors, one perched atop each finger. Wearing the glove for a couple of hours while attending to other tasks, she acquired sufficient "muscle memory" to play 61 notes of Beethoven's "Ode to Joy" with hardly any effort.

Wow.

Of course, learning to play a more complicated piano melody would take more than just a couple of hours wearing such a glove. But her success immediately got me thinking about a problem I'd been grappling with: how to get my kids to learn to touch-type.

Even my youngest, an 11-year-old boy, is pretty quick on the keyboard. But his hands move all over the place, and he rarely uses his pinkie fingers. As I'm an accomplished touch typist, this irritates me, and I am forever hounding him to go back to what my eighth-grade typing teacher used to call the "home position" and use his eight fingers and two thumbs properly. Of course, my son just ignores my urgings.

Introducing a bit of technology, I thought, might be just the ticket to ensure cooperation. So while my wife was sewing eight diminutive vibration motors into the fingers of a pair of cycling gloves, I set about working on the hardware and software for a haptic typing tutor.

The first challenge was how to drive the 14-millimeter-diameter vibration motors I had purchased on eBay (US $13.85 for a set of 10, including shipping). I briefly considered using MOSFET transistors to drive the motors, but I decided to follow Starner's example instead based on the "if it ain't broke, don't fix it" principle: He used Darlington transistor arrays for this purpose. So I used two ULN2003s, one for the four motors on each hand. These chips handle the job without fuss: Each 14-pin IC contains seven Darlington transistor pairs along with diodes to protect against voltage spikes when you switch off inductive loads such as motors. It was a simple matter to wire the inputs to these arrays to an Arduino Nano plugged into a prototyping board and connect the outputs to each glove with short lengths of Cat 5 cable.

Admittedly, the result wasn't nearly as slick as Starner's fully wearable setup. But my kids would be seated at the computer anyway, so a short leash running from each glove to the prototyping board holding the Nano isn't a practical impediment.

I programmed the Arduino to activate a given motor for a quarter of a second corresponding to each character I sent to the microcontroller's serial port—a "1" would vibrate the motor pressing on the left pinkie, a "2" for the left ring finger, a "3" for the left middle finger, and so forth. That was dead simple. The tougher job was to write a program that would run on a laptop computer so that my kids would associate the stimulation of their fingers with the correct sequence of keystrokes you make when touch-typing a word.

For that, I used Tkinter, which provides an easy way to create a graphical user interface with Python, my favorite computer language

RESOURCES_START-UPS

at the moment. It's not as pleasant for composing a GUI as using Visual Studio, but it proved simple enough and perfectly adequate for the task at hand.

The program I cobbled together presents the user with a word, chosen at random from a list of the 100 most common English words. It then says the word out loud (in my ever-patient wife's mellifluous voice) and shows the word spelled out on the screen in blaring 64-point red type, one letter at a time. As it does so, it sends the appropriate character to the Arduino so that the corresponding finger is vibrated. There's a slider for the user to vary the rate at which the program spews out letters. And the person can see what he or she is typing (again in 64 point), which gives instant feedback. A button allows you to advance to another word. Python and Tkinter made all this easy enough to program with less than 200 lines of code.

Far more difficult was convincing my son to practice with the new gizmo. He would do it for a while, and he reported that spending a few minutes getting his fingers vibrated indeed helped him to get the sequence of keystrokes right. But he was more inclined to play with the slider, trying to challenge himself to keep up with rapid-fire bursts of letters. Clearly, I had missed a critical concept in modern pedagogy: gamification.

I've not yet figured out the particulars, but somehow I'll have to add motivational timers, badges, health points, and bright, flashing "game over" blinkers if I want my 11-year-old to benefit from my high-tech typing tutor. Or there's always the ethically dubious B.F. Skinner haptic typing tutor, I suppose. But I'm not sure an Arduino can put out 1,200 volts. —DAVID SCHNEIDER

PROFILE: PRISTINE
BRINGING GOOGLE GLASS TO THE HOSPITAL

CINDY YAMANAKA/THE ORANGE COUNTY REGISTER/CORBIS

HEAD'S UP, DOC: Pristine's software lets surgeons stream video to students while wearing Google Glass headsets in the operating room.

The phrase "the doctor will see you now" may soon mean something new. Pristine, a start-up out of Austin, Texas, has developed a telemedicine app for Google Glass that will let hospital staff send real-time audio and video to specialists, wherever they may be.

Pristine cofounder Kyle Samani was working for a health-care IT company in early 2013 when Google announced the launch of Glass, which packs many of the functions of a smartphone into a sleek head-mounted device. He immediately saw Glass's potential for hospitals. "A hands-free computer in health care makes a lot of sense," Samani says. Doctors wouldn't have to worry about picking up bacteria by handling a tablet or typing on a keyboard, he says, and they could interact with their patients without turning away to enter data. "As soon as Google announced Glass, I started working on this," Samani says.

Samani and his cofounder, Patrick Kolencherry, got their hands on one of the early units that Google doled out to selected "explorers" for US $1,500 apiece. Then they set out to harness Glass's capabilities—but also to strip it of functions that jeopardized patient privacy. Pristine's modified Glass headset can't store audio or video, but instead streams them live through encrypted channels to a remote server, allowing a medical specialist to view them using any computer. The founders also took away e-mail, phone, and text capabilities to make sure patient information couldn't be sent to people outside the system.

According to Tony Danova, a BI Intelligence analyst who authored a report on Glass's sales potential, Pristine is one of many companies trying to bring Glass into the workplace. While Google's first concept video for Glass suggested that it would be a consumer device that people would use in their every-day lives, so far it's actually enterprise apps that are showing the most promise, Danova says. "From a consumer standpoint, Glass still seems a little obtrusive and conspicuous," he says.

In October 2013 Pristine signed up UC Irvine Medical Center as its first pilot customer. In operating rooms, Glass-wearing surgeons tried using Pristine's EyeSight app to stream a first-person video to doctors in training. The app itself worked well, Samani says, but the immaturity of Google's Glass hardware and software posed problems. "[Glass] is definitely still a beta product," he says. "We didn't realize how buggy it would be when we started." Samani's team also had to improve Wi-Fi coverage at the hospital to ensure smooth functioning.

Pristine began generating revenue in February 2014 when Rhode Island Hospital, in Providence, adopted its system for a tryout in the emergency room. Paul Porter, director of special projects and telemedicine at Brown University and manager of the tryout, says he is eager to use Glass to facilitate consultations with specialists. "We're not looking to apply this tech everywhere," he says. "We're looking to put that crucial person in the room at the crucial time." In the hospital's first trial, ER patients with dermatology complaints will have the option of being examined by Glass-wearing doctors, who will transmit everything they see to an off-site dermatologist.

If the system proves useful, Porter can imagine using it for much more critical areas of care, such as emergency treatment of stroke patients: Stroke medications are most effective if given immediately, and doctors lose valuable time in the ER as patients are registered and drugs are prepared. If the paramedics in the ambulance are wearing Glass and can start the intake while still on the road, they can save time and possibly lives. "I think this will be the standard of care," Porter says. "I think we're going to change emergency medicine." —ELIZA STRICKLAND

Company: Pristine **Founded:** May 2013
Headquarters: Austin, Texas
Founders: Patrick Kolencherry and Kyle Samani
Funding: Undisclosed **Employees:** 9
Website: http://pristine.io

WILL QUANTUM DOTS DOMINATE DISPLAYS?

THE TECH PROMISES SHARPER COLOR AT LOWER POWER

RUMPELSTILTSKIN HAD THE ADMIRABLE ABILITY TO CONVERT low-cost straw into valuable gold. Today, display manufacturers are starting to reap the benefits of their own photonic alchemy, converting the light from cheap sources into the precise wavelengths needed for more efficient displays that can show sharper colors.

This magic is accomplished using what are known as quantum dots. These are semiconductor nanocrystals that exhibit a range of unusual electrical and optical properties, but for decades they were largely confined to research laboratories. Now, quantum dots are being used in mass-produced displays for the consumer market, including such items as Sony flat-screen televisions and Amazon.com's Kindle Fire HDX e-reader. And the field is still rapidly growing and evolving. At the Display Week 2014 conference of the Society for Information Display this past June in San Diego, quantum dots were a hot topic, both in the exhibit hall and in presented papers; the symposium schedule included three separate sessions dedicated to the subject.

Quantum dots have many interesting properties, but when it comes to displays the most important thing about them is that they can absorb light of short (blue) wavelengths and then emit it as light of longer (red and green) wavelengths. This might sound a lot like traditional phosphor materials, which made the cathode ray tube (CRT) possible by converting a beam of electrons into visible colors. The difference is that quantum dots produce much more precise emissions. A good phosphor has an emission range of about 50 nanometers, while a typical quantum dot's range is about half that. Just where on the spectrum that range is can be carefully controlled by varying the size of the particles; the larger the particle, the longer the wavelength of the emissions will be. The peak emissions of the quantum dot can be tuned to within 1 nm. This gives excellent control over the color output of the display.

And conveniently, while quantum dots can emit a very narrow range of wavelengths, the light source they are converting from can have a broader range and the light will still be converted with an efficiency of more than 95 percent. All this helps make quantum dots much less wasteful than traditional backlight approaches, where a lot of light is lost in a color-filter layer that screens out undesirable wavelengths. With more of the light getting to the viewer, the result is a display that is brighter without upping power consumption.

DOTTY DISPLAYS: The Kindle Fire HDX is one of the first consumer devices to use displays with quantum dots.

Color reproduction has become an increasingly important topic in the display industry. For years, CRT quality was considered "good enough," even though the typical CRT display was able to show only about 70 to 75 percent of the gamut of colors specified in the National Television System Committee (NTSC) color standard.

Advances in color displays—first with LCDs and more recently with OLEDs—have made it possible to exceed the boundaries of the NTSC standard. Consequently, expanded color-gamut standards have come into play, the most recent of which is ITU-R Recommendation BT.2020, created by the International Telecommunication Union to measure the color space used by next-generation ultrahigh-definition (UHD) televisions. Some prototype quantum-dot-based displays can already reproduce 95 percent of the color gamut specified by Rec. 2020.

Two companies have taken the lead in commercializing quantum-dot technology. QD Vision is the company behind Sony's Triluminus technology, and Nanosys has partnered with 3M Co. to create Quantum Dot Enhancement Film (QDEF), a light-processing film.

The QD Vision approach adds quantum dots to strips of blue LED edge lights around an LCD panel. Some of this light is converted to red and green, which is mixed by a light guide to create a high-quality white backlight for the LCD panel's color subpixels. The Nanosys/3M approach places the QDEF film over the back of the panel, and then a blue LED backlight is applied (typically through edge lighting and a light guide). Some of the blue light is converted in the film layer to red and green light before reaching a subpixel.

A new, third, approach is being developed by a number of researchers. This involves putting the quantum dots directly on the blue LED chip. This can simplify the optical and light-management requirements, but it subjects the quantum-dot material to higher operating temperatures that can decrease performance.

As you might expect, a technology that simultaneously increases color performance and power efficiency is attracting a lot of commercial interest. New products continue to appear; at Display Week, Asus announced the Zenbook NX500, the first high-gamut 4K-resolution notebook computer, which uses 3M's QDEF quantum-dot film.

QUANTUM COLORS: A Nanosys technician works with batches of materials infused with quantum dots of different sizes, resulting in the emission of different colors.

Market research firm IHS projects that the market for displays that incorporate quantum dots will grow from about US $10 million in 2013 to $200 million by 2020. And according to Touch Display Research, the quantum-dot materials market is projected to grow from $70 million in 2013 to $9.6 billion in 2023.

One problem with quantum dots is that they require cadmium, which is on the European Union's Restriction of Hazardous Substances (RoHS) regulation list. However, researchers are working on creating cadmium-free quantum dots. Dow Electronic Materials has licensed technology from Nanoco Group to produce such materials; commercial production is slated to start this year.

In any case, it appears that quantum dots will play an important role in the new UHD television market, while helping LCD panels compete more effectively with OLEDs for a broader range of devices. The end result will be that you'll see colors on the screen that until now you've seen only in real life.
—ALFRED POOR

TOP: AMAZON; BOTTOM: 3M

REFLECTIONS_BY ROBERT W. LUCKY

OPINION

ON REFLECTIONS

After 190 columns, it seems there's still something to say

I'VE WRITTEN A BIMONTHLY REFLECTIONS COLUMN FOR *IEEE Spectrum* since January 1982. Every eight weeks I've faced a blank computer screen as a deadline approached and had little or no idea what I could write about. I thought that after the first dozen or so columns I would use up all the topics worthy of essays, but it seems that there have always been emerging subjects as well as evergreen ones. These columns have accompanied *Spectrum* through much of the half-century of publication that we celebrate this year. Looking back on this collection, I've tried to see how the columns have evolved and what this says about how engineers and engineering have changed. • In the early years I wrote columns about the joys in engineering, about the difficulties in sharing engineering work with friends and family, and how confessing to being an engineer stopped conversation at social gatherings. I was fascinated with how nonengineer friends claimed they could pick engineers out of a crowd of strangers by looks alone. I remembered being picked up by a limo driver at the airport. When I asked how he knew who I was, he gruffly replied, "I can always tell an engineer." I did not consider it a compliment. • I wrote about the engineering life: giving presentations, writing reports, the foibles of management, and the little daily frustrations of unsolved problems. There were columns on the emergence of integrated circuits, computers, and the Internet, but the one that produced the most reader feedback was entitled "Goodbye, Heathkit." This was a nostalgic memory for many engineers, and the passing of the DIY electronics company Heathkit represented a watershed in technology. Integrated circuits had changed everything. They enabled and encouraged ever greater complexity and could be fabricated only in hugely expensive facilities. Electronics was becoming a business for teams of professionals.

In 1987 my essay "The Footsteps of Giants" appeared, in which I wondered if my contemporaries would ever become as famous as the inventors and pioneers who had preceded us. The number of engineers throughout the world was growing, the problems were becoming more difficult, and credit for discoveries was becoming more diffuse. Looking back on this column now, I realize that a number of my contemporaries did indeed become famous, but more for starting technology companies than for inventions per se.

In more recent years I have written more about the technology itself, and some of my old columns about how the world saw engineers now seem quaint. I think that society at large has come to identify with engineers much more. We are the designers of personal computers, cellphones, flat-screen televisions, and other coveted gadgets. Bill Gates and Steve Jobs are idolized, and even Facebook's Mark Zuckerberg got a movie. Of course, none of them were trained as engineers, but they have come to epitomize the public perception of who engineers are and what they do. We are surrounded by technology, and we engineers are its keepers.

While the social aspects of engineering life have slowly receded from my columns, the technology has constantly presented ever more ideas. There are always areas opening up that offer new challenges. There may not be any singular invention as immediately significant as the transistor or laser, but the potential that we now have in software, computing, and networking seems unlimited.

In some of those early columns I wrote about my reticence to answer that ubiquitous question at social gatherings, "What do *you* do?" Now, the hesitation is gone. I am proud to reply that I am an electrical engineer, and I think that I can discern a flicker of respect for that answer. But it seems as if people still don't want to hear more about what I actually *do*. They probably think that I design iPhones, and that's fine with me. ■

ILLUSTRATION BY David Johnson

IMAGINECHINA/CORBIS

Solar's Green Dilemma

Must cheaper photovoltaics come with a higher environmental price tag? BY DUSTIN MULVANEY

SOLAR PANELS GLIMMERING IN THE SUN are an icon of all that is green. But while generating electricity through photovoltaics is indeed better for the environment than burning fossil fuels, several incidents have linked the manufacture of these shining symbols of environmental virtue to a trail of chemical pollution. And it turns out that the time it takes to compensate for the energy used and the greenhouse gases emitted in photovoltaic panel production varies substantially by technology and geography.

That's the bad news. The good news is that the industry could readily eliminate many of the damaging side effects that do exist. Indeed, pressure for it to do so is mounting, in part because, since 2008, photovoltaics manufacturing has moved from Europe, Japan, and the United States to China, Malaysia, the Philippines, and Taiwan; today nearly half the world's photovoltaics are manufactured in China. As a result, although the overall track record for the industry is good, the countries that produce the most photovoltaics today typically do the worst job of protecting the environment and their workers.

To understand exactly what the problems are, and how they might be addressed, it's helpful to know a little something about how photovoltaic panels are made. While solar energy can be generated using a variety of technologies, the vast majority of solar cells today start as quartz, the most common form of silica (silicon dioxide), which is refined into elemental silicon. There's the first problem: The quartz is extracted from mines, putting the miners at risk of one of civilization's oldest occupational hazards, the lung disease silicosis.

The initial refining turns quartz into metallurgical-grade silicon, a substance used mostly to harden steel and other metals. That happens in giant furnaces, and keeping them hot takes a lot of energy, a subject we'll return to later. Fortunately, the levels of the resulting emissions—mostly carbon dioxide and sulfur dioxide—can't do much harm to the people working at silicon refineries or to the immediate environment.

The next step, however—turning metallurgical-grade silicon into a purer form called polysilicon—creates the very toxic compound silicon tetrachloride. The refinement process involves combining hydrochloric acid with metallurgical-grade silicon to turn it into what are called trichlorosilanes. The trichlorosilanes then react with added hydrogen, producing polysilicon along with liquid silicon tetrachloride—three or four tons of silicon tetrachloride for every ton of polysilicon.

Most manufacturers recycle this waste to make more polysilicon. Capturing silicon from silicon tetrachloride requires less energy than obtaining it from raw silica, so recycling this waste can save manufacturers money. But the reprocessing equipment can cost tens of millions

POLICY

ON THE LINE: A factory worker in China inspects crystalline silicon photovoltaic cells.

of dollars. So some operations have just thrown away the by-product. If exposed to water–and that's hard to prevent if it's casually dumped–the silicon tetrachloride releases hydrochloric acid, acidifying the soil and emitting harmful fumes.

When the photovoltaics industry was smaller, the solar-cell manufacturers got their silicon from chipmakers, which rejected wafers that did not meet the computer industry's purity requirements. But the boom in photovoltaics demanded more than semiconductor-industry leftovers, and many new polysilicon refineries were built in China. Few countries at the time had stringent rules covering the storage and disposal of silicon tetrachloride waste, and China was no exception, as some *Washington Post* reporters discovered.

The paper's investigation, published in March 2008, profiled a Chinese polysilicon facility owned by Luoyang Zhonggui High-Technology Co., located near the Yellow River in the country's Henan province. This facility supplied polysilicon to Suntech Power Holdings, at the time the world's largest solar-cell manufacturer, as well as to several other high-profile photovoltaics companies.

The reporters found that the company was dumping silicon tetrachloride waste on neighboring fields instead of investing in equipment that could reprocess it, rendering those fields useless for growing crops and inflaming the eyes and throats of nearby residents. And the article suggested that the company was not alone in this practice.

After the publication of the *Washington Post* story, solar companies' stock prices fell. Investors feared the revelations would undermine an industry that relies so much on its green credentials. After all, that's what attracts most customers and draws public support for policies that foster the adoption of solar energy, such as the Residential Renewable Energy Tax Credit in the United States. Those who purchase residential solar systems can subtract 30 percent of the cost from their tax bills until the incentive expires in 2016.

To protect the industry's reputation, the manufacturers of photovoltaic panels began to inquire about the environmental practices of their polysilicon suppliers. Consequently, the situation is now improving. In 2011 China set standards requiring that companies recycle at least 98.5 percent of their silicon tetrachloride waste. These standards are easy to meet so long as factories install the proper equipment. Yet it remains to be seen how well the rules are being enforced.

This problem could completely go away in the future. Researchers at the National Renewable Energy Laboratory in Golden, Colo., are looking for ways to make polysilicon with ethanol instead of chlorine-based chemicals, thereby avoiding the creation of silicon tetrachloride altogether.

The struggle to keep photovoltaics green does not end with the production of polysilicon. Solar-cell manufacturers purify chunks of polysilicon to form bricklike ingots and then slice the ingots into wafers. Then they introduce impurities into the silicon wafers, creating the essential solar-cell architecture that produces the photovoltaic effect.

These steps all involve hazardous chemicals. For example, manufacturers rely on hydrofluoric acid to clean the wafers, remove damage that comes from sawing, and texture the surface to better collect light. Hydrofluoric acid works great for all these things, but when it touches an unprotected person, this highly corrosive liquid can destroy tissue and decalcify bones. So handling hydrofluoric acid requires extreme care, and it must be disposed of properly.

But accidents do happen and are more likely in places that have limited experience manufacturing semiconductors or that have lax environmental regulations. In August 2011, a factory in China's Zhejiang province owned by Jinko Solar Holding Co., one of the largest photovoltaic companies in the world, spilled hydrofluoric acid into the nearby Mujiaqiao River, killing hundreds of fish. And farmers working adjacent lands, who used the contaminated water to clean their animals, accidently killed dozens of pigs.

In investigating the dead pigs, Chinese authorities found levels of hydrofluoric acid in the river 10 times the permitted limit, and they presumably took these measurements long after much of the hydrofluoric acid had washed downstream. Hundreds of local residents, upset over the incident, stormed and temporarily occupied the manufacturing facility. Again, investors reacted: When major media outlets carried the news the next day, Jinko's stock price dropped by more than 40 percent, translating to nearly US $100 million in lost value.

This threat to the environment needn't continue. Researchers at Rohm & Haas Electronic Materials, a subsidiary of Dow Chemical, have identified substitutes for the hydrofluoric acid used in solar-cell manufacture. One good candidate is sodium hydroxide (NaOH). Although NaOH is itself a caustic chemical, it is easier to treat and dispose of than hydrofluoric acid and is less risky for workers. It is also easier to treat wastewater containing NaOH.

ACID DRAIN: Wastewater exits a plant operated by Jinko Solar Holding Co. In 2011, hydrofluoric acid used by the company for solar-panel manufacturing contaminated river water, killing hundreds of fish and dozens of pigs.

Although more than 90 percent of photovoltaic panels made today start with polysilicon, there is a newer approach: thin-film solar-cell technology. The thin-film varieties will likely grow in market share over the next decade, because they can be just as efficient as silicon-based solar cells and yet cheaper to manufacture, as they use less energy and material.

IMAGINECHINA/AP PHOTO

Makers of thin-film cells deposit layers of semiconductor material directly on a substrate of glass, metal, or plastic instead of slicing wafers from a silicon ingot. This produces less waste and completely avoids the complicated melting, drawing, and slicing used to make traditional cells. In essence, a piece of glass goes in at one end of the factory and a fully functional photovoltaic module emerges from the other.

Moving to thin-film solar cells eliminates many of the environmental and safety hazards from manufacturing, because there's no need for certain problematic chemicals–no hydrofluoric acid, no hydrochloric acid. But that does not mean you can automatically stamp a thin-film solar cell as green.

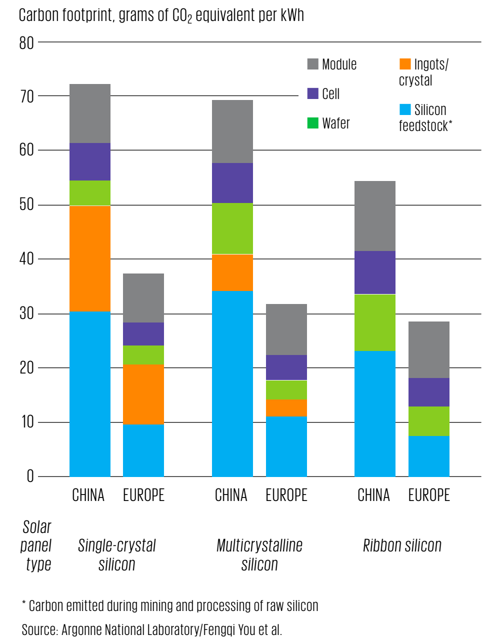
Today's dominant thin-film technologies are cadmium telluride and a more recent competitor, copper indium gallium selenide (CIGS). In the former, one semiconductor layer is made of cadmium telluride; the second is cadmium sulfide. In the latter, the primary semiconductor material is CIGS, but the second layer is typically cadmium sulfide. So each of these technologies uses compounds containing the heavy metal cadmium, which is both a carcinogen and a genotoxin, meaning that it can cause inheritable mutations.

Manufacturers like First Solar, based in Tempe, Ariz., have a strong record of protecting workers from cadmium exposures during manufacture. But there is little information about exposures to workers involved with cadmium at earlier stages in the life cycle of the metal, from the zinc mines where much of cadmium originates through the smelting process that purifies cadmium and turns it into semiconductor materials. Exposures after solar panels are discarded are also a concern. Most of the cadmium telluride that manufacturers dispose of due to damage or manufacturing defects is recycled under safe, controlled conditions. On the postconsumer end of the equation, the industry proactively set up a solar-panel collection and recycling scheme in Europe. Individual companies have also established recycling programs, such as First Solar's prefunded take-back system. But more needs to be done; not every consumer has access to a free take-back program, and indeed many consumers may not even be aware of the need to dispose of panels responsibly.

The best way to avoid exposing workers and the environment to toxic cadmium is to minimize the amount used or to use no cadmium at all. Already, two major CIGS-photovoltaic manufacturers–Avancis and Solar Frontier–are using zinc sulfide, a relatively benign material, instead of cadmium sulfide. And researchers from the University of Bristol and the University of Bath, in England; the University of California, Berkeley; and many other academic and government laboratories are trying to develop thin-film photovoltaics that do not require toxic elements like cadmium or rare elements like tellurium. First Solar has meanwhile been steadily reducing the amount of cadmium used in its solar cells.

Toxicity isn't the only concern. Making solar cells requires a lot of energy. Fortunately, because these cells generate electricity, they pay back the original investment of energy; most do so after just two years of operation, and some companies report payback times as short as six months. This "energy payback" time is not the same as the time needed to recoup a consumers financial investment in solar panels; it measures investments and payback times in terms of kilowatt-hours, not in terms of money.

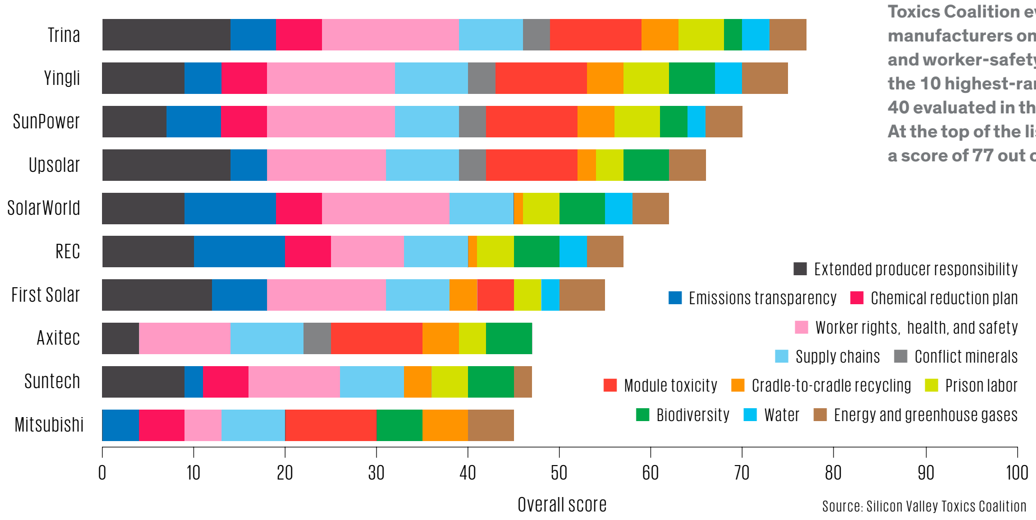
Analysts also judge the impact of the energy used to make a solar panel by the amount of carbon generated in the production of that energy–a number that can vary widely. To do this, we give the energy a carbon-intensity value, usually represented as kilograms of CO_2 emitted per kilowatt-hour generated. Places that depend largely on coal have the most carbon-intense electricity in the world: Chinese electricity is a good example, having roughly twice the carbon intensity of U.S. electricity. This fits with the results of researchers in Illinois at Argonne National Laboratory and Northwestern University. In a report published this past June, they found that the carbon footprint of photovoltaic panels made in China is indeed about double that of those manufactured in Europe.



CARBON IN CREATION: Solar-panel manufacturers need electricity and thermal energy, and carbon emissions from their generation can vary widely with location. Panels produced in China, which relies heavily on coal for power, have a larger carbon footprint than those produced in Europe.

If the photovoltaic panels made in China were installed in China, the high carbon intensity of the energy used and that of the energy saved would cancel each other out, and the time needed to counterbalance greenhouse-gas emissions during manufacture would be the same as the energy-payback time. But that's not what's been happening lately. The manufacturing is mostly located in China, and the panels are often installed in Europe or the United States. At double the carbon intensity, it takes twice as long to compensate for the greenhouse-gas emissions as it does to pay back the energy investments.

Of course, if you manufacture photovoltaic panels with low-carbon electricity (for example, in a solar-powered factory) and install them in a high-carbon-intensity country, the greenhouse-gas-payback time



THE SOLAR SCORECARD: The Silicon Valley Toxics Coalition evaluates solar-panel manufacturers on a range of environmental and worker-safety criteria. Shown here are the 10 highest-ranked companies out of 40 evaluated in the coalition's 2013 scorecard. At the top of the list is China's Trina Solar, with a score of 77 out of 100 possible points.

will be lower than the energy-payback time. So perhaps someday, powering photovoltaic-panel manufacturing with wind, solar, and geothermal energy will end concerns about the carbon footprint of photovoltaics.

Water is yet another issue. Photovoltaic manufacturers use a lot of it for various purposes, including cooling, chemical processing, and air-pollution control. The biggest water waster, though, is cleaning during installation and use. Utility-scale projects in the 230- to 550-megawatt range can require up to 1.5 billion liters of water for dust control during construction and another 26 million liters annually for panel washing during operation. However, the amount of water used to produce, install, and operate photovoltaic panels is significantly lower than that needed to cool thermoelectric fossil- and fissile-power plants.

The choices investors and consumers make could, in principle, have a big influence on photovoltaic manufacturers' practices. But it's often tough to tell how these companies differ in the care they take to protect the environment. The solar industry has no formal ecolabel, like the Energy Star labels on household appliances and consumer electronics that help U.S. buyers identify energy-efficient products. And most people do not go out and purchase solar panels themselves. They hire third-party installers. So even if there were an ecolabeling scheme, it would depend on installers' willingness to choose ecofriendly products.

For now, consumers can help push manufacturers to improve their environmental and safety records by asking installers about the companies making the products they use. This, in turn, would prompt installers to ask the manufacturers for more information.

Researchers at the National Photovoltaics Environmental Research Center at Brookhaven National Laboratory in Upton, N.Y., have long been publishing studies about the possible environmental hazards of photovoltaics. Recently, formal environmental performance ratings for the solar industry have started to emerge.

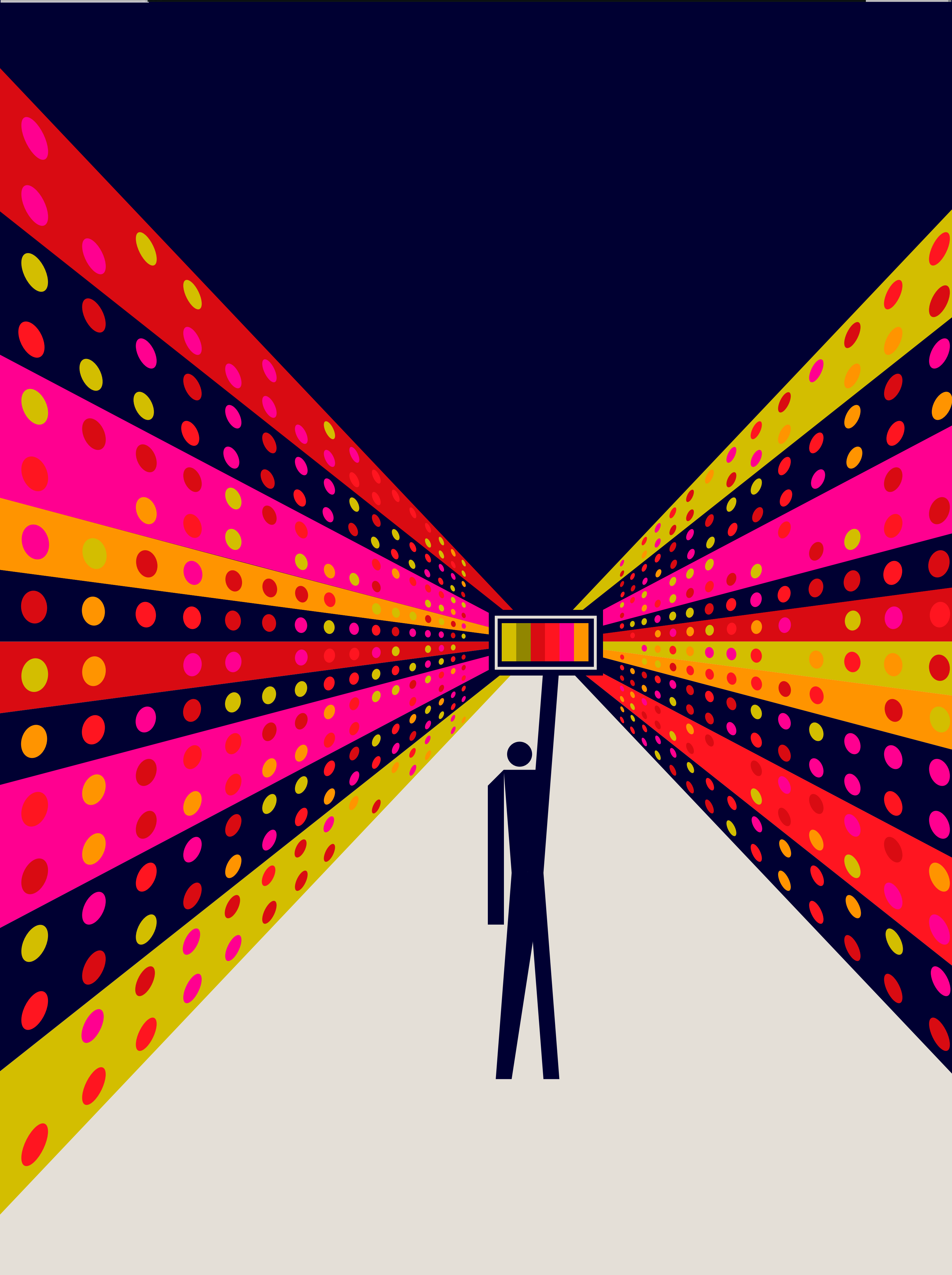
Organizations such as the Center for International Earth Science Information Network are trying to establish some means of determining the environmental, health, and safety performance of manufacturers in developing countries. This group, which includes researchers from Yale and Columbia, is proposing the China Environmental Performance Index, which would operate at the provincial level to help China track progress toward environmental-policy goals.

Meanwhile, the Solar Energy Industries Association, a U.S. national trade organization, has proposed new industry guidelines in a document called the "Solar Industry Environment & Social Responsibility Commitment," aimed at preventing occupational injury and illness, preventing pollution, and reducing the natural resources used in production. The document urges companies to ask suppliers to report on manufacturing practices and any chemical and greenhouse-gas emissions.

In addition, the Silicon Valley Toxics Coalition, which rates the environmental performance of electronics companies, has surveyed and ranked photovoltaic manufacturing companies based or operating in China, Germany, Malaysia, the Philippines, and the United States. Participation is voluntary and so far includes such major manufacturers as First Solar, SolarWorld, SunPower, Suntech, Trina, and Yingli; Chinese manufacturers Trina and Yingli have consistently ranked among the world's top three most environmentally responsible companies. And Sharp, SolarWorld, and SunPower have been carefully tracking the greenhouse gases emitted and chemicals used in the manufacture of their solar panels for several years.

Such initiatives are coming none too soon. Many people today view photovoltaics as a panacea for our energy woes, given how dirty most of the alternatives are. But that does not mean we should turn a blind eye to the darker side of this technology. Indeed, we need to consider it very carefully. And just maybe, with a sustained effort by consumers, manufacturers, and researchers, the photovoltaics industry will one day be truly, not just symbolically, green. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/solar0914



MOBILE'S MILLIMETER-WAVE MAKEOVER

Wireless engineers long considered high frequencies worthless for cellular systems. They couldn't be more wrong

By Theodore S. Rappaport, Wonil Roh & Kyungwhoon Cheun

ILLUSTRATION BY Greg Mably

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People in real estate joke that there are only three things that matter in the business of buying and selling property: location, location, location. The same could be said for radio spectrum. The frequencies used for cellular communications have acquired the status of waterfront lots—highly coveted and woefully scarce. And like beach-home buyers in a bidding war, mobile operators must constantly jockey for these prime parcels, sometimes shelling out as much as tens of billions of dollars for just a small sliver of the electromagnetic pie.

That's because the cellular industry, throughout its four-decade existence, has relied exclusively on a strip of spectrum known as the ultrahigh frequency band, which comprises only about 1 percent of all regulated spectrum. Wireless engineers have long considered this frequency range—between 300 megahertz and 3 gigahertz—to be the "sweet spot" for mobile networking. Wavelengths here are short enough to allow for small antennas that can fit in handsets but still long enough to bend around or penetrate obstacles, such as buildings and foliage. Transmitted even at low power, these waves can travel reliably for up to several kilometers in just about any radio environment—be it in the heart of Tokyo or the farmlands of Iowa.

The trouble is, no matter how much operators are willing to pay for this spectrum, they can no longer get enough of it. The use of smartphones and tablets is soaring, and as people browse the Web, stream videos, and share photos on the go, they are moving more data over the airwaves than ever before. Mobile traffic worldwide is about doubling each year, according to reports from Cisco and Ericsson, and that exponential growth will likely continue for the foreseeable future. By 2020, the average mobile user could be downloading a whopping 1 terabyte of data annually—enough to access more than 1,000 feature-length films.

Wireless standards groups have devised all sorts of clever fixes to expand the capacity of today's fourth-generation (4G) LTE cellular networks, including ones involving multiple antennas, smaller cells, and smarter coordination between devices. But none of these solutions will sustain the oncoming traffic surge for more than the next four to six years. Industry experts agree that fifth-generation (5G) cellular technology will need to arrive by the end of this decade. And to roll out these new networks, operators will undoubtedly need new spectrum. But where to find it?

Fortunately, it just so happens that there's an enormous expanse above 3 GHz that, until now, has been largely overlooked. We're talking about the millimeter waves.

By the ITU definition, the millimeter-wave band, also called the extremely high frequency band, spans from 30 to 300 GHz. In our use of the term, however, we also include most of the neighboring superhigh frequencies, from about 10 to 30 GHz, because these waves propagate similarly to millimeter waves. We estimate that government regulators could make as much as 100 GHz of this spectrum available for mobile communications—more than 100 times as much bandwidth as cellular networks access today. By tapping it, operators could offer hundreds of times the data capacity of 4G LTE systems, enabling download rates of up to tens of gigabits per second while keeping consumer prices relatively low.

If you think that scenario sounds too good to be true, you've got plenty of company. In fact, until very recently, most wireless experts would have said just as much. Historically, operators rejected millimeter-wave spectrum because the necessary radio components were expensive and because they believed those frequencies would propagate poorly between traditional towers and handsets. They also worried that millimeter waves would be excessively absorbed or scattered by the atmosphere, rain, and vegetation and wouldn't penetrate indoors.

But those beliefs are now rapidly fading. Recent research is convincing the cellular industry to take a second look at this vast and underutilized spectrum.

> By 2020, the average mobile user could be downloading **1 terabyte of data annually—** enough to access more than 1,000 feature films

Although new to mobile communications, millimeter-wave technology has a surprisingly long and storied history. In 1895, a year before Italian radio pioneer Guglielmo Marconi awed the public with his wireless telegraph, an Indian polymath named Jagadish Chandra Bose showed off the world's first millimeter-wave signaling apparatus in Kolkata's town hall. Using a spark-gap trans-

ILLUSTRATION BY Greg Mably

mitter, he reportedly sent a 60-GHz signal through three walls and the body of the region's lieutenant governor to a funnel-shaped horn antenna and detector 23 meters away. As proof of its journey, the message triggered a simple contraption that rang a bell, fired a gun, and exploded a small mine.

More than half a century passed, however, before Bose's inventions left the laboratory. Soldiers and radio astronomers were the first to use these millimeter-wave components, which they adapted for radar and radio telescopes. Automobile makers followed suit several decades later, tapping millimeter-wave frequencies for cruise control and collision-warning systems.

The telecommunications community initially took notice of this new spectrum frontier during the dot-com boom of the late 1990s. Cash-flush start-ups figured that the abundant bandwidth still up for grabs in some millimeter-wave bands would be ideal for local broadband networks, such as those in homes and businesses, and for delivering "last-mile" Internet services to places where laying cable was too difficult or too expensive. With great fanfare, government regulators around the world, including ones in Europe, South Korea, Canada, and the United States, set aside or auctioned off huge allotments of millimeter-wave spectrum for these purposes.

But consumer products were slow to come. Companies quickly realized that millimeter-wave RF circuits and antenna systems were quite expensive. The semiconductor industry simply didn't have the technical capability or market demand to manufacture commercial-grade devices fast enough to operate at millimeter-wave frequencies. So for nearly two decades, this enormous swath of bandwidth lay all but vacant.

That, however, is changing. Thanks in part to Moore's Law and the growing popularity of automatic parking and other radar-based luxuries in cars, it's now possible to package an entire millimeter-wave radio on a single CMOS or silicon-germanium chip. So millimeter-wave products are finally hitting the mass market. Many high-end smartphones, televisions, and gaming laptops, for example, now include wireless chip sets based on two competing millimeter-wave standards: Wireless High Definition (WirelessHD) and Wireless Gigabit (WiGig).

These technologies aren't meant for communication between, say, a smartphone and a cell tower. Rather, they're used to transfer large amounts of data, such as uncompressed video, short distances between machines without cumbersome Ethernet or HDMI cables. Both WirelessHD and WiGig systems operate at around 60 GHz in a frequency band typically about 5 to 7 GHz wide–give or take a couple of gigahertz depending on the country. Such bandwidths contain magnitudes more spectrum than even the fastest Wi-Fi network can access, enabling rates up to about 7 gigabits per second.

Equipment makers for cellular networks are likewise beginning to take advantage of the ultrawide bands available in millimeter-wave spectrum. Several suppliers, including Ericsson, Huawei, Nokia, and the start-up BridgeWave, in Santa Clara, Calif., are now using millimeter waves to provide high-speed line-of-sight connections between base stations and backbone networks, eliminating the need for costly fiber links.

Yet even as millimeter waves are enabling new indoor and fixed wireless services, many experts have remained skeptical that these frequencies could support cellular links, such as to a tablet in a taxi zipping through Times Square. A major concern is that millimeter-wave mobile networks won't be able to provide coverage everywhere, particularly in cluttered outdoor environments such as cities, because they can't always guarantee a line-of-sight connection from a base station to a handset. If, for instance, a smartphone user were to suddenly pass behind a tree or duck into a covered entryway, a millimeter-wave transmission probably couldn't penetrate these obstacles.

But whether the signal would actually drop out in such a situation is another story. And, as it turns out, it's a pretty interesting one.

In August 2011, one of the authors, Rappaport–then at the University of Texas at Austin–began working with students on an extensive study of millimeter-wave behavior in the urban jungle. We built a wideband signaling system known as a channel sounder, which allowed us to analyze how a millimeter-wave transmission scatters and reflects off objects in its path–and how quickly these signals lose energy. Then we placed four transmitters on university rooftops and distributed several dozen receivers around campus.

The type of antenna we chose for these experiments is known as a horn antenna, an evolution of the one Bose originally constructed more than 100 years ago. Like a megaphone, it directs electromagnetic energy in a concentrated beam, thereby increasing gain without requiring more transmitting or receiving power. By mounting our antennas on rotatable robotic platforms, we could point the beams in any direction.

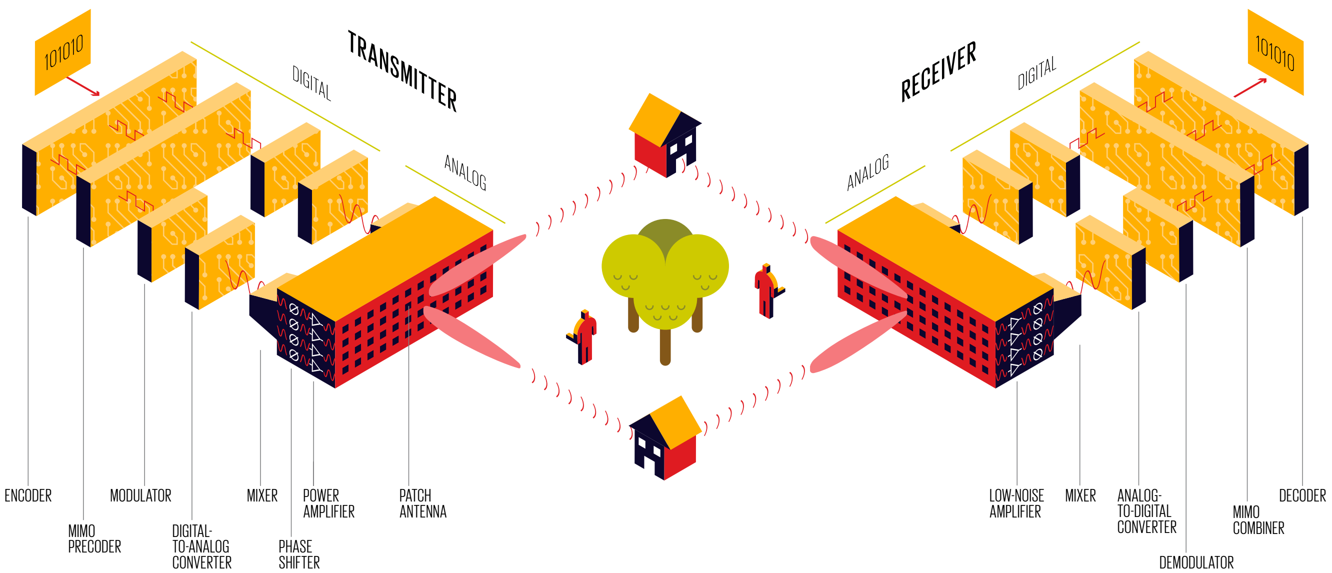
In 1895, a year before the wireless telegraph, **Jagadish Chandra Bose** created the first millimeter-wave apparatus, sending a 60-gighertz signal to a horn antenna and detector 23 meters away

POPULAR SCIENCE MAGAZINE/WIKIPEDIA

Such beam steering will be a key component of future millimeter-wave mobile systems, on both the base station and handset ends of the network. In the real world, as opposed to our experimental setup, mobile equipment such as smartphones and tablets will require electrically steerable antenna arrays that are much smaller and a lot more sophisticated than the ones we used for our tests. More on that later.

In total, we sampled over 700 different combinations of transmitter-receiver positions using frequencies around 38 GHz. This spectrum band is a good candidate for cellular systems because it has already been designated for commercial use in many parts of the world but so far is only lightly occupied.

To the great surprise of our mobile-industry colleagues, we found that this millimeter-wave spectrum can provide remarkably good coverage. Our measurements showed, for instance, that a handset doesn't need a line-of-sight path to link with a base station. The highly reflective nature of these waves turns out to be an advantage rather than a weakness. As they bounce off solid materials such as buildings, signs, and people, the waves disperse throughout the environment, increasing the chance that a receiver will pick up



STAYING IN FOCUS: An adaptive array of 64 tiny antennas, each about the size of an aspirin tablet, forms the heart of millimeter-wave transceivers used in Samsung's 5G wireless prototypes. Individual antenna outputs are honed and steered by phase shifters to create a focused beam of data. That analog data is then converted to digital, which offers precise control over segments of the array and allows for the use of spatial multiplexing techniques—known as multiple-input, multiple-output, or MIMO—to segment the resulting beam. That gives operators the choice of sending information to multiple devices simultaneously or directing multiple beams at one device to improve download speed.

a signal–provided it and the transmitter are pointed in the proper directions.

Of course, as with any wireless system, the likelihood of losing a connection increases as the receiver moves away from the transmitter. We have observed that for millimeter-wave signals transmitted at low power, outages start occurring at around 200 meters. This limited range may have been a problem for earlier generations of cellular systems, in which a typical cell radius extended up to several kilometers. But in the past decade or so, operators have had to significantly shrink cell sizes in order to expand capacity. In especially dense urban centers, such as downtown Seoul, South Korea, they have begun deploying small cells–compact base stations that fit on lampposts or bus-station kiosks–with ranges no larger than about 100 meters.

And there's another reason small cells may be ideal for millimeter-wave communications. It's well known that rain and air can attenuate millimeter waves over large distances, causing them to lose energy more quickly than the longer, ultrahigh frequencies used today. But previous research has shown that over relatively short ranges of a few hundred meters, these natural elements have little effect on most millimeter-wave frequencies, although there are a few exceptions.

To bolster our measurement data, we took our channel-sounding system to New York City, one of the most challenging radio environments in the world. There, in 2012 and 2013, we studied signal propagation at 28 and 73 GHz, two other commercially viable bands, and the results were nearly identical to our findings in Austin. Even on Manhattan's congested streets, our receivers could link with a transmitter 200 meters away about 85 percent of the time. By combining energy from multiple signal paths, more advanced antennas could extend the coverage range beyond 300 meters.

We also tested how well these frequencies penetrate common building materials and found that although they pass through drywall and clear glass without losing much energy, they're almost completely blocked by brick, concrete, and heavily tinted glass. So while users might get some reception between rooms or through transparent windows, operators will typically need to install repeaters or wireless access points to bring signals indoors.

PACKING IN PATCHES: Samsung engineers are working to fit arrays of 28-gigahertz patch antennas into phones like the Galaxy Note II, pictured above.

SAMSUNG

Encouraged by early measurements of millimeter-wave behavior in Austin, the other two of us (Roh and Cheun) and our colleagues at Samsung Electronics Co., in Suwon, South Korea, began building a prototype communication system for a commercial cellular network. In place of bulky, motorized horn antennas, we used arrays of rectangular metal plates called patch antennas. A big benefit of these antennas is their size, which as a rule of thumb must be at least half the wavelength of the signal frequency. Because we designed our prototype to work at 28 GHz (about 1 centimeter), each patch antenna could be very small–just 5 millimeters across, not quite the diameter of an aspirin tablet.

A single 28-GHz patch antenna wouldn't be of much use for cellular transmissions, because gain decreases as antenna size shrinks. But by arranging tens of these tiny panels in a grid pattern, we can magnify their collective energy without increasing transmis-

ILLUSTRATION BY relajaelcoco

sion power. Such antenna arrays have long been used for radar and space communications, and many chipmakers, including Intel, Qualcomm, and Samsung, are now incorporating them into WiGig chip sets. Like a horn antenna or satellite dish, an array increases gain by focusing radio waves in a directional beam. But because the array creates this beam electronically, it can steer the beam quickly, allowing it to find and maintain a mobile connection.

An array that locks its beam on a moving target is called an adaptive, or smart, antenna array. It works like this: As each patch antenna in the array transmits (or receives) a signal, the waves interfere constructively to increase gain in one direction while canceling one another out in other directions. The larger the array, the narrower the beam. To steer this beam, the array varies the amplitude or phase (or both) of the signal at each patch antenna. In a mobile network, a transmitter and receiver would connect with each other by sweeping their beams rapidly, like a searchlight, until they found the path with the strongest signal. They would then sustain the link by evaluating the signal's characteristics, such as its direction of arrival, and redirecting their beams accordingly.

This beam forming and steering can be done in a couple of different ways. It can be done in the analog stage with electronic phase shifters or amplifiers, just before a signal is transmitted (or just after it's received). Or it can be done digitally, before the signal is converted into analog (or after it's digitized). There are pros and cons to both approaches. While digital beam forming offers better precision, it's also more complex–and hence more costly–because it requires separate computational modules and power-hungry digital-to-analog (or analog-to-digital) converters for each patch antenna. Analog beam forming, on the other hand, is simpler and cheaper, but because it uses fixed hardware, it is less flexible.

To get the best of both worlds, we've designed a hybrid architecture. We use phase shifters on the analog front end to form sharp, directional beams, which increase our antenna's communication range. And we use digital processing on the back end to separately control different subsections of the array. The digital input lets us do more advanced tricks, such as aim separate beams at several handsets simultaneously or send multiple data streams to a single device, thereby increasing its download rate. Such spatial multiplexing techniques are known as multiple-input, multiple-output, or MIMO.

For example, in our 28-GHz prototype system, which Samsung announced in May 2013, we equipped each transmitter and receiver with a 64-antenna array about the size of a Post-it note. However, we divided this array digitally into two 32-antenna | CONTINUED ON PAGE 48

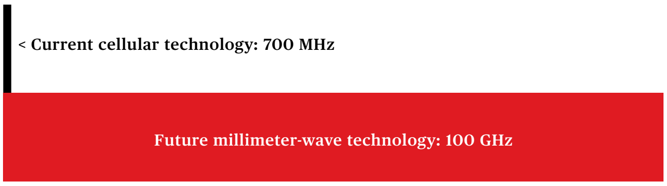
A New Spectrum Frontier

Future 5G mobile networks could tap vast spectrum reserves with millimeter-wave devices. Here's how this emerging technology stacks up against today's cellular systems.

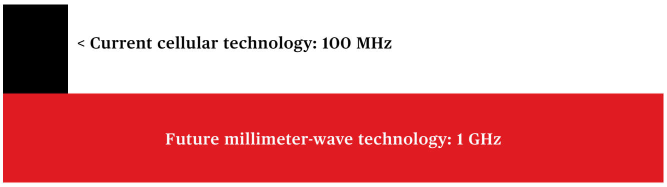
FREQUENCY RANGE

- Current cellular technology: 300 megahertz to 3 gigahertz
- Future millimeter-wave technology: 10 GHz* to 300 GHz

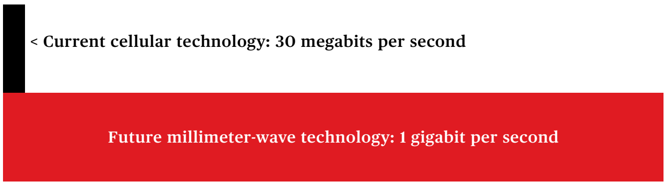
TOTAL AVAILABLE SPECTRUM



MAXIMUM DATA CHANNEL BANDWIDTH



AVERAGE USER DATA RATE



	CURRENT CELLULAR TECHNOLOGY	FUTURE MILLIMETER-WAVE TECHNOLOGY
Single antenna length in free space	At 700 MHz: 21.3 centimeters	At 28 GHz: 0.5 cm
Maximum urban transmission range	At 700 MHz: 3 kilometers	At 28 GHz: 300 meters
Signal attenuation	At 700 MHz *Air:* .005 decibels per kilometer *Heavy rain:* .02 dB/km	At 28 GHz *Air:* 0.1 dB/km *Heavy rain:* 10 dB/km

SOURCES: Zhouyue Pi and Farooq Khan, "An Introduction to Millimeter-Wave Mobile Broadband Systems," *IEEE Communications*, June 2011; Recommendation ITU-R P.676; *Electronic Warfare and Radar Systems Engineering Handbook*, April 1999

*Technically, the millimeter-wave band starts at 30 GHz. However, wireless engineers typically include frequencies as low as 10 GHz when discussing future millimeter-wave systems.

CATCHING BRAIN WAVES IN A NET

A mesh of electrodes draped over the brain could better relay signals to prostheses

By NITISH V. THAKOR

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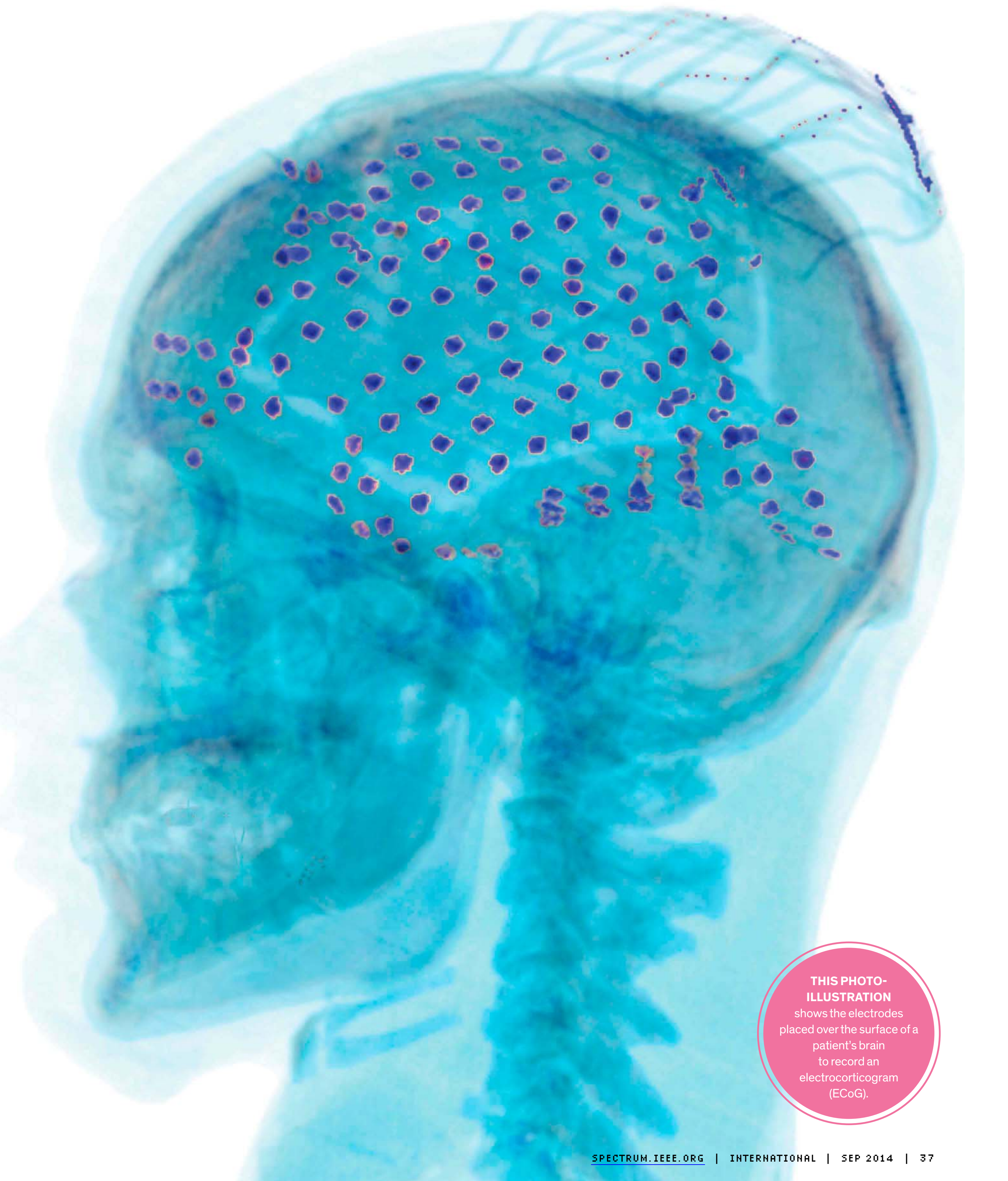

THIS PHOTO-ILLUSTRATION shows the electrodes placed over the surface of a patient's brain to record an electrocorticogram (ECoG).

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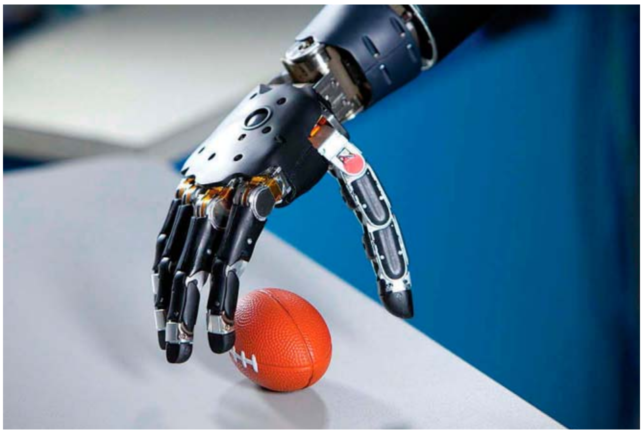
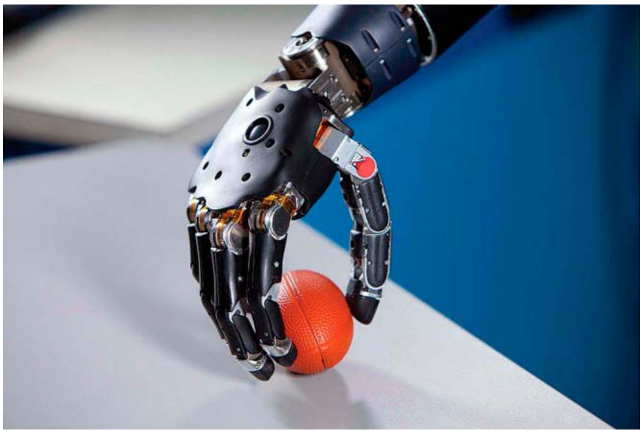
LAST YEAR, AN EPILEPSY PATIENT AWAITING BRAIN SURGERY at the renowned Johns Hopkins Hospital occupied her time with an unusual activity. While doctors and neuroscientists clustered around, she repeatedly reached toward a video screen, which showed a small orange ball on a table. As she extended her hand, a robotic arm across the room also reached forward and grasped the actual orange ball on the actual table. In terms of robotics, this was nothing fancy. What made the accomplishment remarkable was that the woman was controlling the mechanical limb with her brain waves.





HIGH-TECH HAND: Engineers at Johns Hopkins University designed the Modular Prosthetic Limb for use as a brain-controlled prosthesis.

The experiment in that Baltimore hospital room demonstrated a new approach in brain-machine interfaces (BMIs), which measure electrical activity from the brain and use the signal to control something. BMIs come in many shapes and sizes, but they all work fundamentally the same way: They detect the tiny voltage changes in the brain that occur when neurons fire to trigger a thought or an action, and they translate those signals into digital information that is conveyed to the machine.

To sense what's going on in the brain, some systems use electrodes that are simply attached to the scalp to record the electroencephalographic signal. These EEG systems record from broad swaths of the brain, and the signal is hard to decipher. Other BMIs require surgically implanted electrodes that penetrate the cerebral cortex to capture the activity of individual neurons. These invasive systems provide much clearer signals, but they are obviously warranted only in extreme situations where doctors need precise information. The patient in the hospital room that day was demonstrating a third strategy that offers a compromise between those two methods. The gear in her head provided good signal quality at a lower risk by contacting–but not penetrating–the brain tissue.

The patient had a mesh of electrodes inserted beneath her skull and draped over the surface of her brain. These electrodes produced an electrocorticogram (ECoG), a record of her brain's activity. The doctors hadn't placed those electrodes over her cerebral cortex just to experiment with robotic arms and balls, of course. They were trying to address her recurrent epileptic seizures, which hadn't been quelled by medication. Her physicians were preparing for a last-resort treatment: surgically removing the patch of brain tissue that was causing her seizures.

Seizures result from abnormal patterns of activity in a faulty part of the brain. If doctors can precisely locate the place where those patterns originate, they can remove the responsible brain tissue and bring the seizures under control. To prepare for this woman's surgery, doctors had cut through her scalp, her skull, and the tough membrane called the dura mater to insert a flexible grid of electrodes on the surface of her brain. By recording the electrical activity those electrodes registered over several days, the neurologists would identify the trouble spot.

The woman went on to have a successful surgery. But before the procedure, science received a valuable bonus: the opportunity to record neural activity while the patient was conscious and under observation. Working with my collaborator at the Johns Hopkins University School of Medicine, Nathan Crone, my team of biomedical engineers has done this about a dozen times in the past few years. These recordings are increasingly being used to probe human brain function and are producing some of the most exciting data in neuroscience.

PREVIOUS PAGES, LEFT: ISTOCKPHOTO; RIGHT: ADEEN FLINKER/UNIVERSITY OF CALIFORNIA, BERKELEY; THIS PAGE: ED WHITMAN/THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

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As a patient moves or speaks under carefully controlled conditions, we record the ECoG signals and learn how the brain encodes intentions and thoughts. Now we are beginning to use those signals to control computers, robots, and prostheses. The woman in the hospital room didn't need any mind-controlled mechanical devices herself, but she was helping us develop technology that could one day allow paralyzed patients to control robotic limbs of their own.

The machine at the end of a brain-machine interface could be anything: Over the past few decades, researchers have experimented with using neural signals to control a computer cursor, a wheelchair, and even a car. The dream of building a brain-controlled prosthetic limb, however, has received particular attention.

In 2006 the U.S. Defense Advanced Research Projects Agency (DARPA) bankrolled a massive effort to build a cutting-edge prosthetic arm and to control it with brain signals. In the first phase of this Revolutionizing Prosthetics program, the Johns Hopkins Applied Physics Laboratory developed a remarkable piece of machinery called the Modular Prosthetic Limb, which boasts 26 degrees of freedom through its versatile shoulder, elbow, wrist, and fingers.

To give amputees control of the mechanical arm, researchers first tried out existing systems that register the electrical activity in the muscles of the limb stump and transmit those signals to the prosthesis. But such systems offer very limited control, and amputees don't find them intuitive to use. So DARPA issued its next Revolutionizing Prosthetics challenge in 2009, asking researchers to control the state-of-the-art prosthetic arm directly with signals from the brain.

Several investigators answered that call by using brain implants with penetrating electrodes. At Duke University, in Durham, N.C., and the University of Pittsburgh, researchers had already placed microelectrodes in the brains of monkeys, using the resulting signals to make a robotic arm reach and grasp. Neuroscientists at Brown University, in Providence, R.I., had implanted similar microelectrodes in the cortex of a paralyzed man and showed that he could control a computer cursor using neural signals. Another paralyzed patient who underwent this procedure at Brown recently controlled a robotic arm: She used it to raise a bottle to her lips to take a drink, performing her first independent action in 14 years.

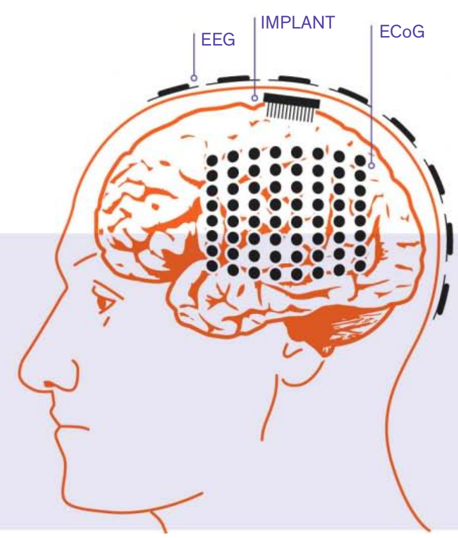
That work certainly demonstrated the feasibility of building a "neural prosthesis." But using penetrating electrodes poses significant challenges. Scar tissue builds up around the electrodes and can reduce signal quality over time. Also, the hardware, including electrode arrays and low-power transmitters that send the signal out through the skull, must operate reliably for many years. Finally, these first demonstrations did not produce smooth, quick, or dexterous movements. Some neuroscientists suggested that many more electrodes should be implanted—but doing so would heighten the risk of damaging brain tissue.

In light of those concerns, the United States' National Institutes of Health challenged researchers to build a neural prosthesis with a less invasive control mechanism. The ideal would be a system based on EEG signals, simply using electrodes attached to the scalp. Unfortunately, the brain signals that external electrodes pick up are blurred and attenuated by their passage through the skull and scalp. This led our team to investigate the middle road: the use of ECoG signals.

ECoG systems provide a better signal-to-noise ratio than EEG, and the data includes high-frequency components that EEG can't easily capture. ECoG systems also do a better job of extracting the most useful information from the brain, as an electrode placed over the motor cortex can specifically listen in on the electrical activity most relevant for controlling a prosthetic arm. Similarly, electrodes draped over the brain areas associated with speech can capture signals associated with verbal communication.

Raw ECoG signals appear to be a confused mess of squiggly lines with little discernible pattern. To make sense of the data, our team performs a spectral analysis to deconstruct the signal and find oscillations at certain specific frequencies. These are the brain waves you may have heard about. Neuroscientists have learned that different oscillation frequencies are associated with specific mental states, such as deep sleep, focused attention, or meditative contemplation.

Just imagine what neural prostheses could do for people who are severely paralyzed or for patients in the late stages of amyotrophic lateral sclerosis (also known as Lou Gehrig's disease). These patients are essentially "locked in," with intact brains but no ability to control their bodies, or even to speak. Could their intentions, translated into ECoG signals, be captured and relayed to robotic limbs?



THREE WAYS TO TAP THE BRAIN To record the activity of brain cells, neuroscientists can use implanted electrodes that penetrate the cortex. This method provides the clearest signal, but it's also the riskiest. In contrast, scalp electrodes for electroencephalography (EEG) carry no risks, but the signal they capture is indistinct. Electrocorticography (ECoG), which uses electrodes draped over the surface of the cortex, may represent the "sweet spot," a compromise between risk and clarity.

ILLUSTRATION BY Nicolas Rapp

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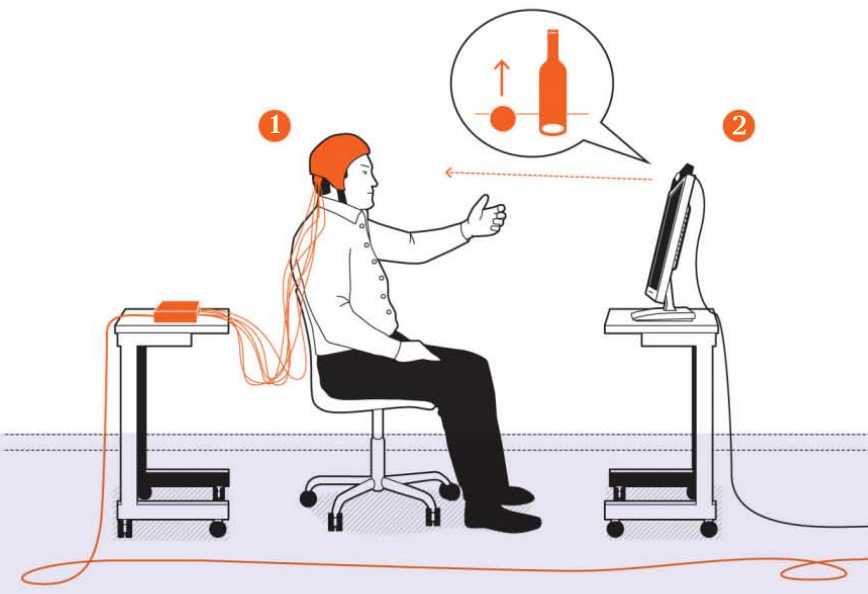

FROM MIND TO MACHINE: Combining brain commands with information from other sensors may provide more sophisticated control of a robotic limb. In our hybrid system, a Microsoft Kinect **[4]** streams video of objects resting on a table **[5]** to a computer screen in front of a test subject. An eye-tracking sensor **[2]** follows the subject's gaze to locate the target object, and ECoG sensors **[1]** record brain activity while the subject reaches toward that target. A computer **[3]** analyzes the brain activity associated with the subject's arm movement and sends a command to a robotic arm. With the help of the Kinect's depth sensor, the arm reaches out and grabs the object.

Here's a simple example of how an ECoG-based neural prosthesis could work. Researchers have previously shown that an imagined movement modulates the brain's electrical activity in the mu band, which has a frequency of about 10 to 13 hertz. Thus, the paralyzed subject would imagine moving a limb, electrodes would capture the mu-band activity, and the BMI would use the signal to trigger an action, such as closing a robotic hand. Since we can use up to 64 electrodes placed about a centimeter apart and spread over a wide area of the brain, we have a lot of data to work with. As we develop better algorithms that can identify the key signals that code for movement, we can build systems that don't just trigger an action but offer more fine-tuned control.

Our team took the first step toward building such a system in 2011, when we painstakingly matched up brain signals with particular movements. Our subject was a 12-year-old boy awaiting surgery for his seizure disorder. In the experiment, the boy reached forward and grasped one of the wooden blocks set before him, then released it and withdrew his hand. When we looked at the data from just a few electrodes that had been placed over his brain's sensorimotor cortex, we discovered that oscillations in the high gamma band, with frequencies between 70 and 150 Hz, correlated well with the boy's actions. We also found that the signal in a lower frequency band changed in predictable ways when he wiggled his fingers.

The next step was to couple the electrical signal to the machinery. We demonstrated that under carefully controlled conditions, epileptic patients with ECoG electrodes placed on their brains could indeed command the Modular Prosthetic Limb to perform simple actions, like reaching and grasping. While this was a considerable accomplishment, we struggled to decode the neural signals reliably and to get the prosthetic limb to move smoothly.

In the end, we decided that it just may not be realistic to expect an ECoG-controlled prosthesis to perform an entirely natural limb movement, such as picking up a pot of coffee and pouring some into a cup. After all, a typical person uses a combination of vision, touch, motor control, and cognitive processing to perform this mundane action. So last year our team began exploring another strategy. We built a hybrid BMI that combines brain signals with input from other sensors to help accomplish the task at hand.

Several epileptic volunteers with ECoG arrays tested our novel system. The first, the woman described at the beginning of this article, focused her eyes on the image of a ball on a computer screen; the computer was streaming video from a setup across the room. An eye-tracking system recorded the direction of her gaze to locate the object she wanted to manipulate. Then, as she reached toward the screen, her ECoG electrodes recorded neural signals associated with that action. All this information was relayed to a robotic arm across the room, which was equipped with a Microsoft Kinect to help it recognize objects in three-dimensional space. When the arm received the signal to reach for the ball, its path-planning software calculated the necessary movements, orientations, and grasp configuration to smoothly pick up the ball and drop it in a trash can. The results were encouraging: In 20 out of 28 trials, this woman's brain signals successfully triggered the robotic arm, which then completed the entire task.

Would this patient have done even better if we'd implanted electrodes in her brain rather than just draping the electrodes over the surface? Perhaps, but at a greater risk of brain trauma. Also, penetrating electrodes register only the local activity of individual cells or small clusters of neurons, whereas ECoG electrodes pick up activity across broader zones. ECoG systems may therefore be able to capture a richer picture of the brain activity taking place during the planning and execution of an action.

ECoG systems also hold the promise of being able to convey both motor and sensory signals. If a prosthetic limb has sensors that register when it touches an object, it could in principle send that sensory feedback to a patient by stimulating the brain through the ECoG electrodes. Similar stimulation is already done routinely in patients prior to epilepsy surgery in order to map the brain regions responsible for sensation. However, the sensations elicited have typically been very crude. In the future, more refined brain stimulation, using smaller electrodes and more precise

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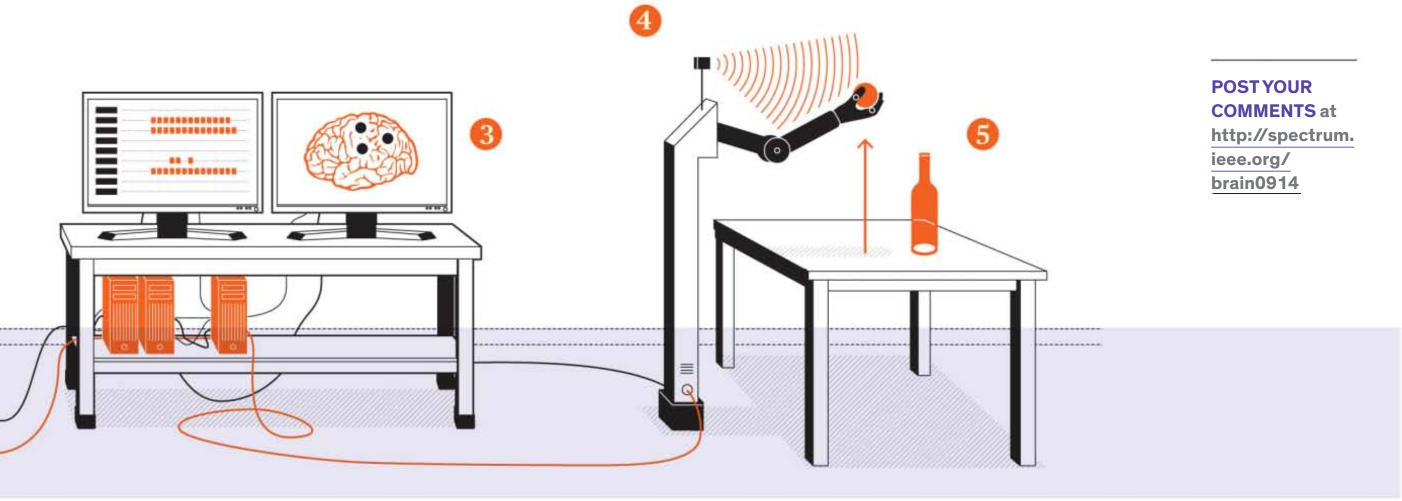

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activation patterns, may be able to better simulate tactile feedback. The goal is to use two-way communication between brain and prosthesis to help a user deftly control the limb.

While it might be tempting to test ECoG systems with severely paralyzed patients—the intended beneficiaries of this neuroprosthetic research—it is imperative to demonstrate that such systems can reliably restore meaningful function before exposing patients to the risks of surgery. For this reason, the clinical circumstances of patients preparing for epilepsy surgery represent an important opportunity to develop technology that will benefit a very different group of patients. We've found that many epilepsy patients are glad they can help others while they're hospital-bound and under observation for the seizures that will provide guidance to their surgeons. Our hope is that these experiments will lead to a technology so clearly useful that we will feel well justified in trying it in paralyzed patients.

Thinking about the cost-benefit concerns gives a sense of déjà vu. I came to Johns Hopkins in the early 1980s, when doctors there had just implanted the first heart defibrillator in a patient. All the same doubts were aired. Was the technology too invasive? Would it be reliable? Would it provide enough benefit to justify the expense? But defibrillators rapidly proved their worth, and today more than 100,000 are implanted every year in the United States alone. The medical community may be nearing the same juncture with brain-machine interfaces, which might well be an accepted part of clinical medicine in just a couple of decades.

So far I've discussed the possibility of using ECoG signals to control prosthetic limbs, but there's another fascinating possibility: Capturing these signals could also help people who have lost the ability to speak. For some people who have suffered a stroke or injury, the brain can still conceive words and generate speech commands, but the signals don't make it to the mouth. When ECoG electrodes are placed over the language areas of the brain, including the regions that govern the muscles of speech articulation, the resulting signals presumably carry information pertaining to both language generation and the physical production of words. A speech prosthesis could decode those signals and send commands to a device that would give voice to the patient's intended sentences.

Early research shows progress in understanding the brain's commands to the mouth muscles. In one study, University of California researchers in San Francisco and Berkeley used an ECoG system to record activity in the motor cortex as their subjects patiently recited syllables such as "ba," "da," and "ga." The resulting measurements showed distinct patterns for different consonants. For example, certain electrodes showed activity during the production of the "b" sound, which requires closure of the lips. Other electrodes registered activity during the "d" sound, in which the tongue hits the roof of the mouth. Still others saw action during the "g" sound, which involves the back of the mouth.

What would it take to build a speech prosthesis? First, we would need to improve our recording hardware. Today's ECoG systems use only a few dozen electrodes on the cortex; clearly, a much higher density of electrodes would produce a better signal. We have already tried out new microelectrode ECoG systems in human patients that can pack 16 electrodes onto a 9-by-9-millimeter array.

Because speech production surely involves many brain regions, we'll also have to improve our signal analysis to decipher neural activity, not just in one area but across large regions of the brain. We'll need better spatial and temporal resolution to determine the exact sequence in which groups of neurons across the cortex fire to produce, say, the simple sound "ba." Once we've managed to map individual phonemes or syllables, we can work toward understanding fluid speech by decoding a succession of brain commands.

Controlling a robot with a thought, speaking without making a sound: With ECoG systems, these magical feats now appear well within the realm of feasibility. By casting a net of electrodes over the surface of the brain, it's possible to capture echoes of the ideas and commands that swirl below, in the currents of the mind. ■

ILLUSTRATION BY Nicolas Rapp

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Fear of Frying

Electromagnetic weapons threaten our data networks. Here's how to stop them

By **WILLIAM A. RADASKY**

Photography by **DAN SAELINGER**


03:59:07

In the 2001 action movie *Ocean's Eleven*,

criminals use an electromagnetic weapon to black out a portion of Las Vegas. Very futuristic, you may say, but the threat is real and growing.

The problem is growing because the technology available to attackers has improved even as the technology being attacked has become more vulnerable. Our infrastructure increasingly depends on closely integrated, high-speed electronic systems operating at low internal voltages. That means they can be laid low by short, sharp pulses high in voltage but low in energy—output that can now be generated by a machine the size of a suitcase, batteries included.

Electromagnetic (EM) attacks are not only possible—they are happening. One may be under way as you read this. Even so, you would probably never hear of it: These stories are typically hushed up, for the sake of security or the victims' reputation. Occasionally, though, an incident comes to light.

In May 2012, for instance, the *Korea Herald* reported that over 500 aircraft flying in and out of South Korea's Incheon and Gimpo airports reported GPS failures, as did hundreds of ships and fishing boats in the sea west of Incheon Airport. The source of the EM fields was traced to the North Korean city of Kaesong, about 50 kilometers north of Incheon. South Korean officials indicated that North Korea had imported truck-based jamming systems in 2010 that had the capability to jam GPS signals. These officials speculated that one purpose of the jamming was to interfere with South Korea's highly digital society. Or perhaps the North Koreans were conducting an experiment, using South Korea as their beta tester.

In decades past, the few key electronic systems that existed worked at higher voltages than today's machines and at lower frequencies, making them less sensitive to EM disruption. Today, though, any digitally controlled infrastructure presents a target: Power, telecommunications, finance, water, natural gas, and more are all coming under the ever-finer control of computers. Right now the power systems in developed areas of the world are installing smart power meters in homes and businesses, along with communications systems to transmit the data. The new wave of distributed renewable power systems requires additional sensors to determine their operating status, so that the grid can operate efficiently and avoid collapse. The increased need for information and the means to communicate it make all these systems vulnerable to anyone who may wish to create problems—and that means hackers, criminals, vandals, and terrorists.

And, unlike other means of attack, EM weapons can be used without much risk. A terrorist gang can be caught at the gates, and a hacker may raise alarms while attempting to slip through the firewalls, but an EM attacker can try and try again, and no one will notice until computer systems begin to fail (and even then the victims may still not know why).

Governments and professional organizations have been aware of the problem (called intentional electromagnetic interference, or IEMI) at least since the 1990s; in the wake of attacks like the one in South Korea, they began to take it seriously. For instance, in 2012 the European Union began funding three projects to deal with assessing EM attacks and protecting critical infrastructures from them. One project, known as Secret (Security of Railways against Electromagnetic Attacks), is meant to find ways to prevent the jamming of railroad equipment that uses the new GSM-Railway wireless communication standard. It's not enough to patch holes that bad actors have discovered; we must also try to anticipate attacks that haven't yet occurred. It may seem strange that we should find ourselves in need of defending against electromagnetic generators, a kind of weapon most people have still never heard of. The reason is obvious: Not only is it getting easier to make these generators, but we are also becoming more dependent on the data networks those generators threaten.

The recipe for frying a network is simple. Begin with a generator, fold in a battery, and garnish with either an antenna to propagate the output or a hardwired connection into the building you have targeted. Even a briefcase-size model could generate EM fields with peaks in the thousands of volts per meter, and those peaks would come fast and short, with a rise time of about 100 picoseconds and

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a pulse width of about 1 nanosecond. Such a pulse would contain frequencies between 100 megahertz and several gigahertz.

Whether the attacker transmits via an antenna or a hardwired connection depends on circumstances. The radiated field method gives attackers greater flexibility, but the power decreases rapidly the farther they are from the target. A hardwired approach lets attackers put the pulsed power where they want it without as much wastage, but it does require that they get close enough to the target to make the physical connection. Even this needn't be very hard: Many commercial buildings have vulnerable communications cabinets and external power outlets, as Daniel Månsson, at the KTH Royal Institute of Technology, in Stockholm, has documented.

An attack might be staged as follows. A larger electromagnetic weapon could be hidden in a small van with side panels made of fiberglass, which is transparent to EM radiation. If the van is parked about 5 to 10 meters away from the target, the EM fields propagating to the wall of the building can be very high. If, as is usually the case, the walls are mere masonry, without metal shielding, the fields will attenuate only slightly. You can tell just how well shielded a building is by a simple test: If your cellphone works well when you're inside, then you are probably wide open to attack.

When the pulsed fields enter the building, they induce a current in the internal wiring that flows into the electronics, either damaging the equipment or just producing a disruption, which in turn might require a manual restart or corrupt some data.

The fields are of two kinds: narrowband and wideband. A narrowband waveform is essentially a single frequency of power, delivered over a period of anywhere from 100 ns to several microseconds. Narrowband attacks are usually of very high power, on the order of thousands of volts per meter. Achieving such strong fields is fairly easy because the electrical energy is concentrated in a narrow band. The frequency can be optimized for one purpose and then modulated for another. For instance, the attackers might beam in a gigahertz wave–perfect for penetrating small apertures in equipment cases–and then modulate it to produce a lower-frequency signal (just as AM radio is modulated to encode music). That lower-frequency signal, in turn, is intended to pour energy into the electronics inside the case. But the attack will succeed only if the frequency matches the resonance pattern in the equipment. If no resonance occurs, or if the resonance is confined to just a portion of the equipment, then the effect will be much less serious, or nonexistent. To increase the odds that such "coupling" occurs, the attacker can continue to shift the signal to other frequencies.

Wideband (sometimes called ultrawideband) packs a different punch. Here, the power of each pulse is spread over a range of frequencies, for example, from 100 MHz to 1 gigahertz. If the range is wide enough–that is, if the ratio of the highest to the lowest frequencies in a single pulse is 10 or more–it's considered hyperband. There's less power at any one frequency, and that means less damage will be inflicted per pulse than in a narrowband attack. But wideband pulse generators can easily produce 1,000 pulses per second for many minutes at a time, and that greatly increases the chance of damaging a system, or at least interfering with communications through a straightforward denial of service. Yury Parfenov, of the Russian Academy of Sciences, Joint Institute for High Temperatures, has demonstrated how a high repetition rate can reduce wired Ethernet communications to nearly zero.

And because each pulse requires minimal energy to generate, the energy supply for such a weapon is modest compared to what a narrowband weapon requires. In our laboratory at Metatech Corp., an EM consultancy in Goleta, Calif., we have built a power supply from an automobile battery and an inverter, and it can operate our wideband pulser for days without losing its charge.

Over the past 15 years, our laboratory and others in Germany, Norway, Russia, Sweden, and the United Kingdom have conducted hundreds of experiments studying how commercial equipment holds up to both narrowband and wideband attacks. The emphasis has been on personal computers, alone and in networks, but more recent testing has included cash machines, industrial control equipment, substation electronics, power supplies, Ethernet components, Wi-Fi networks, automobiles, GPS electronics, cellular phones, tablets, and various sensors.

Computers and other systems based on microprocessors turn out to be vulnerable to radiated narrowband fields above 30 volts per meter, although newer high-speed PCs appear to be resistant up to about 300 V/m at some frequencies. That's largely because U.S. and European rules now limit the amount of EM radiation that such machines can emit to the 1- to 10-GHz range, and those rules have had the effect of increasing the machines' shielding. What's more, as the frequency rises from 1 to 10 GHz, computers become less vulnerable to narrowband attack, according to experiments by Richard Hoad at QinetiQ Group, a defense technology company in England. That's good news, but remember, not all industrial computers use high-speed processors. Slower microprocessors (present in programmable logic controllers, for example) don't emit in the gigahertz range, and so they are not well protected against EM attacks in that same frequency range.

In other experiments, Hoad has determined that the presence of metal connecting cables typically increases the vulnerability of the computer equipment. Attacking and damaging small handheld equipment that has no connected cables, by contrast, requires very high fields, usually with peaks greater than 5 kilovolts per meter.

Cables also weaken the defenses of industrial and power-system controls, as shown by Edward Savage, my colleague at Metatech. He simulated attacks, then found that a disproportionate number of equipment failures had originated in cable interface cards. This work suggests that for hooking together the nodes of a network, fiber-optic cable (without metal components) is definitely preferable to copper cable.

Other researchers around the world have determined which kinds of wideband pulses are most dangerous to which kinds of equipment. For instance, a peak electric field of about 2 kV/m for pulse widths on the order of 200 ps can disrupt

The Walls Have Eyes

To make sure your company's electronics aren't wide open to attack, follow these simple rules of electromagnetic hygiene

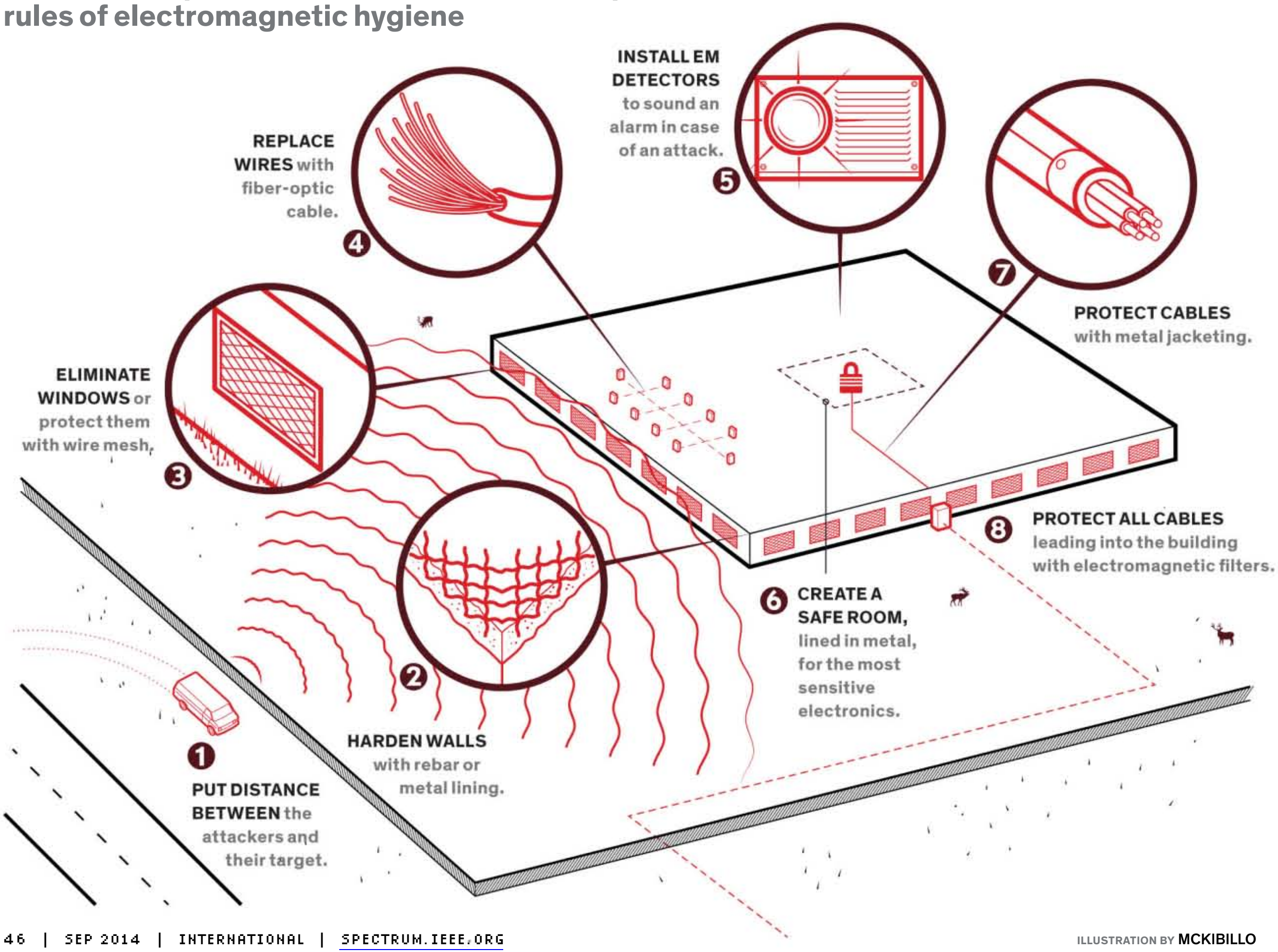

ILLUSTRATION BY MCKIBILLO

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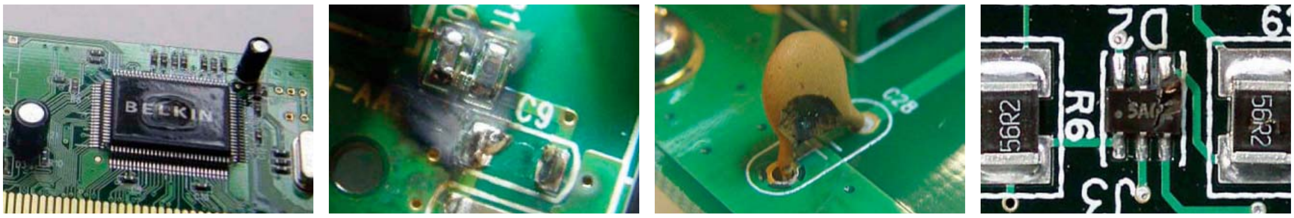


CIRCUITS FLAMBÉ, with crisped chips and broiled boards, resulted from tests with pulsed electromagnetic radiation in the author's laboratory at Metatech Corp., in Goleta, Calif. The damage, from left, is as follows: A lid of an integrated circuit was scorched and warped; the capacitor labeled "C9" was completely blown away; part of a ceramic capacitor was shorn off; and the right-hand edge of a small integrated circuit was blasted.

METATECH CORP. (4)

microprocessor-based systems enough to force administrators to push the reset button (although resets do not always work and sometimes the operating system must be reloaded). Peaks at around 5 kV/m will fry the chips beyond redemption.

In these experiments, the field strengths were determined by placing the targeted equipment within the line of sight of a radiating antenna. Of course, if the way is blocked by windowless walls, particularly walls that contain metals, the fields will be attenuated and any damage or disruption will be diminished, if not prevented.

Our electronics are vulnerable for a simple reason: They were designed to handle naturally occurring electromagnetic radiation, but not the malicious sort. By design, they resist narrowband electric fields below 10 V/m for frequencies above 80 MHz; if they didn't, they'd suffer interference from any passing mobile phone or walkie-talkie, and you'd have trouble operating your PC whenever you received a phone call on your handset. Today's electronic products can also withstand a certain level of electrostatic discharge; otherwise, the gentlest spark from a finger on a dry winter's day would be enough to scramble a computer's brains. Electrical and communication cables also have a certain amount of built-in electromagnetic immunity.

The typical specification (such as the standard IEC 61000-6-1) requires that your home computer, for instance, must survive a 1-kV pulse in the cable–a pulse that can itself be induced by a transient EM field of 1 kV/m. Greater protection is typically required in special cases, such as in a power-generating facility or substation. The usual test for electromagnetic immunity involves waveforms with rise times as fast as 5 ns and pulse widths as long as 700 ms–far less threatening than the faster pulse rates that attackers are capable of sending.

Take the Jolt simulator, an experimental wideband generator developed by the U.S. Air Force (and described in the *Proceedings of the IEEE* in July 2004). It produced an electric field of 50 kV/m from 100 meters away, inducing voltages of 50 kV on short cables. That's more than 10 times what it takes to wreck most unprotected electronics!

Obviously, the mandated immunity levels of commercial electronics are too low to protect against EM weapons. We must take steps to harden them, especially the electronics that control our critical infrastructures.

The first line of defense should be putting as much distance as possible between you and the attacker. For instance, you could surround a building with a broad green meadow protected by fences, thus taking advantage of the falloff in an antenna's electric field strength with distance. That's not always possible, of course, so at the very least, you should locate critical equipment away from the building's outermost walls.

The second line of defense involves the building in which the sensitive electronics are housed. No cable should enter the building without first passing through a specially designed surge arrester and a filter protection device coupled to a low-inductance grounding system. The surge arrester will "clip" a high-voltage pulse, but it will also generate some additional high-frequency noise, which the filter protection device will remove. The third line of defense lies in the walls themselves. Ideally, they should contain no windows, which are rather transparent to high-frequency EM fields; if there must be windows, cover them with metal screens. You should harden the walls with metal, such as concrete reinforced with rebar or even metallic wallboard. Best of all is a complete metal shield.

If you can't seal the entire building, you might instead consolidate critical equipment into a room with a solid metallic wall or a specially designed metal screen. Call this the fourth line of defense. Hospitals already use such "screens" to shield powerful MRI machines; here the purpose is not to keep electromagnetic radiation out but to keep it in (so that it doesn't damage computer systems in other rooms).

Finally, you can try to limit the damage should an attack occur. To reduce the coupling of the fields to the cables and equipment, for instance, you can lay the cables along metallic surfaces, cover the cables and connectors with shielding, and install surge protectors at the connection of the cables to each piece of electronic equipment. Even better: Connect these nodes with optical cable rather than metallic wire.

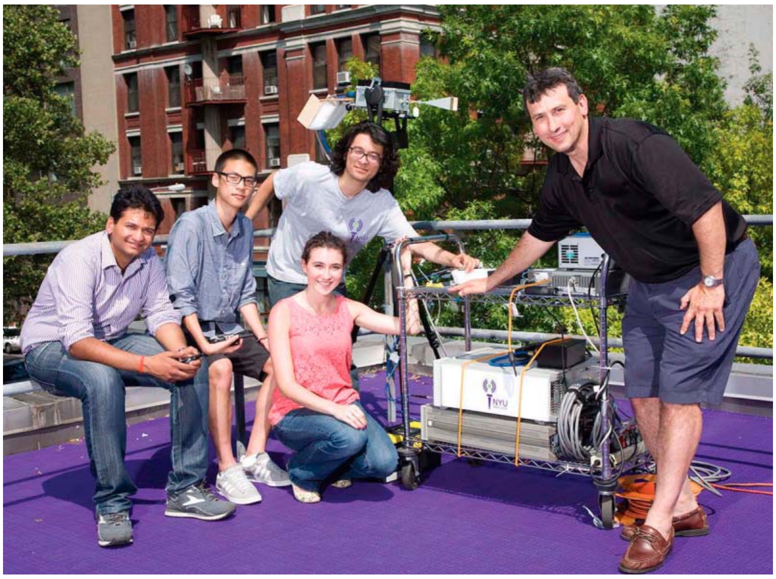
Another obvious way to limit the damage once an EM attack is under way is to shut things down fast. To do that, you need an EM detector to sound the alarm. That's more difficult than it may seem because it requires a detector that can handle all possible attacks, from narrowband to hyperband. Researchers at QinetiQ have built and tested prototype detectors that are good up to 8 GHz, but it will be some time before these products reach the market. Still, even an imperfect alarm would be welcome. Even if it can't mitigate an attack, the information it records could later help forensic analysts to reconstruct the course of events.

Research on cost-effective defenses against EM attack goes on, notably through the International Electrotechnical Commission, in Geneva, the IEEE's Electromagnetic Compatibility Society, and Cigré, in Paris, which studies the reliability of high-voltage power grids. Meanwhile, the operators of threatened facilities must make the best use of the methods that are now available. It's the job of the engineering community to bring those methods to light. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/emattacks0914

CONTINUED FROM PAGE 35 | MIMO channels. Each channel used 500 MHz of spectrum and was capable of forming a 10-degree-wide beam. In a laboratory test, we used these independent beams to transmit nearly error-free data at more than 500 megabits per second to two mobile stations at once. In another test, we used both channels to connect with just one station, achieving a data rate of more than 1 Gb/s. For comparison, a typical data rate with a 4G LTE connection in New York City averages around 10 Mb/s and in theory can be as high as 50 Mb/s.

When we took our prototype outdoors in Suwon, a city near Seoul, we showed that it could maintain similar data rates even when we moved the mobile stations in random directions at up to 8 kilometers per hour—about the speed of a fast jog. We also tested the system's range using transmission power comparable to that of current 4G LTE networks. Even in non-line-of-sight conditions, we found that a mobile receiver could reliably connect with a transmitter up to almost 300 meters away, which supports the measurement results from Austin and New York City. When the stations were in sight of one another, their range was expanded to almost 2 km. We believe that even longer distances are possible, but our experimental license didn't allow us to test them.



BIG-APPLE BIT RATE: Students testing millimeter-wave transceivers in densely populated New York City found that high-frequency waves around the 28- and 73-gigahertz bands could be more useful for sending and receiving data than was once thought.

MARIAN GOLDMAN/NYU

Remember, too, that this prototype was just a proof-of-concept system. By using wider bandwidths, narrower beams, or more MIMO channels, real-world networks could achieve even higher data rates and larger coverage ranges. For instance, computer simulations of imag-

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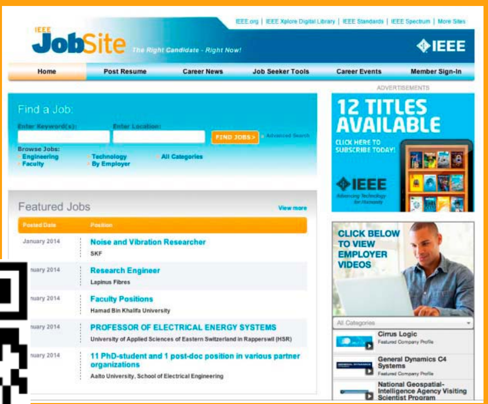

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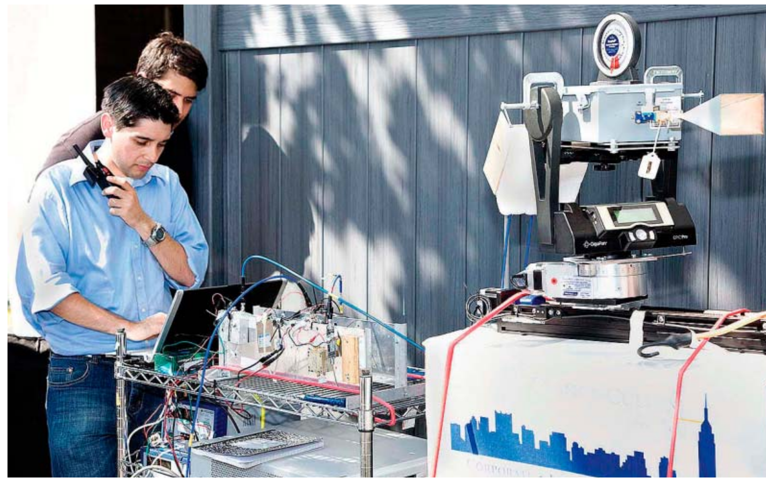
ined small-cell networks using three-dimensional city models suggest that operators could reasonably provide data rates upwards of several gigabits per second.

One important limitation, though, will be the space available in handsets and base stations for these sophisticated antenna arrays. At Samsung, we've begun exploring arrangements of 28-GHz patch antennas in the Galaxy Note II. So far we've found that it's possible to fit as many as 32 of these little radiators around the smartphone's top and bottom edges while still providing 360 degrees of coverage. We expect future millimeter-wave base stations to be able to house 100 or more antennas.

These hardware experiments, and the measurement campaigns in Austin and New York City, have convinced us that millimeter-wave cellular communication will be not just feasible but revolutionary. The work of both our groups, however, is only the beginning. Engineering full-scale millimeter-wave networks will require robust statistical models of millimeter-wave channels, streamlined beam-forming algorithms, and new power-efficient air-interface standards, among many other design challenges. Government regulators will also have to take the initiative in making millimeter-wave spectrum available for cellular services.

Meanwhile, as industry groups worldwide begin considering candidates for 5G technologies, including schemes for better interference management and dense small-cell architectures, they're recognizing that millimeter-wave systems will be a key part of this mix. By 2020, when the first commercial 5G networks will likely start rolling out, millimeter-wave bands will no longer be regarded as the abandoned backwoods lots of radio real estate. They'll be the most fashionable destinations of all. ■



INCREDIBLE SHRINKING CELL: As small, short-range cells that cover distances of just a few hundred meters become more popular in urban areas, they could make millimeter-wave communications, like those being tested by New York University students here, more feasible.

MARIAN GOLDMAN/NYU

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ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

The Electrical and Computer Engineering (ECE) Division of the Electrical Engineering and Computer Science Department at the University of Michigan, Ann Arbor invites applications for junior or senior faculty positions, especially from women and underrepresented minorities. Successful candidates will have a relevant doctorate or equivalent experience and an outstanding record of achievement and impactful research in academics, industry and/or at national laboratories. They will have a strong record or commitment to teaching at undergraduate and graduate levels, to providing service to the university and profession and to broadening the intellectual diversity of the ECE Division. The division invites those with interests in integrated circuits, applied electromagnetics, power electronics, optics, robotics, smart systems, communications, solid-state devices and nanotechnology, biomedical engineering, and all other relevant areas of research to apply.

The highly ranked ECE Division (**www.eecs.umich.edu/ece**) prides itself on the mentoring of junior faculty toward successful careers. Ann Arbor is often rated as a family friendly best-place-to-live.

Please see application instructions at **www.eecs.umich.edu/eecs/jobs**

Applications will be considered as they are received. However, for full consideration applications must be received by December 8, 2014.

The University of Michigan is an Affirmative Action, Equal Opportunity Employer with an Active Dual-Career Assistance Program. The College of Engineering is especially interested in candidates who contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community.

JAMES WORTH BAGLEY COLLEGE OF ENGINEERING
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Mississippi State University invites applications for a faculty position in Electrical and Computer Engineering in High Voltage Engineering, Power Systems, and other related areas. All ranks will be considered. An earned doctorate in electrical engineering, computer engineering, or related field and a clear potential for gaining national prominence through funded research and teaching are required. Senior applicants will be considered for an endowed professorship and directorship of the high voltage laboratory.

Mississippi State University, a Carnegie Foundation Very High Research University, is a comprehensive land-grant institution with more than 20,000 students and nearly 1,300 full-time faculty members. The ECE Department has an approximate enrollment of 400 undergraduate students and 95 graduate students. The department is ranked in the top 10% nationally in research expenditures by the National Science Foundation. The Department houses a High Voltage Laboratory (HVL), which is the largest among North American Universities. The principal objective of this multi-purpose, high voltage facility is to provide a broader effort designed to meet the research and evaluation/testing needs of industry and utilities, and the necessary environment for a strong academic and research program associated with high voltage engineering (**http://www.ece.msstate.edu/research/hvl/**).

The university is located in a vibrant community located in northeast Mississippi. For more detailed information on the department please visit our website **www.ece.msstate.edu**.

To apply: Please submit letter of application describing your background, experience and names of three references with address and phone number, curriculum vitae and other documents online at **www.jobs.msstate.edu**.

Screening will begin November 9, 2014. Applications will be accepted until the position is filled. MSU is an EEO/AA employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status or any other characteristic protected by law. Underrepresented minorities and women are strongly encouraged to apply.

Tufts UNIVERSITY | School of Engineering

Faculty Position in Electrical and Computer Engineering

The Department of Electrical and Computer Engineering (ECE) at Tufts University seeks a tenure-track faculty member at the level of Assistant Professor. Truly exceptional candidates may also be considered at the level of Associate or Full Professor. The department is particularly interested in candidates with expertise in machine learning, millimeter and terahertz devices, or embedded systems. Outstanding candidates from any subfield of electrical and computer engineering, however, are encouraged to apply. Primary evaluation criteria will include an ability to build and sustain cross-disciplinary research programs, the potential for developing collaborations with current faculty, and a strong desire to inclusively mentor graduate and undergraduate students. It is anticipated that the successful candidate will also contribute to one or more of the School's three strategic focal areas: Engineering for Human Health, Engineering for Sustainability, and Engineering the Human/technology Interface.

The past decade has been a period of extraordinary growth for the department, witnessing recruitment of over two-thirds of its current tenured and tenure-track faculty members and over a four- fold growth in research expenditures since 2007. The broader Tufts School of Engineering (SoE) distinguishes itself by the interdisciplinary and integrative nature of its engineering education and research programs within the environment of both a "Research Class 1" University and a top-ranked undergraduate institution. We offer the best of a liberal arts college atmosphere, coupled with the intellectual and technological resources of a major research university. As home to seven graduate and professional schools across three campuses, Tufts University prides itself on its culture of cross-School partnerships. Located on Tufts' Medford/Somerville campus, only six miles from historic downtown Boston, SOE faculty members have extensive opportunities for academic and industrial collaboration, as well as participation in the rich intellectual life of the region.

Candidates should possess an earned doctorate in Electrical Engineering or a closely related discipline. The applicant should clearly describe a research and teaching plan that builds on existing strengths and focal areas within the ECE Department and the School of Engineering. Candidates should upload a letter of application, research and educational plans, curriculum vitae, and the names and contact information for three references to **academicjobsonline.org**. Review of applications will begin November 1, 2014 and will continue until the position is filled. Tufts University is an Affirmative Action / Equal Opportunity employer. We are committed to increasing the diversity of our faculty. Women and members of underrepresented groups are strongly encouraged to apply.

Faculty Positions in Robotics and Mechatronics

NAZARBAYEV UNIVERSITY

Nazarbayev University is seeking highly qualified full-time faculty members at Assistant, Associate and Full Professor ranks to join its rapidly growing program in Robotics and Mechatronics in the School of Science and Technology. Successful candidates must have a Ph.D. degree from a reputed research university, a demonstrated ability for research, excellent English-language communication skills and a commitment to graduate and undergraduate teaching and program development.

Launched in 2010 as the premier national university of Kazakhstan, NU's mandate is to promote the emergence of Astana as the research and educational center of Eurasia. The strategic development of this English-language university is based on the Western model via partnerships with top ranking world universities. The university is committed to be a world-class research university and has made significant investments in research infrastructure, equipment and personnel.

Applications are particularly encouraged from candidates with research interests in the areas of biorobotics, mobile robotics, robot vision, industrial automation, unmanned aerial vehicles, and mechatronic system design. Exceptional candidates with research interests in all topics related to Robotics and Mechatronics are also encouraged to apply.

Benefits include an internationally competitive salary, international health care coverage, free housing (based on family size and rank), child educational allowance, and home-leave travel twice per year.

Applicants should send a detailed CV, teaching and research statements, and list of publications to sst@nu.edu.kz. Review of applications will begin immediately but full consideration will be given to applications submitted no later than September 15th, 2014. For more information, visit http://sst.nu.edu.kz.

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Start date: April 1 , 2015 or at the candidate's earliest convenience

Documents: (1) A curriculum vitae

(2) A list of research activities

(3) Copies of 5 representative papers

(4) A brief summary and future plan of your research and educational statement (within three pages each)

(5) Names of two references including phone numbers and e-mail addresses

(6) An application form (available on our website)

Deadline: December 12, 2014

Inquiry: Search Committee Chair Professor Masamichi Yoshimura (Phone) +81-52-809-1851, (e-mail) job-semicon@toyota-ti.ac.jp

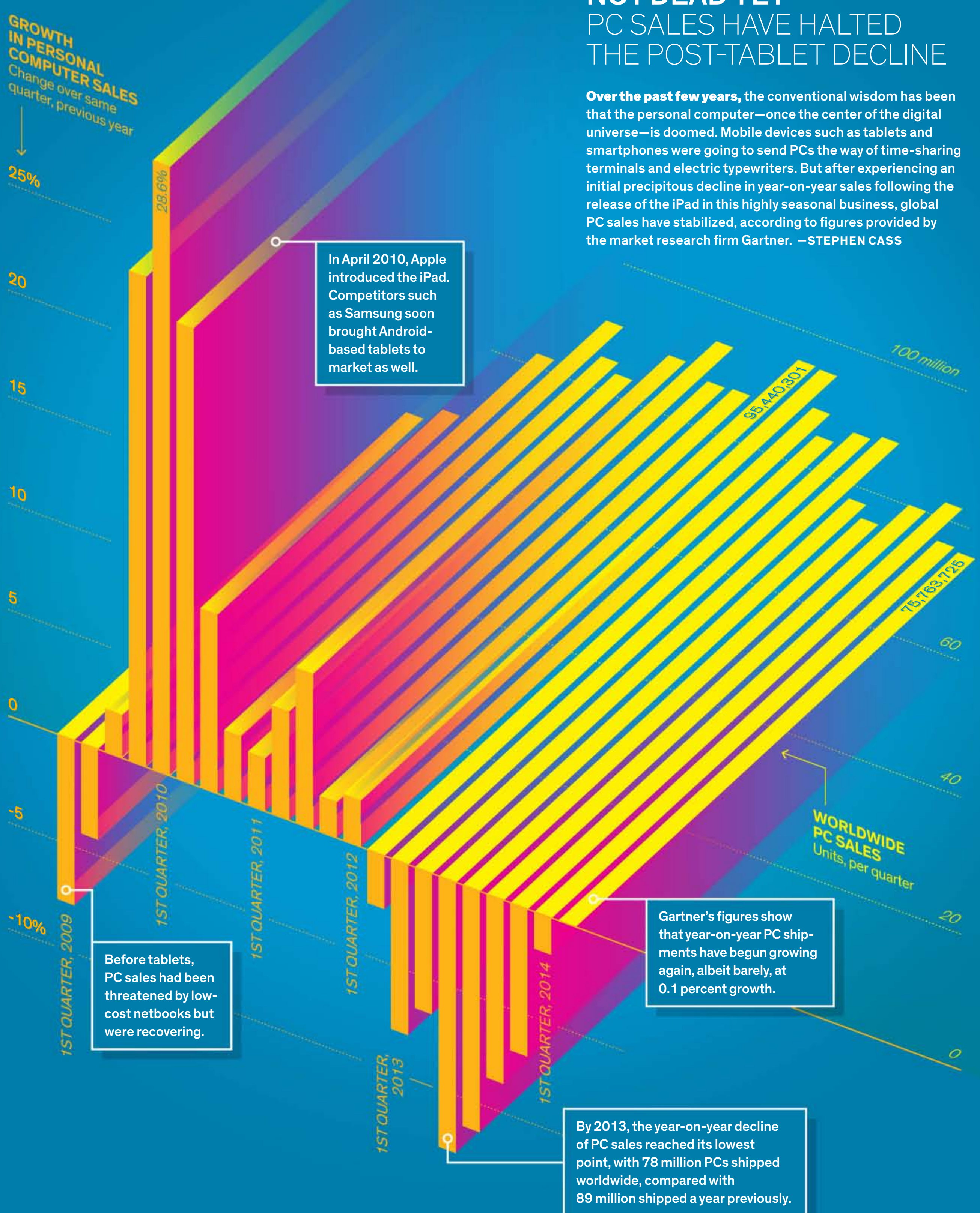
The above documentation should be sent to:

Mr. Takashi Hirato
Administration Division
Toyota Technological Institute
2-12-1, Hisakata, Tempaku-ku
Nagoya, 468-8511 Japan

Please write "Application for Semiconductor materials and devices" in red on the return envelope.

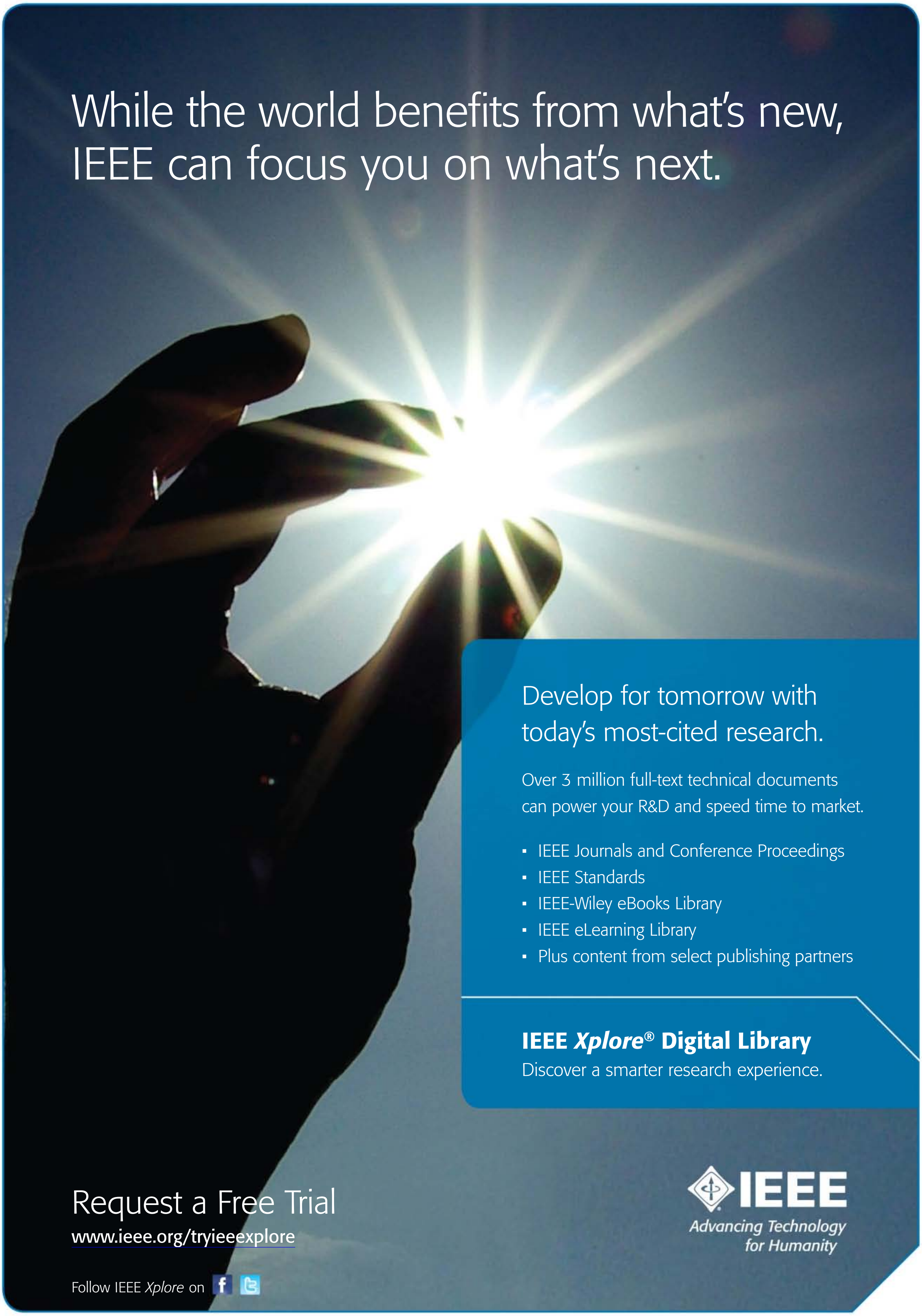
NOT DEAD YET
PC SALES HAVE HALTED THE POST-TABLET DECLINE

Over the past few years, the conventional wisdom has been that the personal computer—once the center of the digital universe—is doomed. Mobile devices such as tablets and smartphones were going to send PCs the way of time-sharing terminals and electric typewriters. But after experiencing an initial precipitous decline in year-on-year sales following the release of the iPad in this highly seasonal business, global PC sales have stabilized, according to figures provided by the market research firm Gartner. —STEPHEN CASS



SOURCE: GARTNER

IN OGRAPHIC Nicolas Rapp



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