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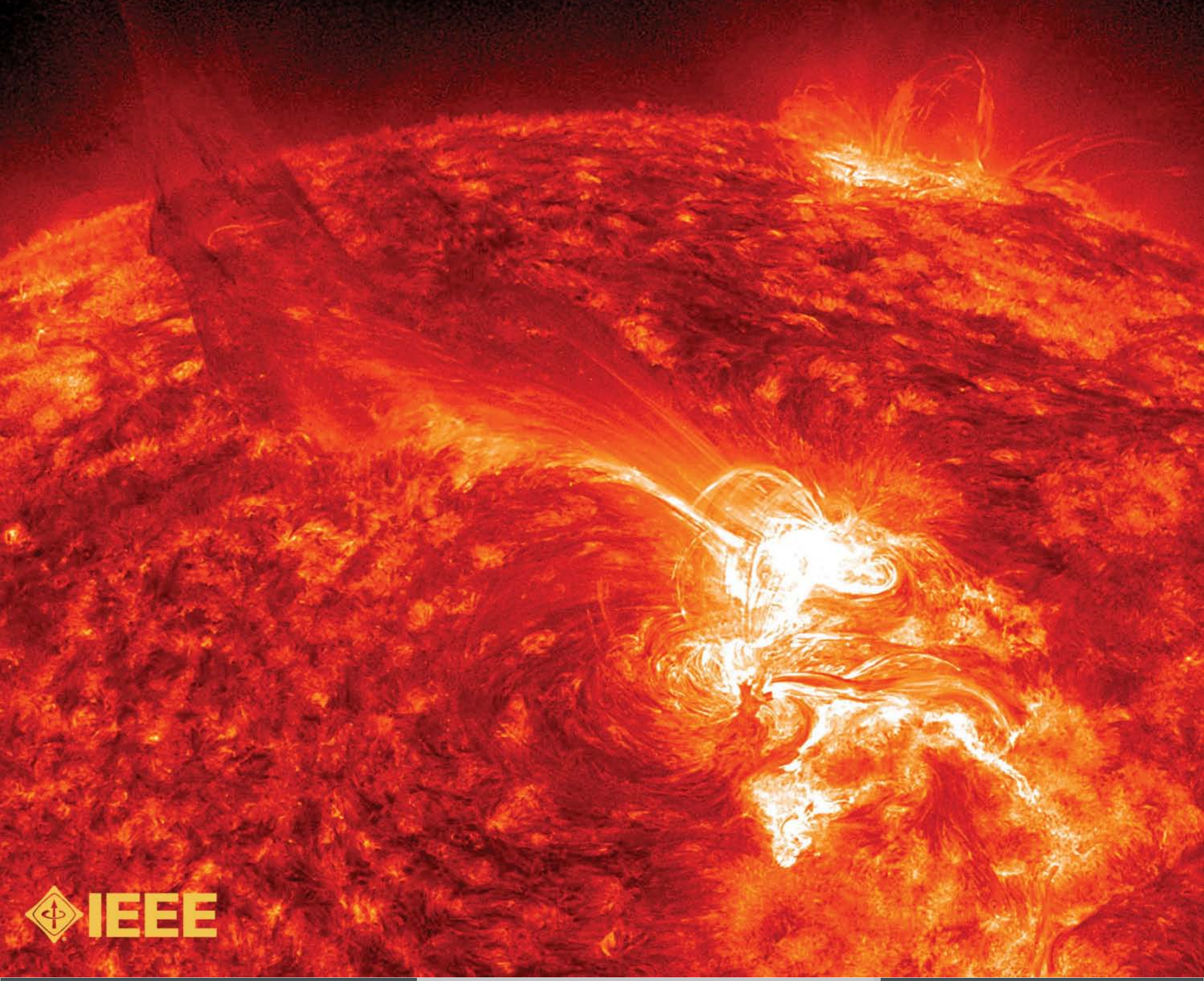
HERE COMES THE SUN

HOW A SOLAR SUPERSTORM COULD TAKE DOWN POWER GRIDS **EVERYWHERE**



IEEE

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COVER: SOLAR DYNAMICS OBSERVATORY/NASA
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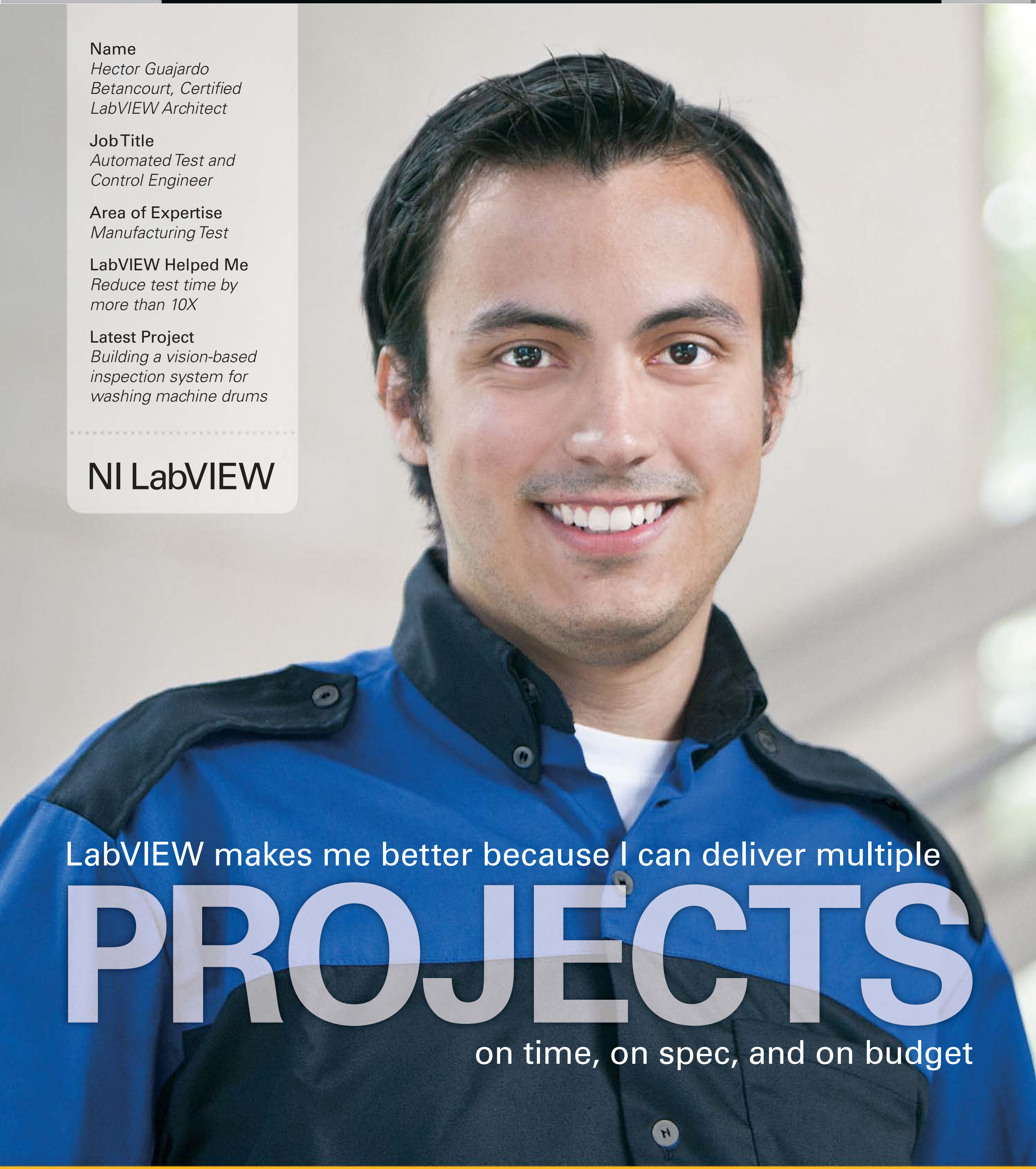
Name
Hector Guajardo Betancourt, Certified LabVIEW Architect
Job Title
Automated Test and Control Engineer
Area of Expertise
Manufacturing Test
LabVIEW Helped Me
Reduce test time by more than 10X
Latest Project
Building a vision-based inspection system for washing machine drums
NI LabVIEW
LabVIEW makes me better because I can deliver multiple
PROJECTS
on time, on spec, and on budget

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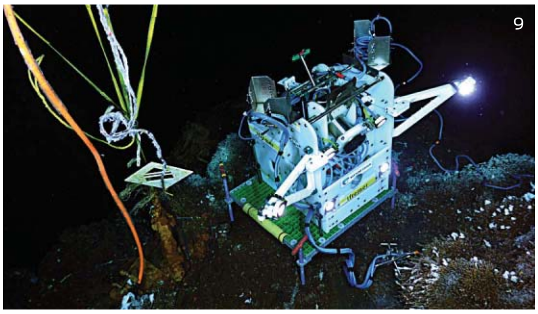

UPDATE

OPINION

DEPARTMENTS

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NCIS: IEEE?

Robert Charette, who writes our blog The Risk Factor, is a busy man. As a risk management expert and a frequent contributor to *IEEE Spectrum*, he has little downtime, but when he does, he likes to watch "NCIS: Los Angeles." A surprisingly accurate episode about an e-bomb attack inspired an e-mail exchange with a consultant for the show, IEEE Senior Member Carlo Kopp of Monash University, in Australia, and some fascinating insights into how high technology gets translated into high drama.

THEINSTITUTE.IEEE.ORG AVAILABLE 3 FEBRUARY

THE HAZARDS OF LIGHTNING
Lightning isn't just dangerous to humans and animals; it's also a significant threat to electronics, wind turbines, and distribution lines. Several members who are experts in the field explain why lightning protection is becoming so important.

IEEE FELLOWS MAKE THEIR MARK ON INDUSTRY
Four Fellows from the class of 2012 have had an impact not only on the technologies in which they specialize but also on industries like power and energy, light control, field-programmable gate arrays, and radio frequency safety programs.

CONFERENCE FOCUSES ON GLOBAL EDUCATION
The 2012 IEEE Global Engineering Education Conference, being held from 17 to 20 April in Marrakech, Morocco, will provide an interdisciplinary forum for academic, research, and industrial collaboration on global engineering education.

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back story

Over the Trench

As a young girl, Associate Editor Eliza Strickland sailed catboats around the idyllic harbors of the Maine coast during family vacations. But that experience didn't count for much when she was asked to take the helm of a research boat in the deep waters near Guam.

She was accompanying an expedition whose task that day was to send a deep-sea probe more than 10 000 meters to the bottom of the Mariana Trench in the mid-Pacific, the deepest spot in the world's oceans. The probe's designer, Kevin Hardy, is the subject of a profile Strickland wrote for this issue ["Going Deep"].

Hardy is a consulting engineer for Virgin Oceanic, the exploration company that hopes to send a manned submersible to the bottom of the Mariana Trench this year. If the company succeeds, its pilot will be only the third person in history to reach that mysterious seafloor—and the first since 1960. Hardy's probes will act as a robotic entourage for the manned sub, filming its maneuvers and collecting water and sediment samples.

The July expedition was a test run to ensure that the probes could do their job. Strickland took the helm briefly during the 11-hour trip from Guam, while the scientists and technicians were all readying their equipment. Of her brief time on the bridge, Strickland says, "Luckily, out on the open ocean there's nothing to run into."

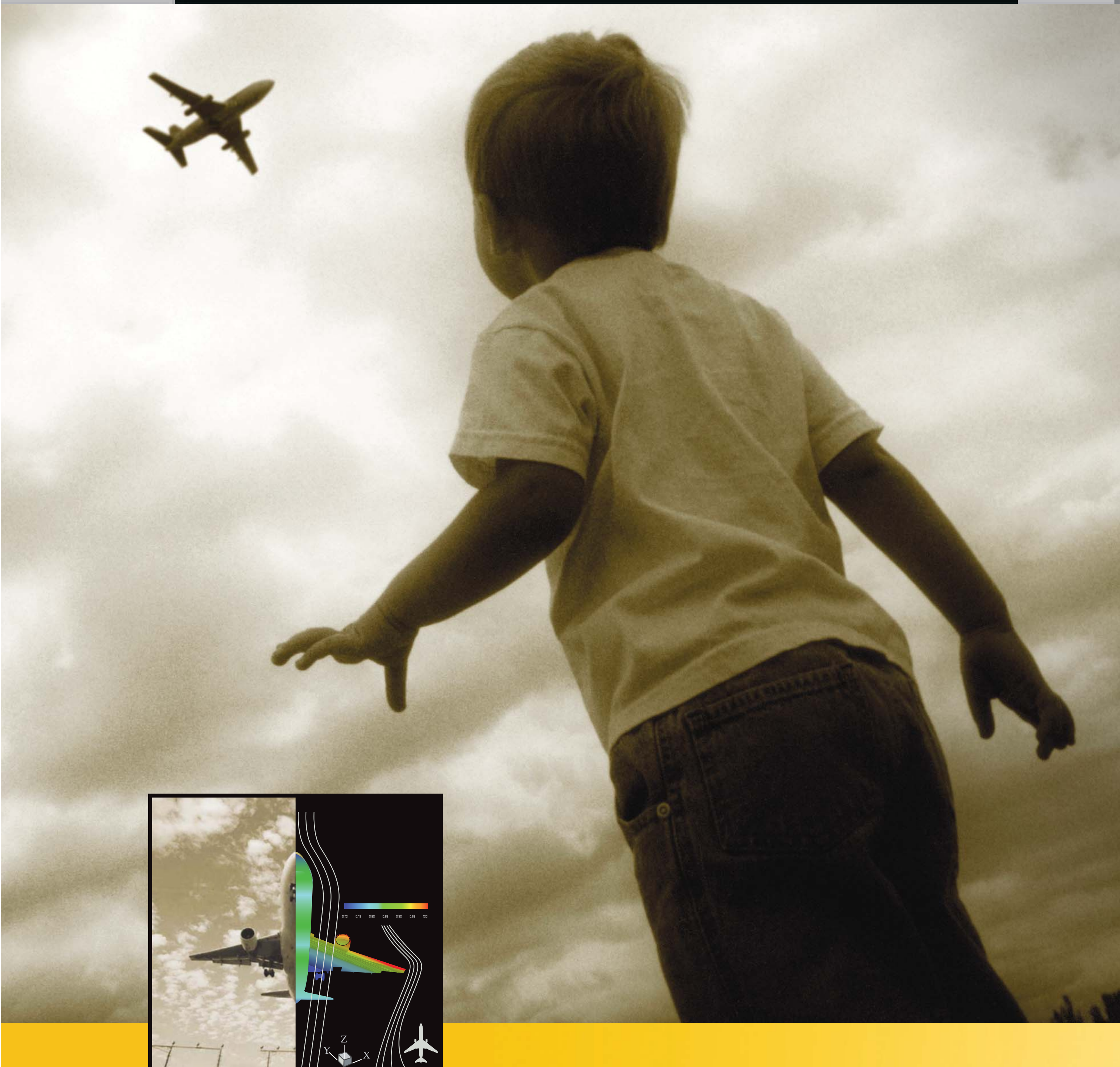
LAURIE RAYMUNDO

In the early evening, shortly after the crew dropped the probes, the weather took a turn for the worse. Tropical Storm Muifa had started blowing about 500 kilometers to the south, and it was roaring north. The waves were soon battering the boat, a retired ferry pressed into service for the expedition. Strickland says she had never experienced ocean swells like those before.

When night came, everyone unrolled sleeping bags on the floor of the ferryboat's spartan cabin. Strickland spent the long dark hours listening to waves slamming against the prow and stray objects tumbling around the cabin. "When I went sailing in Maine as a kid, we watched for seals and harbor porpoises," Strickland says. "Out there in the Pacific, with the nearest help about 11 hours away, I just wanted to see the dawn." ❑

CITING ARTICLES IN IEEE SPECTRUM

IEEE Spectrum publishes two editions. In the international edition, the abbreviation INT appears at the foot of each page. The North American edition is identified with the letters NA. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, The Data is in *IEEE Spectrum,* Vol. 49, no. 2 (INT), February 2012, p. 60, or in *IEEE Spectrum*, Vol. 49, no. 2 (NA), February 2012, p. 72.



contributors

ADA BRUNSTEIN is a linguist-turned-writer in Brooklyn, N.Y., who has lost countless hours to the lexical riches of the Google Ngram Viewer [see The Data, p. 60]. She works in academic publishing, acquiring computer science and robotics books. Brunstein has written for *The Atlantic*, *Technology Review*, and others on science, language, love, religion, robots, women, wine, and whiskey—“often about one under the influence of another,” she says, “but never about all at once.”

ANTOINE DOYEN, based in Paris, got into the pool with Antoine Ravisé to shoot his Dream Jobs portrait [p. 44]. Though the camera was in a watertight marine housing, Doyen hired “a second assistant just to watch the poolside equipment.” His photos have appeared in *The Financial Times*, *Runners World*, and *Vogue*. He is currently documenting the world of competitive tractor pulling. “Using an airplane’s engine on a tractor is quite something!” he says.

JOHN KAPPENMAN writes in this issue about the disastrous consequences a severe geomagnetic storm could have on the electrical infrastructure [p. 22]. “My first assignment as a power engineer was to devise solutions for all the problems these storms pose to power grids,” he says. He failed to do that in the allotted 6 months but stuck with it for more than 30 years. He frequently testifies before Congress and advises U.S. government panels on the topic.

ALAINA G. LEVINE, who profiled Phillip Toussaint for this issue [p. 50], is a Tucson-based science writer who spent her youth acting and singing in choirs. Then she was seduced by the dark side and got her BS in mathematics. But she still enjoys performing: A busy comedienne, she incorporates nerdy humor into gigs for engineering and science organizations.

RICHARD B. MILES, ARTHUR DOGARIU, and **JAMES B. MICHAEL** research optics at Princeton University. Miles is a professor of mechanical and aerospace engineering, Dogariu is a research scientist, and Michael is a graduate student. They measure subsonic and supersonic air motion with lasers and microwaves, accelerating air with surface electric discharges, magnetic fields, and electron beams, and speeding up flames with microwaves. Their work led them to use lasers for standoff detection, as described in “Bringing Bombs to Light” [p. 34]. In short, “we work on air,” Miles says.

CHUN-YUNG SUNG and **JI UNG LEE** write about steering beams of electrons with graphene in “The Ultimate Switch” [p. 28]. Sung supervises graphene and other research at IBM’s T.J. Watson Research Center, in Yorktown Heights, N.Y. Lee is a professor of nanoscale engineering at the University at Albany, State University of New York. Both have been astounded by how far graphene has come since it was first isolated in 2004. “With any luck, this material will take logic beyond silicon, well into the nanoscale,” says Sung.

CLOCKWISE FROM TOP LEFT: PHILIP LAUGHLIN; PETE BROWN/UNIVERSITY OF ARIZONA COLLEGE OF ENGINEERING; STORM ANALYSIS CONSULTANTS; ANTOINE DOYEN

spectral lines

PROPIEDAD INTELECTUAL: The Spanish anti-Internet-piracy law is named for the country's former culture minister, Ángeles González-Sinde.

Spain Declares War on Online Pirates

As 2012 BEGAN—and less than two months after winning control over the Spanish parliament—the right-leaning Partido Popular passed a controversial new anti-Internet-piracy law that will impose strict penalties on website owners who fail to remove copyrighted material from their sites.

Sound familiar? The law, named after the former culture minister, Ángeles González-Sinde [above], gives the Spanish government nearly the same broad-ranging authority found in the equally controversial Stop Online Piracy Act (SOPA) at press time wending its way through the U.S. Congress. Owners of the material can now complain to a government commission that can issue an order to block a website's service.

The Spanish law was initially brought up for consideration and rejected in 2010. Evidence obtained by the Spanish paper *El País* suggests that the United States has been pushing hard for a reevaluation of the measure ever since, using trade agreements as leverage to prod the Spanish government to resurrect it. It's no surprise that the United States has shown such interest. Piracy is epidemic in Spain. Thirty percent of the population uses file-sharing sites, often to download Hollywood movies.

But there are good reasons to think that the Sinde law will only encourage more of this behavior. Because the law goes after only the content provider and leaves intact an individual's right to a digital copy, it may actually encourage Spanish citizens to use peer-to-peer file sharing, says Rosa María Garcia Sanz, a professor in the department of communication law at the Complutense University of Madrid.

In fact, there is little evidence to suggest that the enforcement strategies called for by the new law actually work to stop illegal downloading. France passed a law in 2009, known as Hadopi, or the "three strikes" law. It gives the government the authority to interrupt service for individuals who are caught downloading illegal content after they've received two warnings. Plenty of people took the legislation more as a challenge than a threat; many immediately began avoiding detection, thereby sidestepping the regulation, with the aid of virtual private network servers.

The Sinde law will be just as tough to enforce, according to Professor Sanz: "Even blocking domain name system [DNS] sites," she says, "would just encourage users to use alternative and unregulated DNS servers. In other words, there is a real problem of applying the law because it [is] so easy to circumvent the technical barriers used to block users from reaching the websites."

The same will likely be true in the United States, where SOPA has been held up in the House Judiciary Committee since last year, and a far-flung group of individuals and organizations have targeted companies that have come out in support of the antipiracy measure. Even the Obama administration has suddenly taken an under-the radar position against SOPA. Developers are already providing tools to circumvent the legislation. The Firefox add-on DeSopa was written as a proof of concept, but if the law is implemented, the add-on would allow users to resolve blocked domains by obtaining an IP address through foreign DNS servers.

But these kinds of solutions, which would certainly become popular if SOPA is enacted, carry serious security concerns. They would most likely increase the incidence of DNS hijacking, whereby an attacker redirects queries to a faulty, and potentially malicious, IP address. Security analysts at Sandia National Laboratories, in Albuquerque, raised these concerns in response to both the Senate and House versions of the bill, calling the DNS filtering mandate a fruitless " 'whack-a-mole' approach that would only encourage users and offending websites to resort to low-cost work-arounds."

It's unclear how seriously members of Congress are taking this advice. Indeed, the Obama administration's opposition may make SOPA moot. As U.S. lawmakers pause to catch their breaths after the first rounds of this battle, they might consider taking an even bigger step back to watch how the Spanish effort plays out—to see whether legislation actually brings about the hoped-for result.

—MORGEN E. PECK

Morgen E. Peck is a technology journalist based in New York City and a frequent contributor to IEEE Spectrum. *This article is adapted from her Tech Talk blog post of 9 January 2012.*

ANDREA COMAS/REUTERS

update

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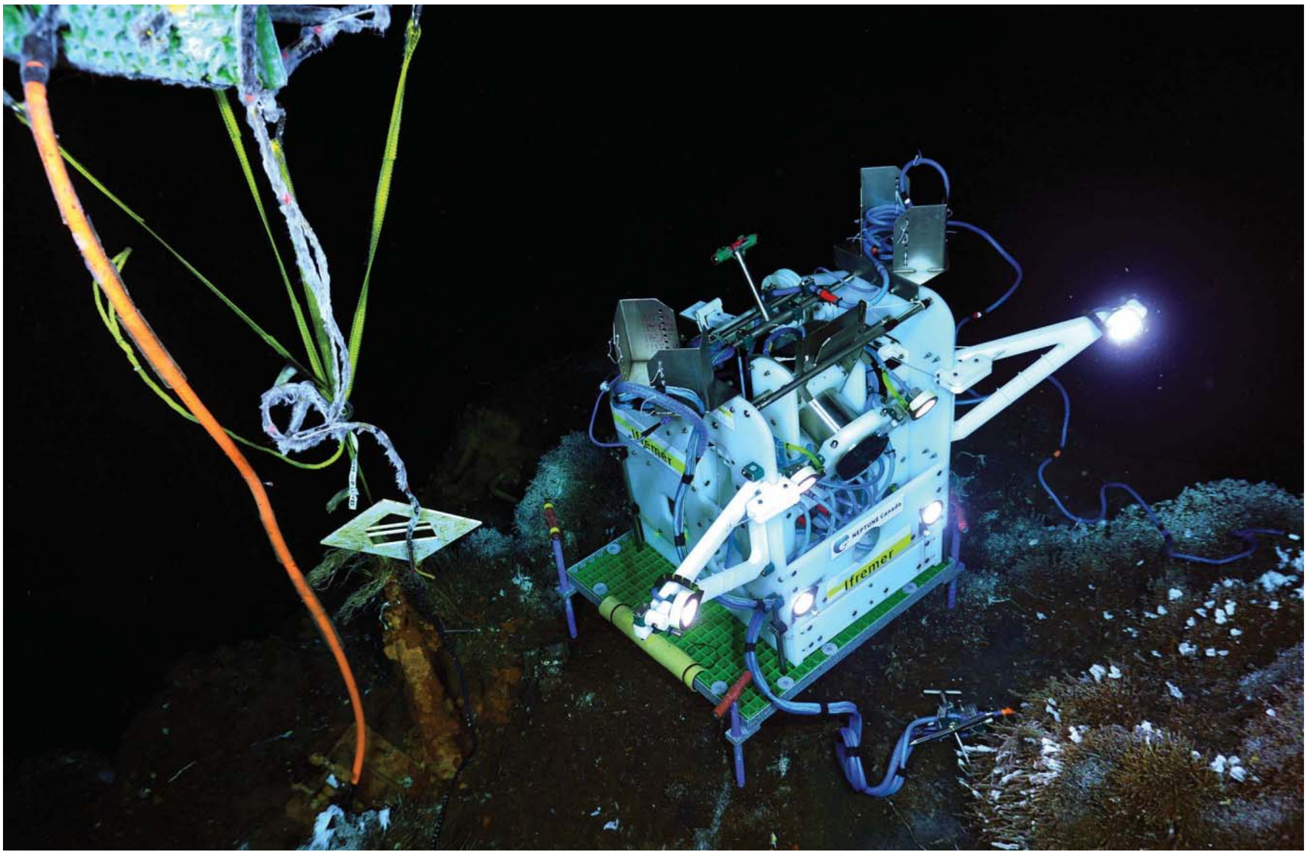

A Tale of Two Neptunes

The Canadian undersea observatory recovers from an outage, and its U.S. counterpart finally gets started

Few things make engineers as proud as seeing their creations shrug off a failure and keep delivering. That's exactly how the designers and operators of Neptune Canada—the world's largest remotely operated undersea observatory—must feel. Since going live in December 2009, Neptune has weathered several insults, including a dangerous encounter with a trawler, but it has still produced a near-continuous stream of live data from over 125 instruments at depths of nearly 2400 meters, including deep-sea video cameras, sonars, seismometers, and robotic crawlers.

At the end of last year, Neptune Canada had managed to bounce back from its biggest technical troubles yet, but now it faces a budget crunch that could put it on life support as early as next month. And that's happening just as the observatory's colleagues in the U.S. Pacific Northwest seem to finally be overcoming budget constraints that held up a sister observatory.

The engineers operating and maintaining Neptune Canada attribute its endurance, in large part, to the redundancy and intelligence built into its design. The observatory consists of an 800-kilometer loop of cable that runs out from a shore station in Port Alberni, B.C., delivering data via optical fiber and DC power to six branching units. Spur lines off those branching units supply power and communications to Neptune's instruments.

No single incident validated this design more than a September electrical fault that could have shuttered the entire system for months. At 14:10 coordinated universal time on 20 September

UNDERSEA INSTRUMENTS: The Tempo-Mini platform, part of Neptune Canada, houses sonar, a seismometer, and other sensors.

PHOTO: CSSF/IFREMER/NEPTUNE CANADA

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84 Number of quantum bits in the largest quantum calculation to date. D-Wave Systems says its quantum computer used 28 qubits for the calculation; the rest were for error correction.

update

2011, Neptune's 10-kilovolt DC power supply sensed a fault condition and automatically went off-line, taking the communications feed down with it. A technician trying to restart the system was able to bring it to just 180 volts at the system's standard operating current of 1.4 amperes, but those measurements enabled the team to pinpoint the fault. Figuring in the cable's resistance of 1 ohm per kilometer, they calculated that the fault was 90 km down the line, in the vicinity of the network's first branching unit going counterclockwise, Folger Passage, 87 meters deep on the continental shelf.

Getting a cable ship out to fix the fault would take two months and cost roughly US $1 million. But getting the rest of the network back online took just 10 hours, thanks to the loop design and the low-power switching capability built into the branching units. "The system design was not only clever but also actually worked as designed," says Benoît Pirenne, Neptune Canada's associate director for IT.

Pirenne and his team reconfigured the stricken system with remote help from Paris-based Alcatel-Lucent, which designed and built the loop. Low-power pulses from either end of the cable instructed the branching units to close off their spur lines. Further commands then closed off connections to the Folger Passage branching unit itself, which isolated the fault. Finally, the team fed power and data into and around the loop clockwise, bypassing Folger entirely.

The entire system was feeding data again, with the exception of those instruments attached to the spur at Folger Passage. They would turn on again two months later when that cable ship and a remotely operated vehicle replaced the faulty branching unit.

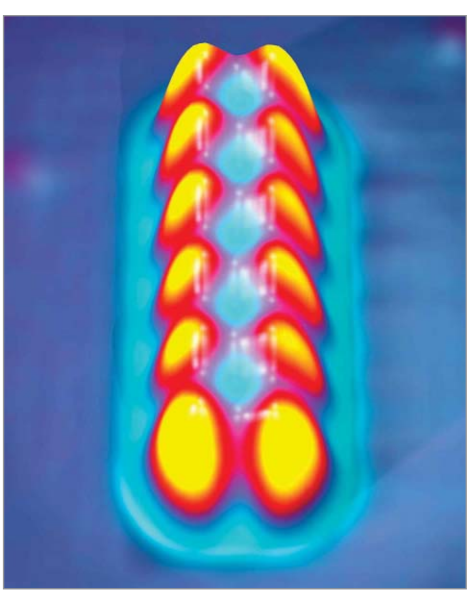
Ironically, about a week before Neptune Canada demonstrated the value of its loop architecture, a group at the University of Washington led by oceanographer John Delaney had installed the first pieces of another remote observatory—one that eschews the loop design that saved the Canadian system. The $76.6 million Regional Scale Nodes (RSN) project is the first major cabled observatory to move forward under the U.S. National Science Foundation's Ocean Observatories Initiative.

When completed in 2014, the RSN (originally also called Neptune) will boast eight nodes strung along 900 km of cable running out from the Oregon coast as two distinct strands. Neptune Canada's Pirenne says that design may not bounce back so elegantly from deep-sea faults. "All through [the September incident] we couldn't but think what's going to happen to our American friends," he recalls.

Undaunted, Delaney argues that the RSN design may prove to be more reliable, because the dynamically changing electrical loads experienced in loop configurations can put stress on components.

Neptune Canada was awaiting Alcatel's postmortem on Folger's faulty branching unit at press time, as well as something more crucial: a funding commitment from British Columbia's cash-strapped government. A five-year joint federal and provincial funding deal is up for renewal in March. Without it, Pirenne and his colleagues could be out of a job by this summer. He says it would be "a big waste of taxpayer dollars if the government would let us down and let a system like that rot in the water."

Delaney, by contrast, has a 25-year commitment of support from the NSF. Of course, budget exigencies could weaken the NSF's resolve. In December, the agency pulled the plug on two telescopes that had been in the works for over a decade. —Peter Fairley



The Littlest Bit

IBM scientists used a scanning tunneling microscope to push 12 iron atoms into place, forming the smallest magnetic storage bit ever. The 12-atom bits can be packed closely together because they use antiferromagnetic coupling, which makes them magnetically neutral. IBM estimates that such bits could lead to a 100-fold increase in storage density over today's hard drives.

SEBASTIAN LOTH/IBM RESEARCH/ALMADEN

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GPS-Interference Controversy Comes to a Boil

Cellular wannabe LightSquared can't reach a deal with GPS community

LOFTY GOALS: LightSquared launched a satellite to provide wireless coverage, but the company's terrestrial network is the real problem.
PHOTO: LIGHTSQUARED

LIGHTSQUARED, a Reston, Va.–based provider of satellite communications, intends to start up a new 4G cellular communications network using a portion of the radio spectrum traditionally reserved for mobile-satellite communications. That should be good news to the many U.S. consumers hungry for more bandwidth. The trouble is, LightSquared's cellular base stations could interfere with certain GPS receivers tuned to the adjacent satellite-navigation band.

Groups with an interest in the matter have been waging a public-relations battle over the past year, and members of the U.S. military and Congress have weighed in, too. Sadly, much of this discourse has shed more heat than light on the controversy. But more levelheaded engineers have also scrutinized the problem in detail, and the technical issues appear to be understood well enough to suggest possible work-arounds. Time to forge a solution, though, may have run out.

If so, LightSquared may have to abandon its ambitious plans. In any event, the current debacle suggests that regulators may need to impose strict standards on receivers, not just on transmitters, if the most valuable parts of the spectrum are to be used efficiently in the future.

LightSquared and its predecessor companies have been contemplating building a cellular network since at least 2003. The impetus was to improve mobile-satellite communications by offering customers the ability to connect to a cellular network in certain places. Someone who used the company's satellite-based system for making calls from Yukon mountaintops, for example, could also stay connected in the urban canyons of New York City or San Francisco using an "ancillary terrestrial component," a cellular network operating at the same frequencies as the satellites.

The U.S. Federal Communications Commission granted approval for such a fully integrated satellite-terrestrial service more than five years ago. But on 26 January 2011, in response to LightSquared's request, the FCC waived some of its previous requirements by permitting LightSquared's retailers—the companies selling voice and data packages to consumers—to offer wireless service from the terrestrial network without any accompanying satellite service.

"That put it on the radar," says Keith Barker, president and CEO of the Questiny Group, an engineering consultancy that works on satellite and other wireless communications systems. At that point, a lot of people who depend on GPS started to worry about the tens of thousands of 1500-watt base stations that LightSquared was planning to deploy throughout North America. Those stations would be transmitting on frequencies just below those that GPS uses.

Scott Pace, director of the Space Policy Institute at George Washington University, in Washington, D.C., says, "The basic physics of the matter is that you can't put something this large and powerful next to GPS and not have an impact."

The FCC's waiver, however, also required LightSquared to address GPS interference concerns by forming a technical working group made up of its engineers along with their counterparts in government and the GPS industry.

One member of that group is Rich Lee of Greenwood Telecommunications, a Denver-based engineering consultancy. LightSquared retained Greenwood to participate, but Lee, who is also involved in two GPS start-ups, says that this didn't compromise his objectivity. "I think we've helped LightSquared and the GPS industry by calling balls and strikes," he says.

The final report of the working group, issued in June 2011, makes very clear that without action, satellite navigation would indeed suffer. For example,

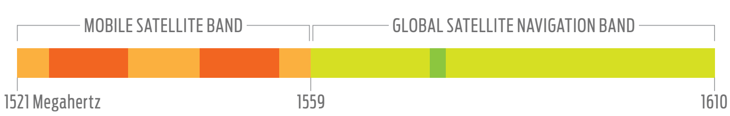
$1000 Cost to decode a human genome using Life Technologies Corp.'s Ion Proton Sequencer chip. The Human Genome Project did it for US $2.7 billion.

update

the group's aviation subteam wrote, "For the originally defined LightSquared spectrum deployment scenarios, GPS-based operations are expected to be unavailable over entire regions of the country at any normal operational aircraft altitude." Such dim assessments prompted LightSquared to propose that, rather than transmitting in its two 10-megahertz-wide frequency slots, the company's base stations would for a time just use the one farthest from the satellite-navigation band.

high-precision corrections to standard GPS location fixes. Awkwardly, these corrections are sometimes broadcast from satellites on frequencies in the mobile-satellite band, near those LightSquared's new system would use.

Can those GPS receivers be modified to cope, perhaps with the augmentation signals being sent on other frequencies? Sure. But it may be too late for calm discussion of such technical fixes. In a December 2011 request to the FCC, LightSquared backed away from its earlier



BAND AID: Most GPS receivers use a small patch of the navigation band [green]. To avoid interference, LightSquared initially offered to not use its portion of spectrum [orange] closest to the GPS band.

According to Lee, curtailing frequencies in this way, and better managing emissions from base stations to limit the power levels around them, would make LightSquared's operations compatible with most kinds of GPS receivers, including those used in cars and aircraft.

But GPS equipment designed to provide accuracy to within a centimeter or better would still suffer. These high-end units are susceptible to interference because they were purposefully designed with relatively broad RF filters on their front ends. This allows them to sense the timing of GPS waveforms very precisely and also facilitates the reception of what are known as augmentation signals—

conciliatory offer, arguing that "unlicensed commercial GPS receivers simply are not entitled to interference protection from LightSquared's licensed operations in the [mobile satellite service] band." "Now it's a slugfest," says Barker.

What lessons can be learned from this messy episode? Perhaps it's that spectrum regulators need to concern themselves more with receivers, not just transmitters. Right now, "the FCC has no regulations covering GPS receivers," says Barker. "We need definitely to have receiver-protection standards," says Lee. "GPS can be protected, but you have to take action on both sides."

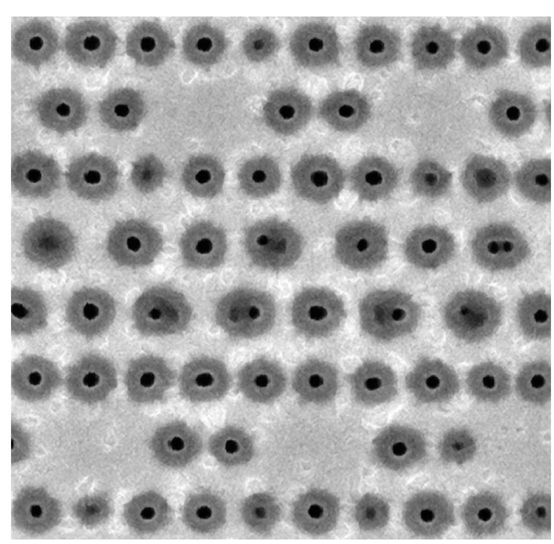
—David Schneider

Self-Assembly Takes Shape

Researchers exploit new ways to make ICs pull themselves together

Engineers in California have made an important advance in a technique that could help chipmakers create denser and cheaper integrated circuits. It might also extend the life of the traditional lithography process. With a method called directed self-assembly, the engineers were able to pattern contact holes for transistors in memory and logic circuits.

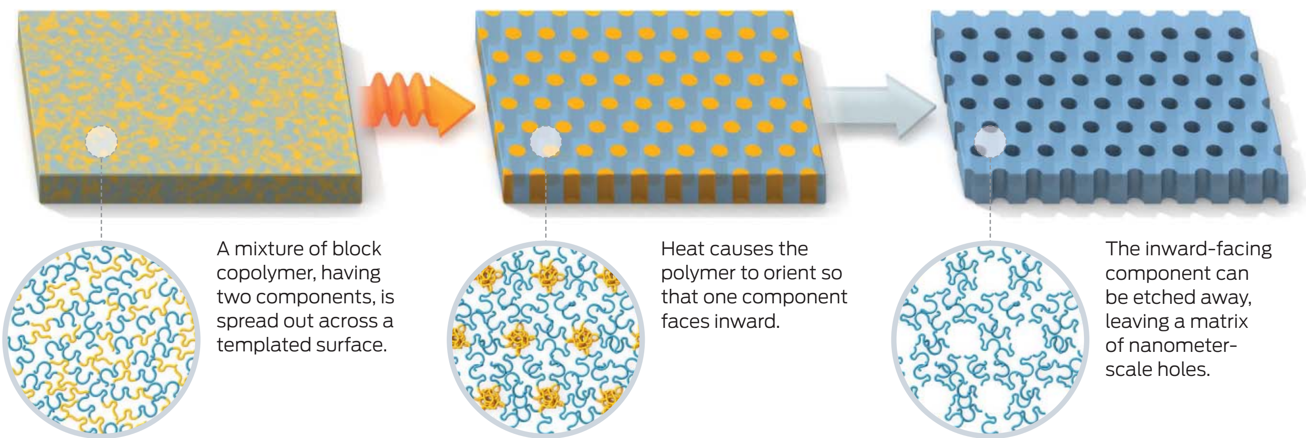
Today's chips are made using lithographic tools that expose photosensitive materials to light with a 193-nanometer wavelength. But this approach has become increasingly challenging, especially when it comes to making the holes in which the electrical contacts to transistors are formed. Currently, holes are created from the intersection of two etched lines, a process that typically requires two separate lithographic steps and has become increasingly inaccurate as chip features have shrunk. State-of-the-art logic chips now require that holes be placed as little as 60 nm apart.



ALL TOGETHER: Templates [in gray] were used to assemble static RAM contact holes [black].

IMAGE: XIN-YU BAO/HE YI/CHRIS BENCHER

40 Years since the iconic HP-35, the first pocket scientific calculator, was introduced. It marked the beginning of the end of the slide rule.



EMILY COOPER

Directed self-assembly, which harnesses the ability of some molecules to rearrange themselves into ordered, nanometer-scale structures, has long been eyed as a way to make smaller features. But the process doesn't naturally lend itself to chip designs, in which transistors and contacts are placed at varying distances. Molecules that self-assemble tend to form highly regular and extended arrays of alternating lines or tiled configurations of close-packed circles.

A group led by H.-S. Philip Wong, an electrical engineering professor at Stanford University, has found a way around this limitation by using ordinary lithographic methods to carve indentations that can act as guiding templates for smaller self-assembled features.

The team coated the entire surface of the silicon with a copolymer, each molecule of which consisted of a string of polystyrene linked to a string of poly(methyl methacrylate), or PMMA. When heat was applied, the PMMA side of each chain was drawn to other PMMA chains, balling together to form vertical cylinders within a matrix of polystyrene. Dissolving the PMMA left a polystyrene surface with holes that could be filled with conductive material to form electrodes. Successive etching steps left holes only where the indentations had been.

At the December IEEE International Electron Devices Meeting, in Washington, D.C., Xin-Yu Bao, formerly a postdoctoral researcher in Wong's lab, showed that these small indentations could be used to reproduce a design for a memory circuit, an IBM 22-nm static RAM. Wong says the demonstration puts directed self-assembly in the running to compete with long-delayed, next-generation lithography tools, which use extreme ultraviolet light (EUV) to create patterns. Directed self-assembly "can do what EUV can do, without the [US] $100 million investment," says Wong.

At the SPIE Advanced Lithography symposium in San Jose, Calif., this month, Wong's team will show that their template technique can pattern holes for a broad range of logic circuits, including adders and flip-flops, using a standard library of circuit components. These designs require simple indentations capable of holding one or two holes. But by altering the shape and size of the guiding templates, Wong says he expects to be able to create close-packed holes in squares, *L*'s, *T*'s, and other configurations. He believes that this alphabet of shapes will enable chipmakers to drive holes even closer together than can be accomplished with conventional lithography.

A number of other research groups are working on different aspects of directed self-assembly. "What Stanford has done is to take all those ingredients and bake a pie," says Chris Bencher, who is a member of the technical staff at Applied Materials and has collaborated with Wong's group.

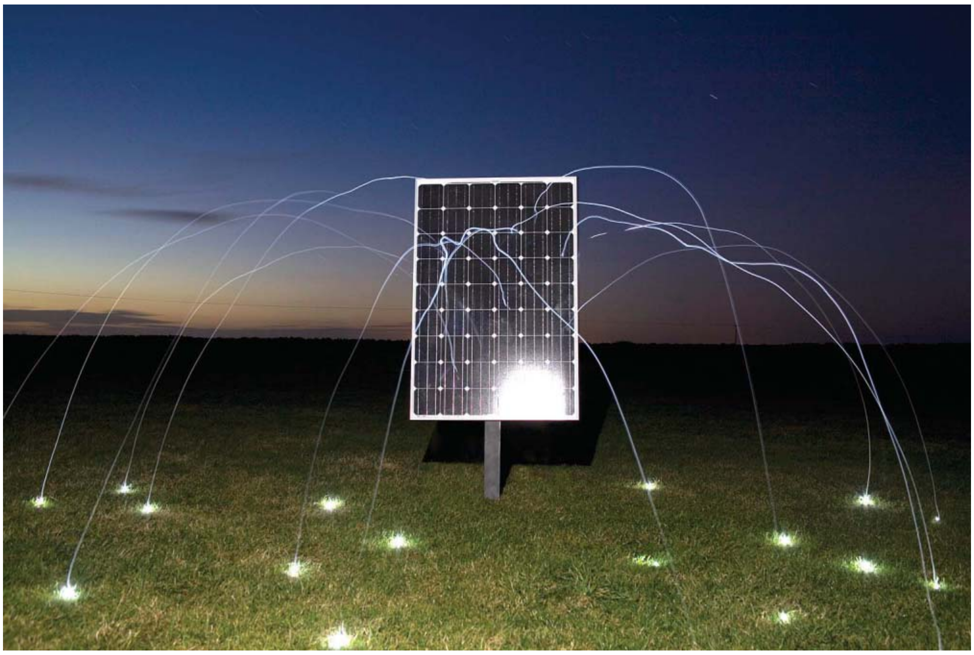
But Bencher notes there are two ways to make arbitrary patterns with directed self-assembly. One is to pattern small troughs, as Wong's group has done. The other is to create a regular array of self-assembled structures and then eliminate the ones that aren't needed. He suspects that Wong's technique, which will require fewer steps, might be the first to make its way into industrial semiconductor manufacturing but that the latter method may ultimately be better suited to driving down the distance between holes.

Whichever strategy is adopted, researchers must still work to reduce the rate of defects from factors like impurities in the polymer. Bencher and his colleagues have found that roughly one out of every 25 million holes is missing. That's a low rate, but it's still too high to meet the exacting standards of the chip industry, whose ICs have upward of a billion contacts. But, says Bencher, "we are definitely getting close."

—Rachel Courtland

1.11 TERAHERTZ The new frequency record for a microelectronic transmitter. The transmitter, constructed at Technische Universität Darmstadt, is smaller than 1 square millimeter.

update



Nanostructures Catch the Light

Razor-thin solar cells could be cheap but need a little help holding light in

EFFICIENCY MAY be the first parameter you think of when you hear the word *photovoltaics*. However, a less-talked-about factor can have a big impact, too—how thin a solar cell is. Researchers have recently come up with new ways of slimming down cells using structures smaller than the wavelengths of visible light.

"The main aim is to use as little material as possible to absorb sunlight," says Shanhui Fan, associate professor of electrical engineering at Stanford. High-efficiency materials, such as III-V semiconductors and crystalline silicon, are expensive. With other materials such as amorphous silicon, cost is less of an issue, but the electrons and holes that carry charge travel only short distances before being lost as heat. "The thinner the cell gets, the easier it is to get the carrier out," Fan explains. However, the thinner a solar cell is, the more likely that photons will pass right through it before they can be absorbed.

Commercial crystalline silicon cells can be 180 micrometers thick, Fan says. But some companies are pushing to get down to 50 µm, while his lab and other researchers are aiming for designs that are only a micrometer or two thick. In theory, techniques such as adding random nanoscale texturing to the surface of cells could enhance light absorption by as much as 50-fold, Fan says, by changing the angles at which photons travel through the cells, but nanophotonics can improve that by another factor of 10.

One approach is called plasmonics. Photons striking small, metallic structures can create plasmons, which are oscillations of electron density in the metal. The effect can increase the scattering of light within the solar cell, giving it more of an opportunity to absorb the photons. Vivien Ferry, a postdoctoral researcher at Caltech, says her team is creating plasmons using hemispheric bumps on the contacts of a 90-µm-thick solar cell made of hydrogenated amorphous silicon. Ferry says the nanostructured device produces 15 percent more current than a commercially produced, randomly textured solar cell.

Another nanophotonics trick in the works is using photonic crystals to construct reflectors. Photonic crystals are periodic structures with features smaller than the wavelength of the light they are designed to deal with. Miro Zeman, who heads the photonics materials and devices group at Delft University of Technology, in the Netherlands, says his lab has built photonic crystal reflectors at both the back of the cell and in the middle. The reflectors force light to bounce around inside the silicon, increasing the chances that it will be turned into electricity.

Another photonic crystal scheme would use the structures in a 1-µm-thick layer of crystalline silicon. According to Ounsi El Daif, a researcher at Imec in Leuven, Belgium, the photonic crystal layer can then be joined to an amorphous silicon layer. Because the film is so thin, "traditional texturing techniques cannot really work in this case," El Daif says. Theoretically, he says, such a photonic crystal could increase photon absorption by 37 percent.

These technologies are still years from being commercial products, Fan says. But they might be worth the wait.

—NEIL SAVAGE

GEIR PETTERSEN/GETTY IMAGES

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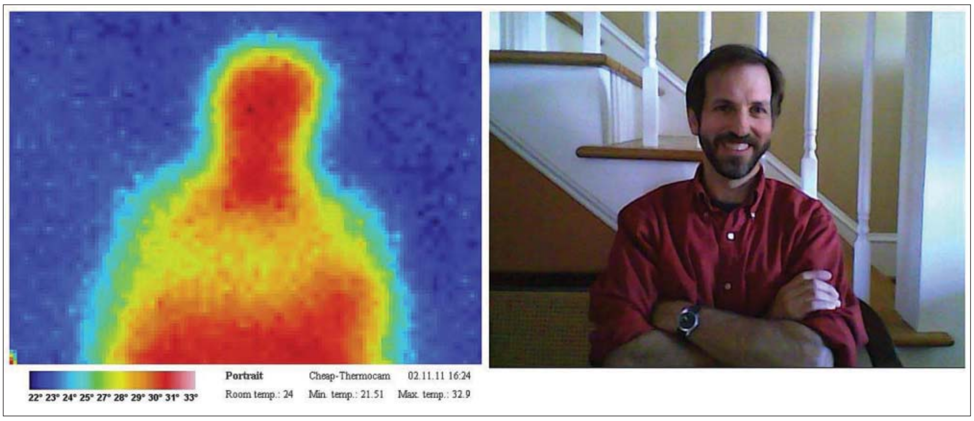
hands on



TEMP WORK: Thermal portraits [top left] are fun, but the device also finds energy leaks: Cool air produces the blue in this scan [bottom left]. A professional imager shows the effect in greater detail [bottom right].

IMAGES: DAVID SCHNEIDER

IR EYE

A cheap infrared scanner can replace an expensive thermal-imaging camera

A RECENT ENERGY audit at my place of worship indicated that the insulation in the walls and ceiling was pretty poor. That was obvious enough from casual inspection. But some subtle cracks revealed themselves only through the use of high technology—thermal imagery, which showed the locations of several air leaks in vivid detail.

Seeing those results, I was so impressed that I went off to the Web to check out thermal-imaging cameras, only to discover that they typically run several thousand dollars. Ouch. This type of imagery shouldn't be confused with run-of-the-mill infrared photography, which uses wavelengths only slightly longer than 0.75 micrometers or so. Thermal-imaging cameras sense much longer wavelengths, typically 8 µm or more.

The difference is critical: Unless you're taking a picture of something heated to the point of being almost red hot, infrared photography, like normal photography, requires that the object be illuminated. And all you see in the image is how much of the incident infrared light is reflected. Thermal imaging, on the other hand, senses the infrared radiation given off by everyday objects of modest temperature. So it can work stealthily in total darkness, which is why the military, which cares less about cost than I do, often uses it to sense enemy movements.

But my Web search also turned up a US $200 device capable of creating thermal images. Its resolution is lower than that of commercial thermal-imaging cameras, and each image takes much longer to obtain. Those seemed reasonable trade-offs. Of course, I'd have to build it myself.

The Cheap Thermocam is the brainchild of two 18-year-old students, Max Ritter and Mark Kohl, from Mindelheim, Germany. The project earned them an award in the 2010 Jugend Forscht, the largest science and technology competition for young people in Europe. Ritter has a website where he documents what is needed to build the device, including sources for virtually all the required components.

The strategy for reducing cost here is to avoid having to buy an imaging array of any sort. Instead, the thermocam uses what you might think of as a single-pixel infrared sensor: Melexis's MLX90614-DCI ($67 from Future Electronics. Note: Buy only the DCI version, which has high sensitivity and a very narrow field of view). That sensor is attached to a simple pan-and-tilt mechanism, which does a line-by-line scan to produce an image. A laser pointer (also mounted on the pan-and-tilt) and a webcam affixed to the main enclosure allow the thermocam to generate a matching picture of the area scanned.

The project also includes an Arduino microcontroller, which handles low-level communication with the Melexis sensor and generates the necessary signals for the servomotors in the pan-and-tilt mechanism. A program written in Java does most of the computational heavy lifting. I ran it on a PC under Windows 7 and had no problem.

On his website, Ritter indicates that he will soon be selling a custom printed circuit board to replace the generic Arduino and enclosures to make construction that much easier. I simply purchased an Arduino Uno board ($30) along with a nice powder-coated metal enclosure for it (PRT-10033, $30 from SparkFun Electronics).

I departed from Ritter's design in other minor ways, too. I bought what I thought would be more robust servos (Hitec HS425BB, two for $13 each) and a pan-and-tilt mechanism (DDT500H, $25), all from Servo City. I got a laser module with digital control (COM-08654, $19) along with a plastic mount for it (COM-08674, $5), both from SparkFun, instead of the $8 module that Ritter had suggested, mostly because feedback on the SparkFun website indicated that the power wires on the cheaper module have a tendency to work loose.

Assembly took just a few hours, mostly spent modifying the metal enclosure so that it would hold the pan servo firmly in place and I could mount the whole thing securely to a tripod. The Java software worked straightaway, although the Arduino code took a bit of tweaking to get the thing to pan in the correct direction with my particular servos.

The one thing that put me on edge, though, was a secondary Arduino program that Ritter includes with his code distribution. This code issues a stern warning up front: "This program will change the EEPROM settings of your MLX90614-DCI sensor to work best with the Cheap Thermocam. Please make sure you only use this with the DCI version, otherwise you will destroy your sensor." The word *destroy* certainly got my attention. And Melexis's documentation confirmed that it is perfectly possible to change certain settings that shouldn't be altered. I didn't want to run this program until I had figured out exactly what it did and until I had recorded the factory EEPROM settings on the sensor so that I could restore them.

FACE-OFF: A commercial thermal imager [left] produces higher-resolution images and works much faster, but the tripod-mounted Cheap Thermocam [right] does basically the same job—and on a budget. PHOTO: DAVID SCHNEIDER

Meanwhile, I was scanning various corners of my own home to check out what the Cheap Thermocam could do. Quite a lot, really. It could, for example, show where the weather stripping was leaking air on one side of my front door. Sure, my hand could sense the ingress of cold air there, too, but the thermal images also showed other, more subtle areas of heat loss, such as along baseboards or at electrical outlets.

To get a better sense of how valuable the Cheap Thermocam would be for tracking down such things, I contacted Mark Bashista, owner of Home Performance NC, a home-energy auditing business based in Pittsboro, N.C. He was kind enough to let me tag along on one of his energy audits, where we compared the Cheap Thermocam's images with ones from his $8000 FLIR B60 thermal-imaging camera.

"I was impressed by the contrasts [the Cheap Thermocam] showed, and the resolution isn't horrible," says Bashista. "But to have to use a tripod and to wait 3 minutes makes it impractical for a home-energy auditor." Bashista suggests that the unit might be more valuable just using the Java software's live-temperature function, which reports in real time the temperature of a single spot.

Bashista wasn't overly concerned about the limited resolution, because the images he obtains are often most useful not for discovering flaws, he says, but for communicating results to his clients. "It helps to explain what's going on."

Energy audits aside, the Cheap Thermocam has considerable novelty value, particularly if you use it to scan people. Forget Kirlian photography and energy auras. Now you've got a gizmo that can measure the actual energy people emit. You'll of course need to switch off the laser module so as not to risk eye damage, but it shouldn't be too hard to get things framed up without it. That the subject has to hold still for a few minutes during the scan demands a little patience, but I suspect it will only add to the sense of metaphysical intrigue.

Oh, and as for that second Arduino program? As it turns out, my concerns were unjustified: The new settings adjust the internal digital filters to reduce the sensor's time constant (which is initially set to about half a second) by a factor of 10 or so. The resulting images don't appear noticeably noisier and are much less blurred—just the ticket for a high-quality energy portrait.

—DAVID SCHNEIDER

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tools & toys

A SOFT TOUCH

Telikin's new touch-screen desktop computer targets seniors—and runs Linux

IN 1984, Apple's slogan was "The computer for the rest of us." Twenty-seven years later, people are still trying to build that machine—a computer for folks who really don't want to know about computers. Interestingly, the target market is exactly the same. In 1984, it was your parents, the ones whose VCR clocks forever blinked 12:00. In 2011, it's still your parents. Nowadays, their DVR always shows the right time, but they finally need a computer to keep up with you and the grandkids.

The touch-screen Telikin All-in-One is directly aimed at that demographic, and it takes a bold approach: Seniors today want to run Linux. There's no clue to what distribution it's based on, because it's been firmly locked down. You can't install software on it via any normal means, and you don't get a terminal or a file browser or even a desktop. The only way you know it's Linux is by catching the image of Tux the Penguin during an ungraceful screen flicker at boot-up.

First things first, however: Plug in the keyboard and mouse. The keys have large-print letters for failing eyesight, although the keyboard itself felt mushy. The scroll-wheel, three-button mouse feels cheap, and it tracks well on only the most mouse-friendly surfaces. Worse, the operating system supports only one button and the scroll wheel. Telikin should have gone old-school, Apple-style, with a one-button mouse.

Once the computer has booted up, a home screen displays panes of large text and a column of functions on the left for news, video chat, e-mail, and Web. A pane in the upper right tells you things you need to do, like create a user profile or set up your e-mail account. Missing, though, is a prompt to put the computer on a network, even though many of the setup tasks it suggests require network connectivity.

A complete wizard for setup would be very welcome: The target audience for this computer can't be expected to proceed without direct prompting and contextual help. Especially important in this regard is the one very nice feature that should be moved front and center. Instead, the item every savvy child of a technophobic parent desires—a remote IT function—is buried deep within a system setup menu.

Put in your info as the user's Tech Buddy and you now have an account on the Telikin support site, permitting you to take remote control of this particular machine. This feature would be needed even if the All-in-One didn't run a mysterious version of Linux that's sure to be different from anything you've ever encountered.

An hour into my exploration of the computer, I remembered one of its major features: its touch screen. Having plugged in the mouse

Telikin 18-inch Touch Screen All-in-One Desktop
US $699
http://telikin.com

TELIKIN

and keyboard, I simply forgot! But I blame Telikin as well as myself—this is a computer that can't make up its mind whether to behave like a desktop or a tablet. For one thing, there's no virtual keyboard. The touch screen makes the physical mouse redundant—why not dispense with the physical keyboard as well? This uncertainty also shows itself on the software side: Click-dragging with your finger does what you would expect on a desktop machine—it selects text. But the more desirable behavior on a touch-screen device—not to mention on a machine where the emphasis is on consuming media rather than creating and editing it—is iOS-like scrolling.

As I began to use the touch screen, my attitude toward the computer significantly improved. The screen responds well, and all the buttons and scroll bars are nicely sized for all fingers—easy to hit and not too close together. Making scroll bars unnecessary to begin with would have created a more touch-friendly interface, of course, but at least they're not a problem.

Unexpectedly, I began to compare the All-in-One to the iPad. Both try to make computing far more accessible. But iPads have small text and buttons, an elegant user interface that hides important information, icons that get all wobbly if you touch one for too long, and a penchant for deleting things after a careless poke at the screen. iPads are highly portable for folks who might not be, and yet may be too heavy for arthritic hands. The All-in-One, while not as pretty, might be a better choice for the exact market the company is targeting. The computer has a handy DVD slot, and its screen is big enough to watch movies on. In fact, the one thing it might be missing isn't the ability to run apps; it's a remote control for the DVD player.

In reviewing this sort of computer, the experienced user must put himself in a mind-set he probably never had—that of someone truly intimidated by everything about a computer. Did Telikin do enough to assuage such a user's fears? I have to say yes: When you poke at this computer, the result is just about always what you'd expect, and I was unable to make it do anything I thought my children's grandparents would consider scary or confusing. For a senior who needs a computer for iPad-appropriate activities but for whom an iPad is unreadably small, a desktop computer with a touchscreen may be the best of all possible devices.

—Harry Teasley

POMEGRANATE SOFTWARE

MATHSTUDIO

A new smartphone and tablet app runs 300 math functions and your own scripts as well

Back in 2009, I began a review of a cute little mobile mathematics program by saying, "You never know when you'll be dining out with your friends and have to work out a partial derivative or two." The program—originally designed for Palm Pilots and Windows Mobile phones—is still as attractive as ever, now running on iPhones and iPads and all manner of Android devices.

MathStudio is an updated version of SpaceTime (see "The Mobile Polynomial," *IEEE Spectrum*, January 2009). With more than 300 numerical and symbolic math functions, programmability, and eye-popping graphics, it's like having a miniature version of Mathematica, at a miniature price.

Because MathStudio is available for Windows, smartphones, and tablets, you can write scripts on a Windows machine, transfer them to a tablet, and bring complex calculations along with you wherever you go. *Spectrum* strongly discourages doing higher math while driving, however.

I spent some time with MathStudio on my iPad and found it easy and fun to use. (I did not search for possible errors in its symbolic math, which has a number of difficult cases that have tripped up other math programs in the past.)

MathStudio is a natural for students and for engineers who occasionally need a comprehensive math program but don't need the full horsepower and daunting complexity of Mathematica or Maple. It's a huge leap from the usual calculator program for tablets and smartphones. And the price is right.

—Kenneth R. Foster

MathStudio, by Pomegranate Software, is available for Android phones and tablets, the Apple iPhone and iPad, and computers running Microsoft Windows, at costs that range from US $20 to $30. With the free limited-time version of SpaceTime for Windows, available only to *IEEE Spectrum* readers, you can create scripts that will run with MathStudio on smartphones and tablets as well as Windows. Go to http://www.mathstudio.net/spacetime-ieee for a copy.

careers

PASSPORT TO ENGINEERING

A new ID card will establish an engineer's credentials throughout the EU

IN THE CARDS: The engineerING card is already valid in Germany and the Netherlands. *PHOTO: FEANI*

Engineers in the European Union are free to work anywhere in the 27 member states, but recognition of their professional qualifications is often a stumbling block. That could soon change.

A new professional card—resembling a European driver's license—documents educational and professional qualifications in accord with internationally recognized standards. It's available now in Germany and the Netherlands, with several more countries slated to adopt it next year.

The new "engineerING card" comes as demand rises for internationally mobile engineers in Europe. Countries like Germany and Sweden are reporting an acute shortage of engineers, particularly in high-tech sectors. At the same time, firms need engineers who can be flexibly deployed throughout Europe.

"I think a card based on international standards could be a really good way to help young engineers find work outside their home country," says Martin Kast, a German telecom engineer with Ericsson who was transferred to Spain three years ago. "In fact, it could be really handy right now for many of the unemployed young engineers in Spain who are looking for jobs abroad."

The engineerING card is the brainchild of the European Federation of National Engineering Associations (FEANI), based in Brussels, which represents 3.5 million engineers and more than 500 000 engineering students across the region. The card has yet to be adopted by the European Parliament and the European Council, but it's expected to be immediately useful, nonetheless.

"We aim to show that the engineerING card can function today internationally without a legal EU framework behind it," says Lars Funk, head of the profession and society division at the Association of German Engineers (VDI). "That said, we expect that EU officials with whom we have worked closely to meet all their requirements will honor our grassroots efforts and officially recognize the engineerING card."

The initiative coincides with efforts by the European Commission to revise its Professional Qualifications Directive, with one of its aims being the launch of a portable professional card to streamline recognition procedures.

The biggest issue that engineering organizations have with the directive is its definition of a "competent authority"—which, says FEANI secretary general Dirk Bochar, "aren't always competent. And those that are competent aren't always the authorities. In Italy, for instance, all applications for professional qualifications must go through the Ministry of Justice. These people have neither the ability nor the capability of judging and evaluating whether an engineer coming from Belgium or Bulgaria is equivalent to one from Italy."

Bochar argues that the professional card for engineers should ideally be the responsibility of national engineering organizations. "Or, at the very least, the ministries or other authorities should delegate responsibility to us to issue the cards for engineers," he says.

Under the FEANI scheme, engineerING cards are issued by a national register commission consisting of experts from relevant engineering organizations, university engineering professors, and officials from the responsible ministry. Each registry commission operates its own database, which stores all professional documents in digital form. National databases are to be linked to a central server in Brussels.

The card provides information on education, professional experience, and continuing professional development based on international standards, such as the European Qualifications Framework and the European Accreditation of Engineering Programmes. All information appears in English along with the language of the country of issue. Valid for 10 years, the card is available on a voluntary basis to European engineers only.

The card could save European engineers both time and money—up to six months and several hundred euros—currently spent obtaining a series of documents that have to be certified and translated individually. In Germany, the engineerING card can be processed within a couple of weeks and costs €95 (about US $125) for those engineers belonging to an association such as VDI, and €120 otherwise.

Qualification barriers that have undermined the career aspirations of many engineers in Europe could soon disappear. "For engineers and engineering companies," Funk says, "it's a win-win deal." —John Blau technically speaking BY PAUL McFEDRIES

Tufte-isms

Graphical excellence is that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space. —Edward R. Tufte

WE LIVE in an age characterized by *PowerPointlessness*, where Microsoft PowerPoint presentations are not only ubiquitous but laden with sounds and transitions that have no discernible purpose.

It's an age of the *triple delivery*, where presenters hand out text, display it on the screen, and then read it aloud. It's an age, too, of the *charticle*, a news article that consists of a graphic with a depressingly small amount of explanatory text.

The sad irony here is that as information overload has gone from a theoretical concept to an all-too-present reality, information formats designed to reduce that overload, such as presentations and newspaper articles, are increasingly dumbed down and lacking in substance.

Fighting the good fight against this trend are the proponents of **information design**, the art of presenting data in efficient, accurate, and easy-to-understand ways. Their guru is Edward R. Tufte, a statistician, Yale professor, and author of several influential books on **analytical design** and **visual literacy**, most notably *The Visual Display of Quantitative Information* and *Envisioning Information*.

My purpose here isn't so much to examine Tufte's ideas and measure his considerable influence but to see how those ideas and his influence have shaped the language. Tufte, it turns out, is not only a doyen of **data visualization** but also a neologist par excellence who has coined a number of memorable and useful terms.

Tufte's most famous coinage might be **chartjunk**, which refers to chart elements that not only serve no purpose but may in fact hinder understanding. "Credibility," Tufte notes, "vanishes in clouds of chartjunk." In Tuftese, when chartjunk takes a cartoonish form (for example, increasingly tall piles of dollar bills to illustrate rising prices) the result is a **chartoon**.

Tufte has famously said that when it comes to the visual display of information, "above all else show the data." So one of the key principles in good information design is to shoot for a high **data-ink ratio**, which is the ratio of **data-ink** (the elements that convey the actual data) to the total ink used in the graphic. To calculate this, first distinguish the data-ink from the **redundant data-ink** (data elements repeated unnecessarily) and the **non-data-ink** (elements that are used ostensibly to support the data, such as grid lines, axes, labels, and legends, or as decoration, such as background colors, data markers, and of course, chartjunk). "Ink" here refers to both text and graphical elements.

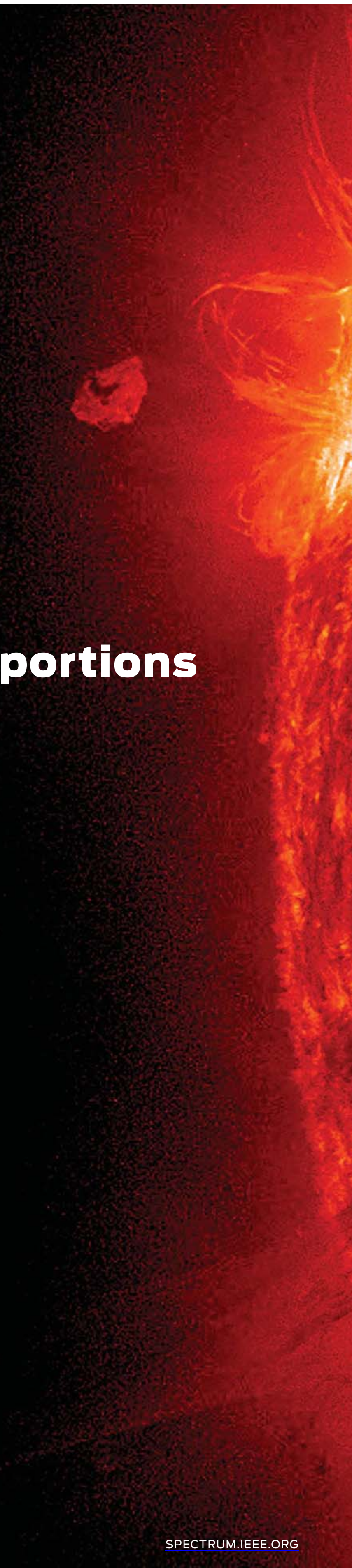
Similarly, Tufte counsels that the representation of numbers in a graphic should be proportional to the actual values of the numbers, and he tellingly calls this ratio the **lie factor**, because if the visual representation of an effect is much larger than the actual effect, then the graphic is lying about the data.

When you eliminate or at least minimize the redundant data-ink, non-data-ink, and any other **non-information** and keep the lie-factor ratio around 1, you increase the overall **information density** (or **data density**) and ensure that your design isn't **data-thin** or otherwise an example of **disinformation design**.

Tufte also introduced the world to **small multiples**, a data visualization that uses multiple versions of the same image or chart to illustrate different aspects of a data set. He was also the inventor of the **sparkline**, a small, simple word-size infographic designed to be displayed in line with text.

The goal, in short, is to use analytical design to increase **information resolution** (the paradoxical design strategy that when you need to clarify something, add *more* detail) and make information **quantitatively eloquent**. How does all this help us as we try to navigate a world drowning in data? Appropriately, I'll let Professor Tufte have the last word: "There is no such thing as information overload. Only bad design." ❑

GREG MABLY



A Perfect Storm of Planetary Proportions

How a solar superstorm could take down power grids everywhere BY JOHN KAPPENMAN

Luminous fingers of intense red, green, and violet light flicker and pulse across the northern and southern skies like a vast cosmic conflagration. Within minutes, millions of people are tweeting, texting, and blogging about the wondrous sight. But then the sky turns a deep blood red, and fascination turns to panic.

Linked to the celestial spectacle are enormous fluctuations of the magnetic field in Earth's magnetosphere, which are causing immense flows of electric current in the upper atmosphere over much of the planet. Those huge currents disturb Earth's normally quiescent magnetic field, which in turn induces surges of current in electrical, telecommunications, and other networks across entire continents. Streetlights flicker out; electricity is lost. A massive planetary blackout has occurred, leaving vast swaths of North and South America, Europe, Australia, and Asia without power.

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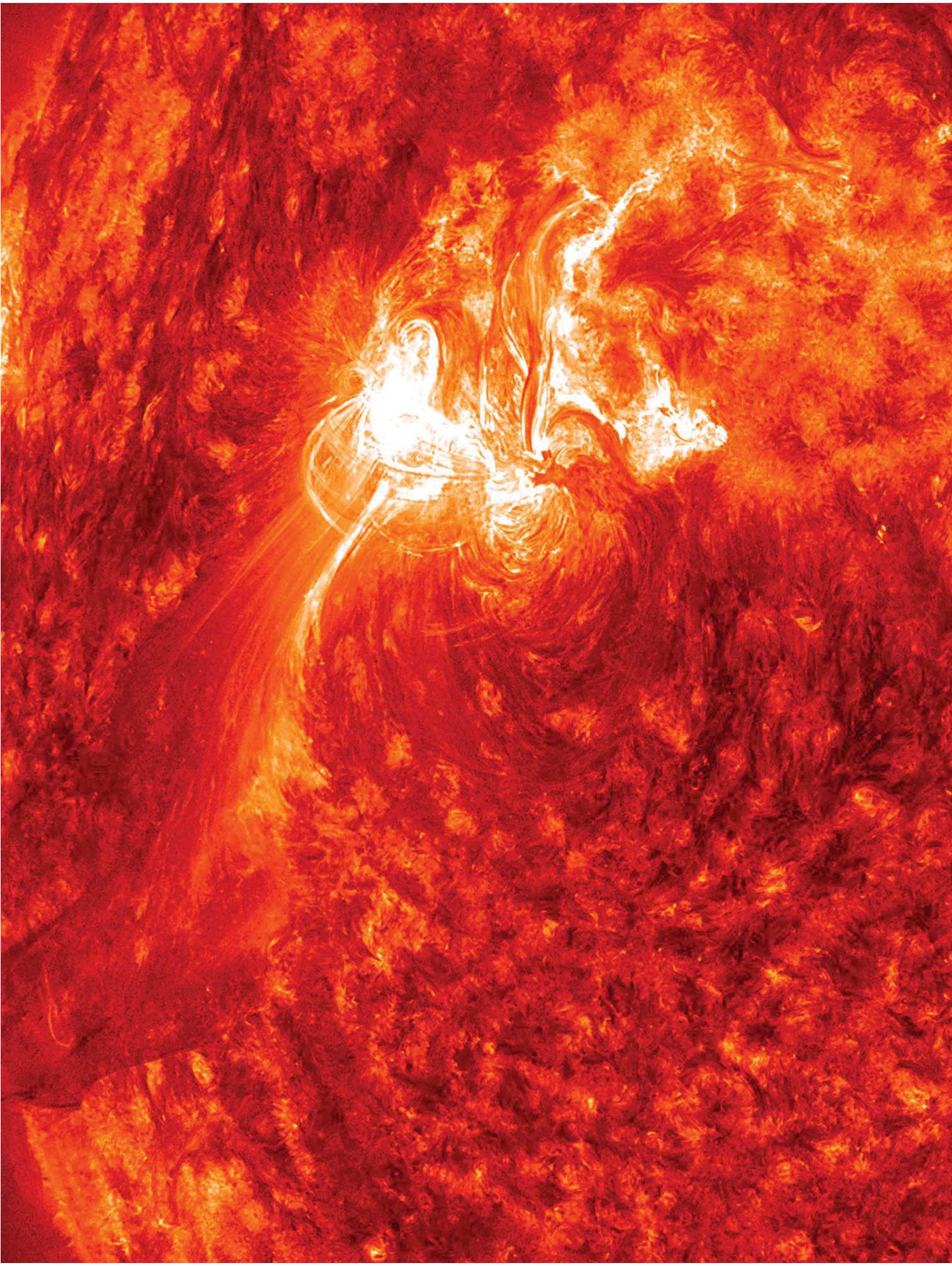

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Within a few months, the crisis has deepened. In many areas, food shortages are rampant, drinking water has become a precious commodity, and patients in need of blood transfusions, insulin, or critical prescription drugs die waiting. Normal commerce has ground to a halt, replaced by black markets and violent crime. As fatalities climb into the millions, the fabric of society starts to unravel.

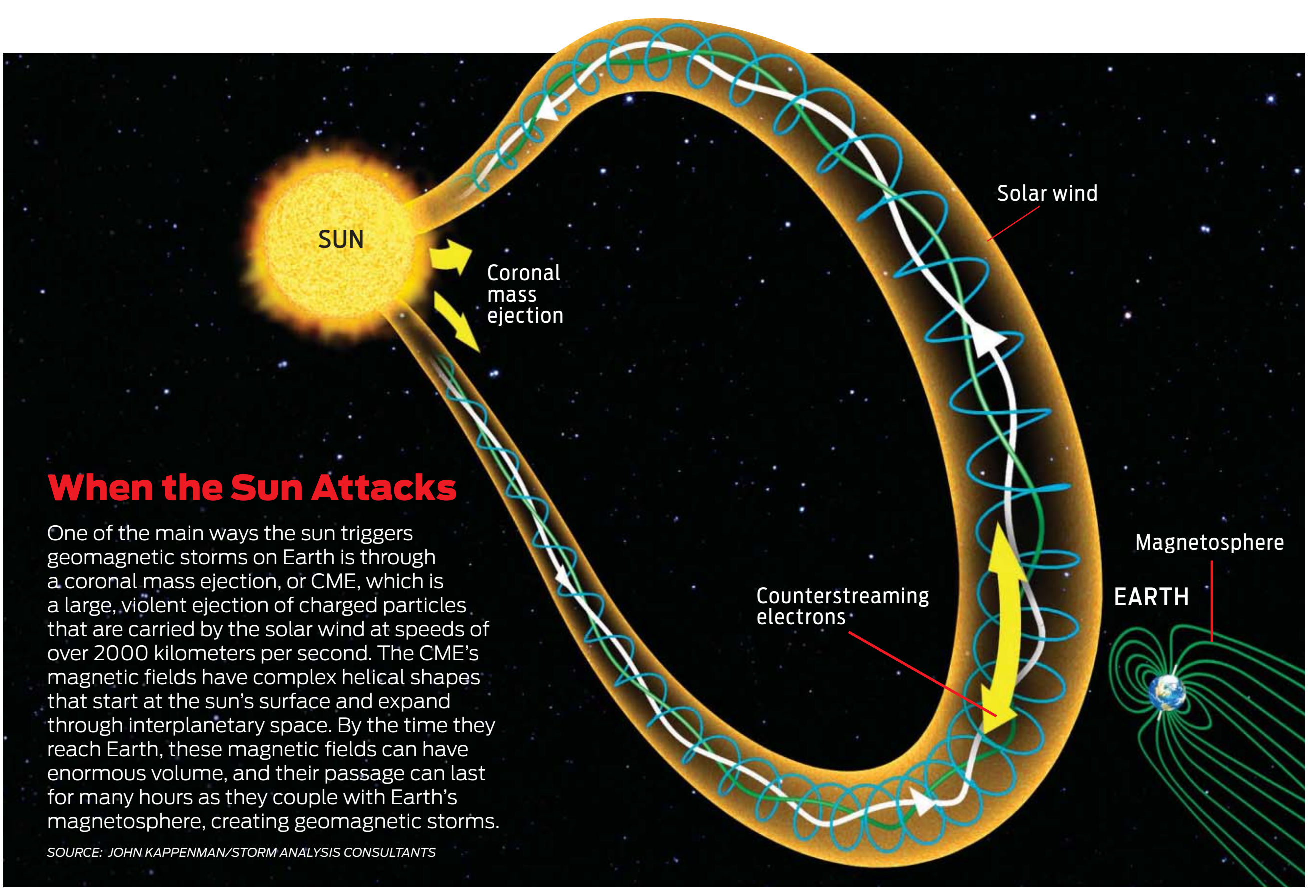
Of course, no geomagnetic storm has ever wreaked such global havoc. But the last time we had a truly powerful storm was in 1921—decades before developed economies became utterly dependent on electrical infrastructure. The doomsday scenario described above is based closely on the warnings of numerous government panels and industry studies I've participated in during my more than 30 years of investigating the problem that extreme space weather poses to power grids. A 2008 U.S. government report prepared for the Federal Emergency Management Agency put the yearly financial impact of such an event at more than US $1 trillion. And like other reports before and since, it predicted catastrophic damage not just to electricity grids but also to oil and gas pipelines, undersea communication cables, telephone networks, and railways. Repairing that critical infrastructure would take months or even years.

Now is a good time to consider the awesome and cyclical tempestuousness of our star: Solar activity tends to occur in cycles that peak in frequency and intensity every 11 years, and the next peak is expected later this year or early the next. To be sure, not every peak—also known as a solar maximum—brings a killer storm; the last notable one occurred in March 1989. It took down Quebec's entire grid within seconds, leaving 6 million customers without power for 9 hours. A later surge in the storm destroyed a large transformer at a New Jersey nuclear plant and nearly took down U.S. power grids from the mid-Atlantic through the Pacific Northwest.

But that geomagnetic storm was not so bad, it turns out. A recent forensic analysis I did of historic storms, including the planetwide event in 1921 and an even bigger one in 1859, strongly suggests that Earth has been lashed by superstorms up to 10 times as powerful as the 1989 event. The bad news is that it's likely—certain, even—that such a storm will happen again. And when it does, it will be one of the worst disasters in recorded history.

From where we sit, the sun seems quiet enough. And yet it is constantly bombarding Earth with electrons, protons, and radio through X-ray waves. The charged particles are ejected from the star's upper atmosphere and carried through space at a clip of 300 to 400 kilometers per second, arriving at our atmospheric doorstep about four days after leaving the sun. Under normal circumstances, this solar wind produces only negligible effects on Earth.

Occasionally, though, the sun erupts violently, emitting solar flares or throwing out coronal mass ejections consisting of billions of tons of charged particles. At such times, the solar wind blows considerably harder, at speeds of over 2000 km/s, organized into strong magnetic fields and with particle densities and temperatures an order of magnitude higher than normal. When it hits Earth's upper atmosphere, the solar wind connects with and expands Earth's magnetosphere, including the long tail-like portion that streams out from the nighttime side of the planet. This magnetotail swells and elongates until it becomes unstable and breaks in two.



When the Sun Attacks

One of the main ways the sun triggers geomagnetic storms on Earth is through a coronal mass ejection, or CME, which is a large, violent ejection of charged particles that are carried by the solar wind at speeds of over 2000 kilometers per second. The CME's magnetic fields have complex helical shapes that start at the sun's surface and expand through interplanetary space. By the time they reach Earth, these magnetic fields can have enormous volume, and their passage can last for many hours as they couple with Earth's magnetosphere, creating geomagnetic storms.

SOURCE: JOHN KAPPENMAN/STORM ANALYSIS CONSULTANTS

PREVIOUS PAGE: SOLAR DYNAMICS OBSERVATORY/NASA; THIS PAGE: JOHN MACNEILL

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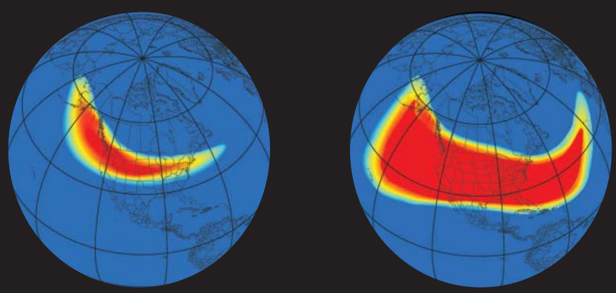
Worse and Worst

By comparing data from the geomagnetic storm in March 1989 [left] with magnetometer readings taken during the May 1921 superstorm, the author has estimated the intensity and geographic reach of the 1921 event [right]. The colored regions show the intense geomagnetic field disturbances caused by the eastward electrojet—a large electric current that builds up in the atmosphere—over North America. Not only was the 1921 storm more intense than the 1989 storm, but it had a much larger geographic footprint. Unfortunately, no data exist to depict the 1921 storm's much larger westward electrojet, but it would have engulfed much of the planet.

SOURCE: ANDREA GRYGO/STORM ANALYSIS CONSULTANTS



March 1989 May 1921

ANDREA GRYGO/STORM ANALYSIS CONSULTANTS (2)

The part of the magnetotail that's no longer attached to Earth drifts off into space, while the rest snaps back violently, like a broken rubber band. In the process it forces plasma back into Earth's upper atmosphere, where a large current of more than a million amperes—called an electrojet—builds up at an altitude of about 100 km and produces brilliant auroras. In average-size storms, this electrojet extends only over the globe's higher latitudes, like a halo circling one of the poles. But during very large storms, such as those in 1989 and 1921, it can also reach down to the lower latitudes, where most of the world's population and its infrastructure dwell.

That's not the only means by which the sun can upset Earth's geomagnetic balance. Coronal mass ejections that are big enough can collide directly with Earth's magnetosphere, releasing enough energy to collapse it on the daytime side of the planet from more than 64 000 km to less than 25 000 km in just a minute or two. The solar wind can buffet the magnetosphere, creating giant electromagnetic waves, much as hurricane winds kick up surf on the ocean. At lower latitudes, space weather can set off geomagnetic activity of a lesser intensity but longer duration, which can be as damaging to electric grids near the equator as other types of storms can be at higher latitudes.

But how does all this space weather cause damage down on the ground? It's a multistep process. First, the intense magnetic field variations in the magnetosphere induce electric fields and currents over large areas of Earth's surface. In turn, this geoelectric field creates what are known as geomagnetically induced currents, or GICs, which flow in any available conductor, including high-voltage transmission lines, oil and gas pipelines, railways, and undersea communications cables. These interconnecting networks essentially act as giant antennas that channel the induced currents from the ground. Hit with a 300-ampere GIC, a high-voltage transformer's paper tape insulation will burn, its copper winding will melt, and the transformer will fail, either right then and there or in the future.

High-voltage power grids are designed to withstand the loss of any single important element, such as a substation transformer, and then recover within a half hour or so. For a terrestrial storm like a hurricane or a tornado, this approach works well. But a severe geomagnetic storm covering an entire continent would cause multiple failures all at once. During the first 30 seconds of the 1989 storm, the Quebec grid experienced 15 simultaneous failures—and the unsurprising result was a province-wide blackout. And that storm, remember, was far from the worst Earth has seen.

It took scientists a while to make the connection between something happening on the sun and something happening on Earth. Given the separation between the two events of hours or days and 150 million km, maybe that's not too surprising. The first person to begin connecting the dots was a British amateur astronomer named Richard Carrington, who while doing daily sunspot observations saw a huge "white light" flare on the sun on 1 September 1859. This flare was both preceded and followed by incredible bloodred auroral displays that engulfed the planet from the poles to the tropics.

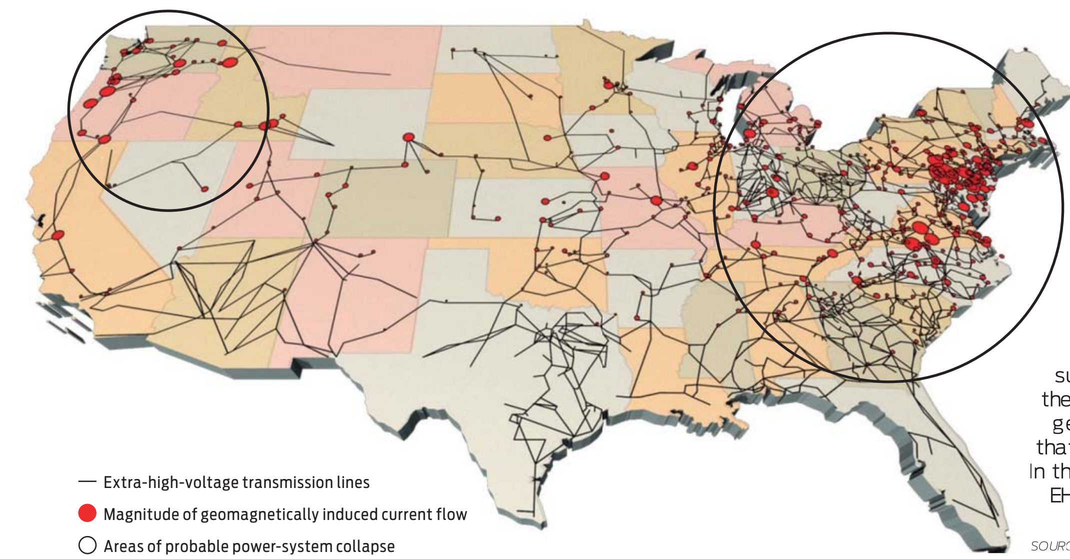
In that era, the only widespread electrotechnology was the telegraph. Electrical current surged through telegraph lines and blew out the batteries that supplied power to them. Telegraph operators were stunned by arcs of electricity leaping from their equipment. Other enterprising operators disconnected the batteries, reconnected the telegraph armature directly to ground, and were able to continue working with just the "celestial" current flowing through their lines.

Over the next few decades, others would expand on the connection between solar activity and geomagnetic storms. But skeptics were also plentiful, including the great physicist Lord Kelvin, who until his death in 1907 remained convinced that Maxwell's equations ruled out any kind of direct influence the sun might have on Earth.

The debate went unresolved until 1959, when the Soviets' Luna 1 satellite finally confirmed the existence of the solar wind. Carrington was long dead by then, of course, but the 1859 storm, one of the most severe in recorded history, is now known as the Carrington event [see "Important Dates in Solar History"].

Could another hemisphere-walloping event occur during the approaching solar max? There's really no telling. The fact is, geomagnetic storms can occur at any point in the solar cycle, and not all solar flares or coronal mass ejections will trigger a storm. Most of them, after all, will be pointed away from Earth. Of the earthbound ones, the damage they do depends on, among other things, the polarity of the magnetic field carried by the solar wind. If the polarity is the same as that of Earth's magnetic field, most of the particles will be deflected harmlessly into space. Eventually, though, we will get a Carrington-class flare that will trigger a superstorm the likes of which we have never seen. For that we are woefully unprepared.

The 1989 geomagnetic storm that blacked out Quebec led to many sobering studies and some potentially promising research, but not much actually changed. No regulations were added to require utility companies to harden their infrastructures, monitor for geomagnetically induced currents, or report transformer failures following geomagnetic storms—and so



Lights Out

A simulation of an extreme geomagnetic storm at 50 degrees geomagnetic latitude shows a widespread collapse of the power grid in the eastern and northwest portions of the United States, which together have a population of more than 130 million people. The black lines indicate extra-high-voltage transmission lines and major substations. The red dots indicate the locations and magnitude of the geomagnetically induced currents that would flow across the network. In this scenario, more than 300 large EHV transformers would either fail or suffer permanent damage.

SOURCE: PETER VARNER/STORM ANALYSIS CONSULTANTS

for the most part, the utilities haven't. There is still no design code for the grid and its components that takes into account threats from space weather.

358 billion kWh
U.S. ANNUAL ELECTRIC ENERGY USAGE IN 1950

3555 billion kWh
U.S. ANNUAL ELECTRIC ENERGY USAGE IN 2000

Meanwhile, the world has become more electrified. In the United States, the extra-high-voltage (EHV) portion of the power grid has grown by a factor of 10 since the late 1950s. China's grid is even more vulnerable, because portions of it now operate at even higher voltages—1000 kilovolts versus a maximum of 765 kV in the United States. Higher voltages can force higher GICs to flow into the grid, because the resistance of high-voltage lines is lower per unit length than it is for lower-voltage lines. But China is just following a worldwide trend: In general, utilities are pushing voltages higher to reduce the amount of energy lost over long distances. But they do so without considering the heightened risk.

Of all the parts of the power grid, high-voltage transformers are among the most likely to fail in a geomagnetic storm and also among the most difficult to replace. If a big storm were to knock out several hundred transformers in one fell swoop, manufacturers wouldn't be able to supply replacements quickly—there is no global stockpile. EHV transformers, which can handle voltages of 345 kV or higher, weigh about 200 tons and cost about $10 million each. Building one requires exquisite, near-artisanal craftsmanship, including meticulously hand winding the paper-tape insulation around the copper winding at the transformer's core. One EHV transformer can take several weeks to assemble and test, and it takes years to train skilled assemblers. Even the largest transformer plants can build only about 30 to 50 per year. With the shortage of skilled labor and specialized materials that would likely accompany a prolonged blackout, simply maintaining that level of output would be a challenge, never mind ramping up new production.

There is a quick and relatively cheap fix to help protect these transformers from geomagnetically induced currents: They can be retrofitted to block the inflow of GICs. But no utilities anywhere routinely protect their multimillion-dollar transformers in this way. Also worrisome is that many transformers in the United States, Western Europe, and Japan are fast approaching the end of their useful lives. The average age of U.S. transformers is about 40 years. Over the decades, each of these devices has likely experienced at least minor overheating and other insults from GICs. An aged transformer that's been exposed to repeated injury is of course far more likely to fail than a brand-new transformer.

Unfortunately for grid operators and others who have to deal with the consequences of geomagnetic disturbances, existing tools for assessing severe space weather fall short. The space-based Solar and Heliospheric Observatory now offers gorgeous images of solar flares as they burst forth from the sun's surface, while the Advanced Composition Explorer satellite makes very precise measurements of the solar wind. As a result, computer models of space weather can now accurately predict when the solar wind will reach Earth. But space weather

Important Dates in Solar History

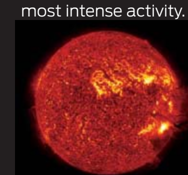
Connecting the dots between solar activity and geomagnetic storms has created a new awareness of extreme events.

SEPTEMBER 1859
Richard Carrington, a British amateur astronomer, observes a "white light" flare on the sun. The accompanying solar superstorm becomes known as the Carrington event.

MAY 1921
Probably the largest solar storm of the 20th century produces auroral observations from the poles to the tropics and damages major portions of the telephone and telegraph systems in the United States and Europe.

MARCH 1989
A large geomagnetic storm knocks out Quebec's power grid, leaving 6 million Canadian customers without electricity for 9 hours and damaging power stations in the northeastern United States.

2012–2013
The sun enters solar maximum, the phase of most intense activity.



MAP: JOHN MACNEILL; PHOTO: NASA SCIENCE VISUALIZATION STUDIO

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experts still don't know which kinds of solar activity will likely cause real damage.

The traditional way of gauging solar storm intensity is the G-scale, which rates storms from 1, the least severe, to a maximum of 5. It's based on an 80-year-old metric known as the K-index, which reflects the change in Earth's magnetic field over a 3-hour period. For instance, the most severe storm has a K-index of 9 (which corresponds to a G-scale rating of 5), meaning the magnetic field variation exceeds 500 nanoteslas during the 3 hours. That's relatively small compared to Earth's average magnetic field of about 60 000 nT.

But for the power grid, the K-scale's 3-hour time scale is useless because the magnetic spikes of greatest concern happen over just a few seconds or minutes; the higher the rate of change, the greater the impact. Experts use the shorthand "dB/dt" to refer to this rate of change. But whether the change happens over 30 seconds or 3 hours, it would register the same value on the K-index. And while the index tops out at 500 nT, actual storms can go much higher. The 1989 storm, for example, had fluctuations of 400 to 500 nT per minute over North America, so according to the K-index, it was among the worst. However, my analysis of data from the 1921 storm indicates it reached an intensity of 5000 nT per minute—10 times as great as the 1989 event [see illustration, "Worse and Worst"].

Of the several K-9 storms that have come after the March 1989 storm, all had lower dB/dts and as a consequence were far less destructive. However, this may have created a sense of complacency within the electric power industry that it has done enough post-1989 to prepare for the "worst" storms.

Hundreds of Fukushimas?

In a massive geomagnetic storm that could trigger a long-term power outage across large portions of the globe, the world's 400-some nuclear plants would be particularly vulnerable to catastrophic failure, for two reasons.

First, as events in Japan last March made clear, nuclear power plants often have inadequate backup power on-site. At the Fukushima Dai-ichi complex, even if the diesel generators had not been flooded, they had only enough fuel for seven days, the industry norm.

To sustain emergency operations beyond a week, all nuclear plants require a functioning connection to the grid. That's because even after nuclear fission ceases, fuel rods in the reactor cores and spent fuel pools continue to generate decay heat for years, requiring cooling with water circulation pumps. It can take several megawatts of power to operate that equipment. So when both on-site and outside power supplies suffer a long-term outage, as they did at Fukushima, the result is a core meltdown. Even worse would be a fire in a spent fuel pool, which can hold 10 times as much fuel as the core but has no containment structure.

Nuclear plants are also vulnerable because they're so big. To feed a gigawatt of electricity from a nuclear plant into the grid requires many high-voltage transformers and transmission lines, and each connection is an entry point for geomagnetically induced currents. In a comparison I did of nuclear plants versus other types of power plants and substations, there were 50 percent more GICs at nuclear plants than at other facilities.

So a massive solar storm that knocks out nuclear power plants' ability to transmit power and destroys their backup power systems could very well trigger dozens or even hundreds of meltdowns. *—J.K.*

Fortunately, protecting against the space-weather threat should be neither expensive nor difficult. Almost all modern power grids use a three-phase design, in which each of three lines carries an alternating current whose phase is separated from the other two by a third of a cycle.

The three-phase transformers used in this scheme are directly grounded through their neutrals. The ground is assumed to be an infinite sink that can absorb any brief, large fault current and at the same time keep the voltage across the grid from spiking and damaging equipment. In retrospect, that design is flawed: During a geomagnetic storm, the sink becomes a source of GICs, flowing into the grid from the ground.

Preventing the inflow of GICs into the grid through the neutral-to-ground connection is the best long-term solution. One idea is to install capacitors at the neutral-to-ground juncture, which would block the inflow of GICs or any other direct current but otherwise allow the continuous flow of small AC currents that are common from the neutral to the ground. The challenge is devising a way to automatically bypass the capacitor in the event of an actual fault and allow a large AC current—say, more than 20 kiloamperes—to flow to ground from the neutral. Such gear was developed under a research program I directed for the Electric Power Research Institute in the early 1990s. But the switching devices of that era were too slow, expensive, and complex, and they couldn't handle high currents.

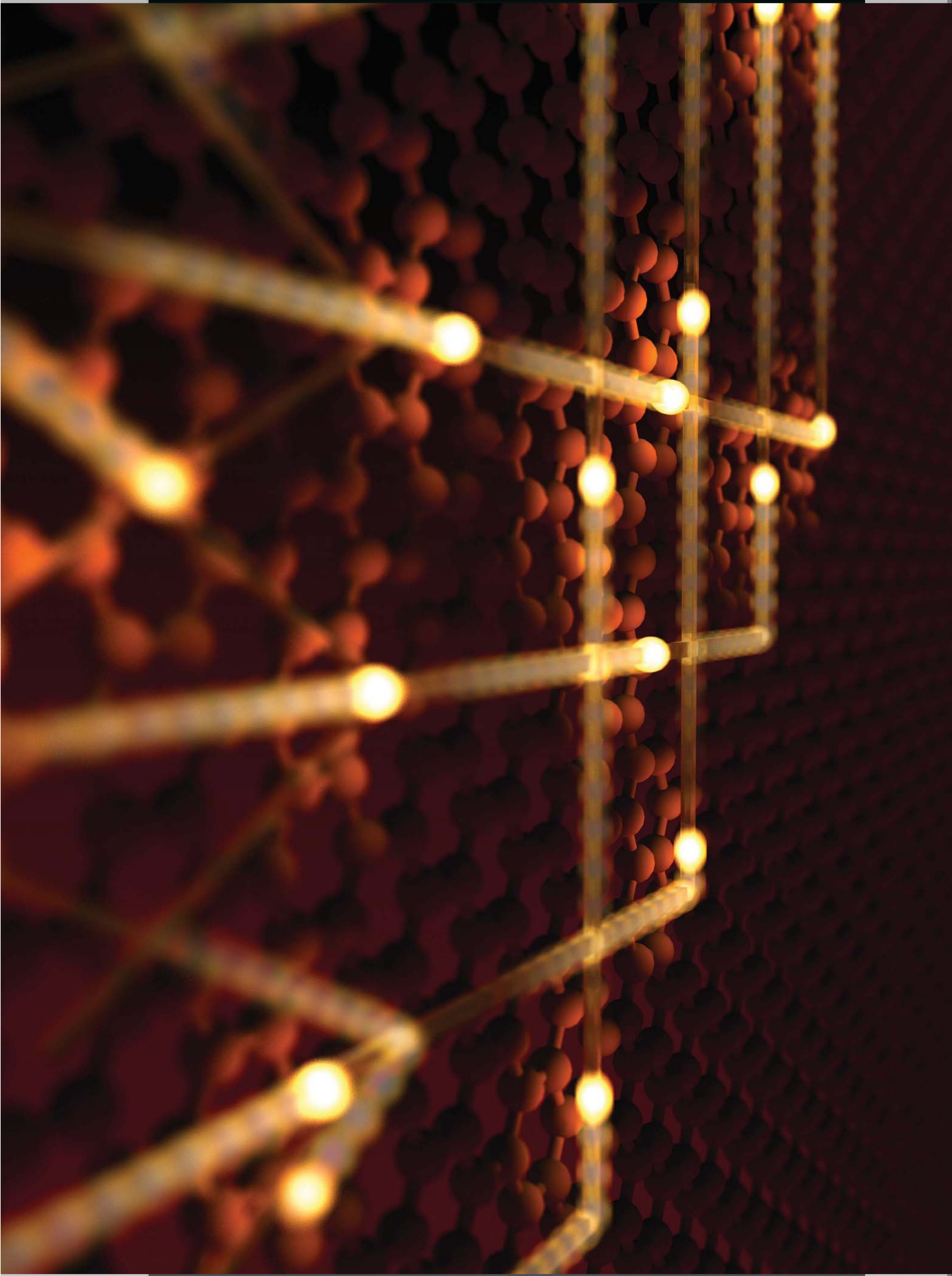
Recently, though, an old technology has been revived that appears to have all of the right qualities: the trusty vacuum tube. A start-up called Advanced Fusion Systems, based in New Rochelle, N.Y., has developed a capacitor bypass device that uses a high-power vacuum tube that it says can bypass the capacitor within a fraction of an alternating current cycle, far speedier than any existing mechanical switch, power transistor, or spark gap could.

The design is still being vetted, but if it proves successful, retrofitting the neutral-to-ground connections with these bypass devices would be far less costly than having to replace tens or hundreds of the transformers themselves following a major geomagnetic storm.

So here you are at the end of the article. If you never gave much thought to geomagnetic storms before (and let's face it, you never did), I hope you now appreciate the extraordinary risk that extreme space weather poses to our critical systems and even our way of life.

Our infrastructure has greatly expanded and grown more complex—and also more vulnerable. We engineers have presided over this growth and can feel justifiably proud of what it has brought society. But we have also unintentionally created a disaster in the making, and it is time we addressed it. As an engineering community, we should realize there are no reprieves from the laws of physics. If we do nothing—if we stand by and wait for politicians to appreciate the risks and act on them—we may witness one of the worst catastrophes of all time. ❏

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/solar0212



The Ultimate Switch

Graphene could replace the transistor with switches that steer electrons just like beams of light

BY CHUN-YUNG SUNG & JI UNG LEE

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From the outside, transistors seem so simple and straightforward. But inside, they're actually a mess. If you could watch them working at the level of atoms, you'd see the electronic equivalent of a game of bumper cars. Electrons moving through even the best transistor channel can't go in straight lines. Instead they're buffeted continually by a host of imperfections and vibrations, which together put a strict limit on speed and generate a lot of heat in the process.

The good news is that it doesn't have to be that way. By a quirk of quantum mechanics, electrons moving through atom-thick sheets of carbon—known as graphene—don't suffer much at all from these sorts of collisions. Instead, they behave like massless particles, speeding along in straight lines for long distances just like photons do. And just like light, these electrons can be made to bend or bounce back when they move from one medium to another.

What can you do with this light-mimicking behavior? Well, here's what we'd like to do: Replace the logic circuitry at the heart of every computer processor. Everyone today agrees that the days of the ever-shrinking CMOS transistor are numbered; the only disagreement is about what that number is. After 50 years of steady miniaturization, chipmakers have just about shrunk the device to its limits. The future gets hazy beyond 2020, but we know that to continue making faster, cheaper, and more energy efficient chips, we'll need a new technology.

In the United States, the hunt for novel computing devices that can start replacing CMOS transistors in the coming decade has crystallized into a massive effort called the Nanoelectronics Research Initiative, which includes many of the world's biggest chipmakers, state and federal agencies, and dozens of universities. Light-like graphene logic is just one of a half dozen or so possible successors to CMOS, but we think its combination of features makes it the heir apparent.

For one thing, graphene logic will be extraordinarily fast. Instead of manipulating information by turning the flow of current on and off through a transistor channel, graphene logic could perform calculations by bending, reflecting, focusing, and defocusing electrons moving at 1/300th the speed of light—about 10 times as fast as electrons in conventional silicon CMOS devices. Logic devices built from graphene will consume less power and take up far less real estate than CMOS or optical switches. And unlike any other technology being considered, graphene devices have the potential to simplify and speed up chips by creating truly reconfigurable logic. Such logic would be able to change its type on the fly: In response to electronic signals, an AND gate, for example, could be transformed into an OR gate and then back again. We have already shown that the fundamental physics of these graphene switches works just as theorists expected, and we are now on the verge of creating the very first reconfigurable devices.

AS YOU MIGHT IMAGINE, no ordinary semiconductor can be used to shuttle electrons around like beams of light. In the silicon CMOS transistors that make up today's chips, electrons can barely move a few nanometers before they bounce off an impurity or are buffeted by acoustic waves generated by the crystal. Other semiconductor materials aren't much better.

But graphene is different. First isolated in 2004, the material consists of a single sheet of carbon atoms arranged in a honeycomb-like lattice of hexagons. Roll it up and you've got a carbon nanotube. Stack it and you can make graphite. Material scientists still disagree about what they should call the stuff: Some say it's a "zero bandgap semiconductor," others simply refer to it as a semimetal. However you identify it, graphene is quite different from any other material we're used to working with.

Graphene's symmetrical, two-dimensional crystalline structure is responsible for most of its unique qualities. Electrons surrounding each carbon atom can take on only a limited set of energies; each electron occupies a level that corresponds to an allowed quantum state. Like all materials with a periodic arrangement of atoms, these allowed electrical states overlap in space and meld to form a new spectrum of allowed states—a band structure. In an ordinary semiconductor, electrons that are stuck to atoms are confined to the valence band, and those that are free to move around the lattice occupy the conduction band. But in graphene, these two bands actually touch, and they take on a highly unusual property.

If you calculate the energy of any free electron in graphene, you'll find that, just as with the photon, its energy is directly proportional to its momentum. (A photon doesn't have mass, but it has a momentum that arises from its wavelike, quantum-mechanical nature.) Because they are effectively massless, electrons in graphene always move at the maximum velocity possible, regardless of how energetic they are.

As a result, once they've been set in motion, electrons in graphene require no energy to keep going. What's more, quantum mechanics prohibits one of the most basic outcomes of a collision—that of recoil. An electron in graphene isn't allowed to completely reverse its direction of motion. This prohibition allows it to move virtually unimpeded through a graphene sheet and tunnel effortlessly through such barriers as *p-n* junctions.

While an electron or hole moving in silicon typically gets deflected after moving a few atom lengths at most, in graphene these charge carriers can travel in straight lines across tens of thousands of atoms at 10 times the speed they can in silicon. At room temperature, graphene's electrical conductivity beats that of silver, the least resistive metal.

One of the first things you might think to do with this material is to use

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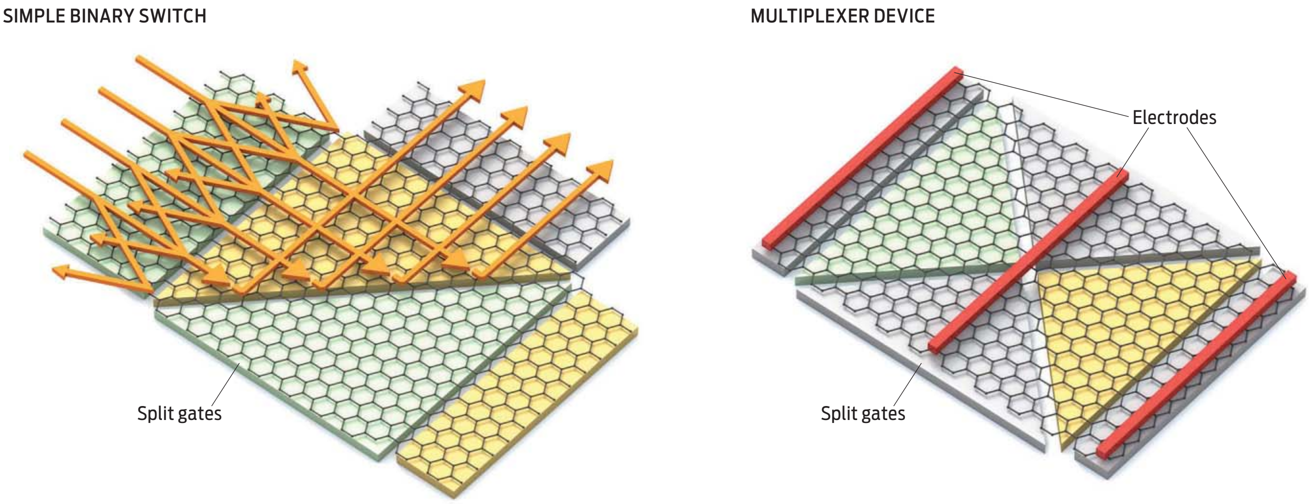
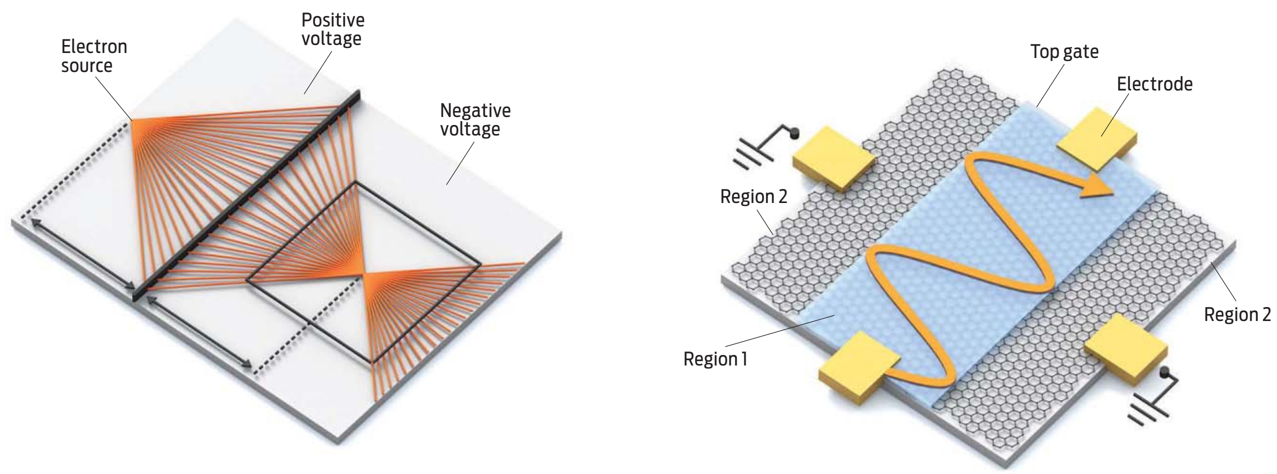


REFRACTIVE LOGIC: One way to make a simple binary graphene device is to divide a square gate beneath a graphene sheet into two triangles [left]. Electrons are reflected if the gates have opposite voltage and pass through the device if the voltages are the same. A more complex gate scheme [right] can be used to support multiple logic functions.



LENSES AND FIBERS: Electrons can be focused and defocused at the interface between gates with opposite voltages [left]. They can also be made to bounce back and forth in the electronic equivalent of an optical fiber, which can be built with fields generated by top and bottom gates [right].

it to make fast transistors. And indeed, researchers have done just that. With the support of the United States' Defense Advanced Research Projects Agency, colleagues of ours at IBM have shown that graphene can be used to build speedy radio frequency switches on silicon wafers. Since the work began in 2008, graphene transistors have been built that can amplify signals over a wide range, up to frequencies of 280 gigahertz. Researchers expect to be able to create switches capable of handling 500-GHz signals by 2013.

These transistors are great for radio frequency circuits such as RF amplifiers or mixers. But the technology isn't well suited for making logic devices. For one thing, graphene isn't really a semiconductor. Because graphene in its natural state has no bandgap, a vanishingly small amount of energy is needed to knock an electron free of its valence band. So graphene switches are always in some conductive state. Current can be made to move back and forth, but it can't easily be turned on and off, meaning there's no easy way to represent bits.

Engineers have some tricks that can be used to create an artificial bandgap. They can, for example, pattern graphene into very thin ribbons or apply an electric field across two layers of graphene stacked one on top of the other. But while these sorts of approaches do create a bandgap, they have the side effect of reducing electron speed. In nanoribbons, for example, electrons have a tendency to get scattered by the edges of the ribbon. And neither technique is far enough along to create speedy transistors with high enough on-off ratios and low enough leakage current to compete with present-day chips.

IF WE TOSS OUT THE IDEA of making transistors, we can take advantage of graphene's best properties and, if we're fortunate, end up with a new technology that can keep the world on a Moore's Law–like progression toward cheaper, lower power and better-performing processors.

Given the fact that we're contemplating treating electrons just like light, you might ask why we don't simply build logic from photonic systems. Optical devices like lasers have long been an attractive way to make speedy computing circuitry. Instead of transistors, the systems use a combination of amplifiers, modulators, emitters,

BRYAN CHRISTIE DESIGN (4)

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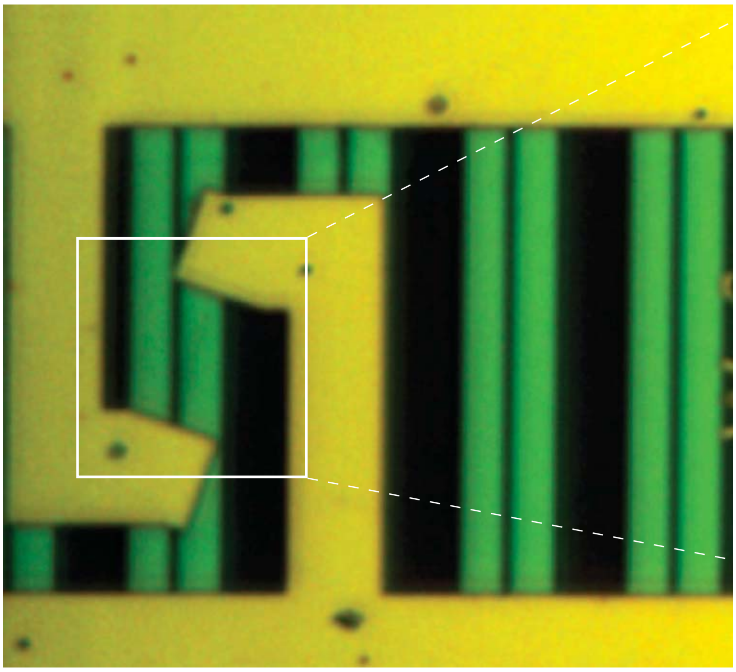

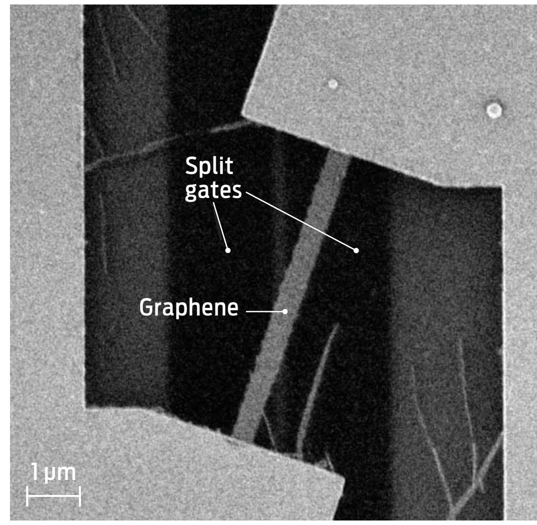

GATE TEST: Laboratory experiments have shown that graphene's resistance to the flow of current varies, depending on how it is angled when placed atop a pair of gates. The results suggest that the fraction of electrons that pass through the gate interface changes with the angle, just like light.

detectors, and waveguides to manipulate photons and perform computations.

But optoelectronic circuits themselves aren't a practical option for next-generation logic. The components can't get any smaller than the wavelength of light they're manipulating, which for optical circuits means feature sizes on the order of one micrometer, dozens of times the size of today's CMOS devices. The light sources needed also draw a lot of power, making them impractical for microprocessor chips.

Graphene offers a good compromise—electrons in a graphene switch will move much faster than they can in ordinary transistors, and at the same time, the devices themselves will take up much less space and consume far less energy than a photonic system.

As with a CMOS transistor, the basic unit for manipulating electrons in reconfigurable graphene logic is a simple straight *p-n* junction. These can be created by making a four-layer stack. At the very bottom, embedded into the substrate, two patches—or gates—made of conductive material are built. An insulating layer of oxide is placed on top, and then a rectangle of graphene is placed on top of that. Electrodes placed on top of the graphene, at either end of the rectangle, are used to supply a reference current to the device.

By applying a positive voltage on one gate, you can pull electrons from the nearest electrode into the graphene, creating an *n*-doped material. Applying a negative voltage to the other gate will draw holes from the other electrode into the graphene, creating a *p*-doped material. The resulting *p-n* junction isn't like the kind you'll find in a normal diode or transistor; it won't rectify current by allowing it to go in only one direction. Charge carriers pass freely across the barrier. But the junction does have the unique property of being angle dependent. The chance that an electron will get transmitted or reflected at the junction depends on its angle of approach.

In 2007, theorist Vadim Cheianov of Lancaster University, in the United Kingdom, and two colleagues suggested this angle-dependent behavior could have an important application in electronics. The group showed that if electrons are injected from a single point on one side of a perfectly straight graphene *p-n* junction, the particles spread out, refract when they hit the junction, and then refocus to a point on the other side.

It may not sound too profound, but this sort of behavior isn't really seen in the natural world—you can't focus light with a flat lens. But graphene bends a stream of electrons differently than the way most materials bend light: It has the electronic equivalent of what's referred to in optics as a negative index of refraction. An electron traveling through an *n*-doped region of graphene effectively takes on negative energy when it moves into a *p*-doped region, and conservation of momentum demands that it be bent in this counterintuitive way. So far, the only way to manipulate electromagnetic radiation in this fashion is to use artificial materials, which are constructed by manipulating metal wires. It turns out that graphene is a natural electronic analogue to these metamaterials.

Beyond focusing and defocusing electrons, graphene's refractive properties can also cause the total internal reflection of electrons. The material can be set up to accomplish this trick by taking advantage of the same angle dependence in a graphene *p-n* junction. For example, if the gates beneath a sheet of graphene are properly spaced, electrons sent toward a junction at a shallow angle—say, 45 degrees or less—won't be able to pass through the boundary; they will all be reflected. To let the electrons pass through the junction unimpeded, you simply reverse the voltage on one of the gates, creating a uniform *n-n* or a *p-p* device.

INSPIRED BY these remarkable capabilities, a number of Nanoelectronics Research Initiative researchers, including teams at our two institutions—IBM and the University at Albany, State University of New York—have been investigating how this refractive behavior can be used to manipulate electron flow and make logic switches.

At the start, most of our research was theoretical. We realized that to make proper logic, we had to come up with designs that could *Continued on page 54*

JI UNG LEE, ET AL.

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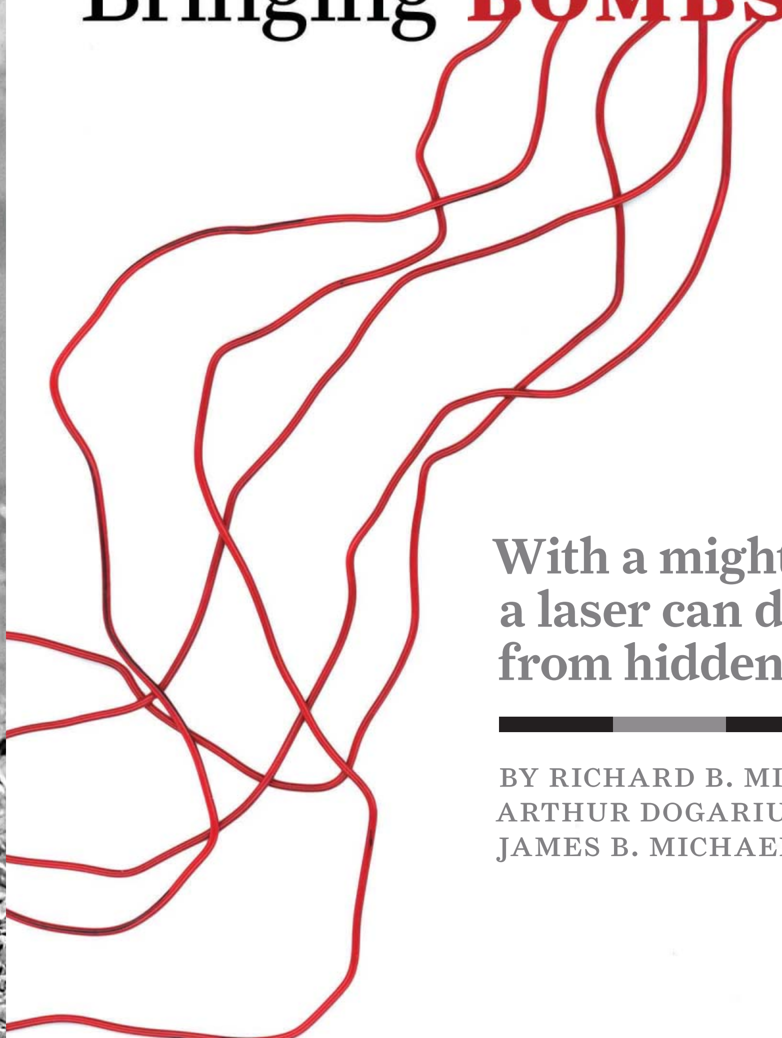
WALK SOFTLY: A mine-clearer's work still depends on metal detectors and sniffer dogs, with all the dangers that this entails. Technology may provide a better way to do the job.
PHOTO: UNITED STATES MARINE CORPS

Bringing BOMBS to Light



With a mighty zap, a laser can detect fumes from hidden explosives

BY RICHARD B. MILES, ARTHUR DOGARIU & JAMES B. MICHAEL

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UNDERMINED: The wreckage of a U.S. Army vehicle in Afghanistan [above] shows the effects of an improvised explosive device; two soldiers died in the 2010 blast. Dogs and their handlers [left] are put at risk to find IEDs, which can be quite small [right].

CLOCKWISE FROM TOP: DAVID GUTTENFELDER/AP PHOTO; KIRSTY WIGGLESWORTH/AP PHOTO; EROS HOAGLAND/REDUX

Today we rely on dogs to sniff out hidden explosives. The problem is, you can't debrief a dog, so you can't identify the kind of explosive or even be sure that the animal is smelling explosives rather than packaging material. And who wants to risk the lives of dogs and their handlers? If you had an instrument that could safely identify any explosive at a distance—with the doglike power to detect molecules at concentrations of just one part in billions—you could get around these difficulties.

The problem of land mines is certainly not new, nor is even the problem of hidden homemade bombs, called improvised explosive devices (IEDs), although the latter came to prominence during the wars in Iraq and Afghanistan. Now these ghastly devices are proliferating around the world: The number of such bombings has increased from close to zero a decade ago to more than 4 000 per year in Afghanistan alone. It's a concern that will be with us for a long time, and as such it deserves serious efforts to address. Nor is the problem merely one of war and sabotage. Any device capable of sniffing explosives at a distance could also monitor all sorts of peacetime poisons and pollutants—carbon monoxide, mercury vapor, the oxides of nitrogen and of sulfur, and of course carbon dioxide and methane, the principal greenhouse gases.

We propose to find and identify such materials at a distance by using a laser to sample the spectroscopic fingerprints of trace gases in a distant volume of air. We use two complementary techniques to probe that volume: one involving a backward-propagating laser generated in the air sample itself, and the other a radar echo off ions and electrons from trace

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gas molecules that have been selectively ionized by a laser. At Princeton University we are examining both approaches because either one, taken alone, may sometimes be inconclusive and because at this early stage in development it's important to have more than one option. We've already achieved promising results in our research, which has been funded by the United States' Office of Naval Research.

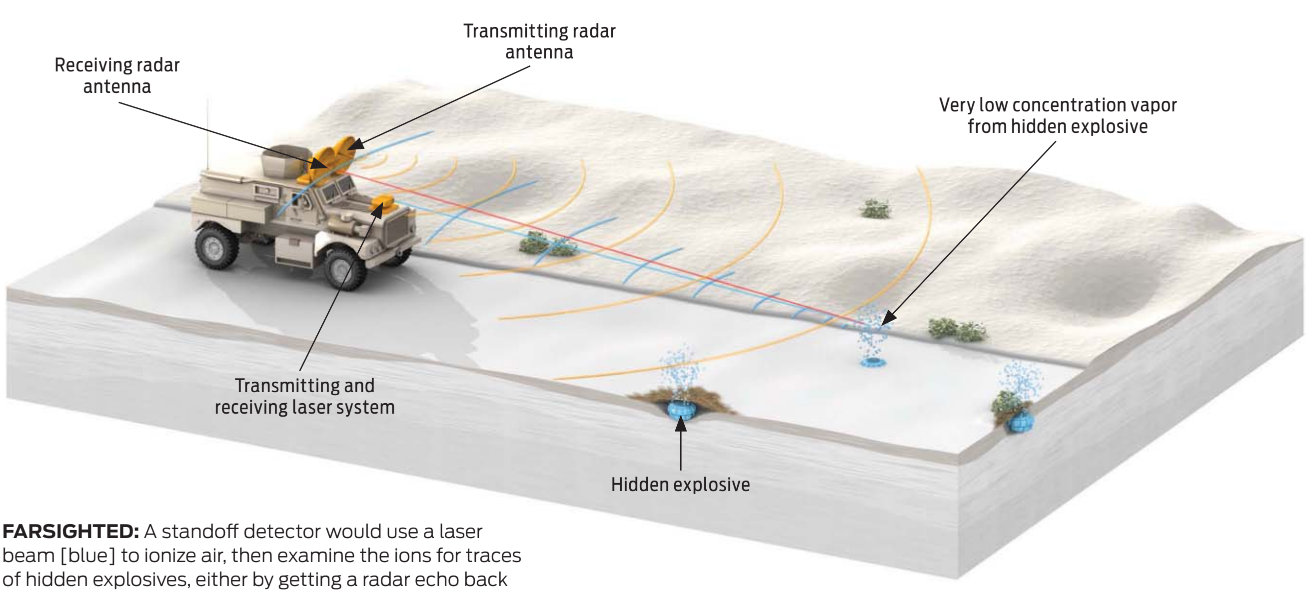
WHAT WE WANT is a way to analyze the air remotely, without a physical sample, at a reasonable range—say, 30 meters—with high sensitivity and a low rate of false alarms. For this "standoff" capability we also need to put the transmitter and the detector together, with the detection signal returning to the spot where the initial burst of energy was emitted in the first place, as with a typical radar or sonar system.

There are many different ways a laser can sample the air above a suspected bomb. It can induce fluorescence or Raman scattering (which, like fluorescence, produces a signal with a distinct spectroscopic signature in the visible, infrared, or ultraviolet regions for each kind of molecule in the air). Or, if it's powerful enough, the laser can turn the air into a bright spark, so that its molecular constituents break apart and each element emits its characteristic spectrographic signature.

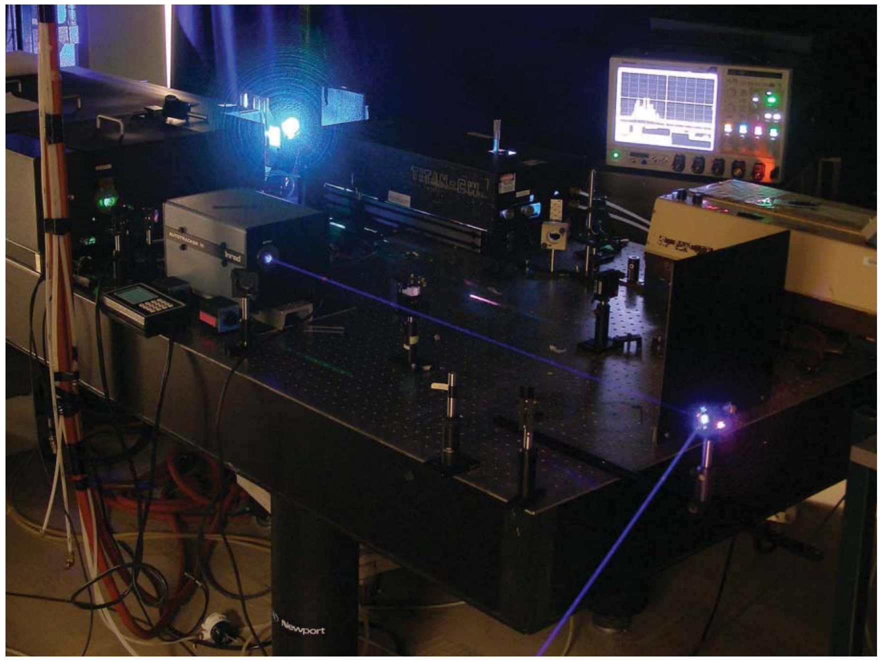
All these techniques produce light with telltale spectral features, but they don't work well at a distance. That's because the light the air gives off is incoherent, so it goes in all directions, and the intensity drops off rapidly with range. Also, the light is in the visible and infrared portion of the spectrum, so during the day, background sunlight tends to wash out the signal. Finally, there isn't much light to begin with—the molecules wafting from any explosives are so diluted by the surrounding air that only a few photons from them can be detected. Another approach, differential absorption light detection and ranging (known as DIAL), uses the backscattering from air, from particles in the air or from distant surfaces, to detect the absorption of a laser tuned to the proper wavelength and propagating through a cloud of the trace species. However, to make DIAL sensitive to within parts per billion requires paths of hundreds of meters through the cloud of trace molecules and entire minutes to process the data.

We propose instead to rely on coherent processes, in which the molecules act together as a marching band rather than as a milling mob. These processes include coherent anti-Stokes Raman scattering and coherent Stokes Raman scattering, which use laser beams to produce new laser beams that can indicate the presence of trace constituents. Both of these methods, however, have a serious drawback: The beams of laser light they create point away from the source lasers. To receive such a signal, you'd have to put the transmitter at one side of the target area and the receiver at the other—a most impractical setup in a battle zone. In addition, these techniques suffer from background interference from other coherent processes going on in the air, which tend to mask the signal coming from the material of interest, thus limiting the sensitivity you can obtain to a concentration of a part per million or so. That sounds pretty good, but in reality you need to be able to detect parts per *billion*, dog-nose style.

THERE IS, in fact, a way to produce a laser beam that shines back at you, one bearing information you can use to identify the materials present at its source. By focusing a pulsed ultraviolet laser onto a targeted spot in the air, we have been able to create a region where the laser intensity is high enough to break up oxygen, freeing each molecule's two oxygen atoms. The beam is transmitted through a lens that focuses it on a spot 30 or so meters away; there it converges and then diverges, giving this region an hourglass shape. Because the laser pulse is very brief—on the order of nanoseconds—the intensity is high enough to break molecules of oxygen into their constituent atoms over a few millimeters in the thin midsection of the hourglass. This happens so rapidly during the pulse that the same pulse subsequently excites many of the oxygen atoms into a high-energy state, creating what's called a population inversion. This unstable condition then leads to the familiar laser chain reaction in which an excited atom drops to a lower energy state, emitting a photon of a particular wavelength,



FARSIGHTED: A standoff detector would use a laser beam [blue] to ionize air, then examine the ions for traces of hidden explosives, either by getting a radar echo back to a dish on top of the vehicle or via a backward-propagating "air laser" beam [red]. *ILLUSTRATION: BRYAN CHRISTIE DESIGN*



MODEL BUILDING: The authors' lab at Princeton University has shown that both the air-laser and the radar REMPI techniques can detect traces of chemical vapors. Next, the method must be proved to work over a distance of tens of meters.
PHOTO: JAMES B. MICHAEL

and that photon in turn stimulates another excited atom to emit a photon of the same wavelength and phase. These two photons go on to stimulate photon emission from two more atoms, and then there are four photons. The cascade amplifies the beam exponentially.

You might imagine that the laser light created by this process spreads out evenly in all directions—but no. Because the number of photons grows exponentially with distance, and because the lasing region is a few millimeters long and only a fraction of a millimeter across, the amplification is thousands of times as great along the length than along the breadth. This creates two beams, one that follows the path of the excitation laser and another that projects back in the opposite direction.

The beam that returns is, of course, the interesting one. There is no mistaking it for light that may have scattered straight back from the original beam, which at an ultraviolet wavelength of 226 nanometers is impossible to see. The return beam is also invisible, but it's at a wavelength of 845 nm, slightly too far into the infrared region to be visible. Still, that beam is remarkably bright, with a peak energy that's a million times as great as what you'd find in the scattered light.

Although this midair laser lacks mirrors—which would increase the efficiency of the lasing and channel all the output in one direction—its light nevertheless has all the characteristics of a true laser. First, the energy is concentrated into narrow, well-directed beams. Second, the pulse of light given off lasts less than a thousandth as long as the incoherent fluorescence that would have occurred were the oxygen atoms not lasing, so almost no atoms are left to fluoresce and almost all the energy goes into lasing. The atoms pour about 500 times as much energy into the return beam as into the fluorescence. Finally, the laser light is very monochromatic.

We get our ultraviolet excitation pulse by combining a pulse from a frequency-tunable laser with another pulse from a second laser and sending them together through a crystal with nonlinear optical properties. The crystal produces the required 226-nm light. The return pulse from the air laser carries very little energy—a few hundred nanojoules, corresponding to a photon conversion efficiency of 0.1 percent or so. We can elicit a significantly more energetic return pulse by using another laser beam to create a spark in the air just before the ultraviolet pulse arrives. That way we prime the process with additional free oxygen atoms.

The brightness and spectral purity of the return beam make it easy to distinguish from scattered sunlight using nothing more than a simple filter. Also, because the beam arrives within a window of just a few nanoseconds, we can suppress noise even further by recording only the signal when the return beam arrives. This is too fast for regular camera shutters, but it's well within the capability of electronic shutters.

THE IDEA of using one laser to create another dates back to the 1960s, when people began using dyes as lasing materials, exciting them with other kinds of lasers. The point was to make laser light of different wavelengths, and any loss in efficiency incurred by this two-step process was a small price to pay for that ability. Even mirrorless lasers are also well known—examples include the X-ray laser, the nitrogen laser, and naturally occurring interstellar lasers.

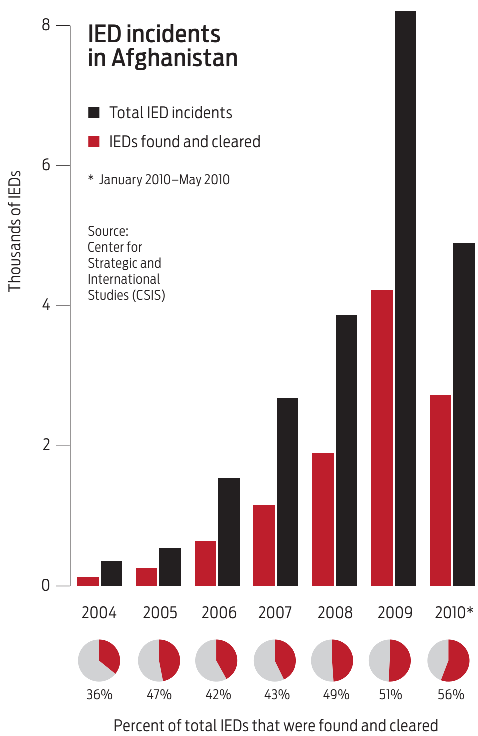
It occurred to us that we could use the two-step lasing process to identify trace molecules in the air. The trick is to exploit the way the returning air-laser beam behaves in response to changes in the outgoing pulse. The interaction is highly nonlinear: Even a small variation in the outgoing laser produces a big change in the return laser beam. If the ultraviolet excitation pulse is not focused tightly, the air laser does not produce as much light—and we can affect the focus using another laser.

We send this other laser beam out on top of the first one, and we tune the second laser so that its light will be absorbed by a specific trace molecule and no other. If the trace molecule is out there, waiting to be found, it will take in the energy and thus heat the air. Just a very little heating along the beam path makes the air behave as a lens, changing the focus of the ultraviolet laser. That change in focus then indicates that the molecule of interest is present. We establish that the focus has indeed changed by comparing the brightness of the backward laser beam altered by this telltale heating of the air with that of another laser beam that we send out simultaneously and focus on a nearby point.

Right now we're examining the processes involved in the formation of the backward laser beam. We've observed that the shape of that beam changes with the wavelength of the outgoing ultraviolet laser, but we still don't understand why. Also, the air-laser beam has a "spiky" nature, and we want to figure out where those spikes come from. Understanding these processes will allow us to minimize the pulse-to-pulse fluctuations of the backward propagating beam and improve the detection sensitivity of the air laser.

BECAUSE THE DETECTION of trace molecules is both difficult and important, it's a good idea to give bomb detectors in the field another method to double-check it. This backup method should be complementary, using a different physical phenomenon. We have opted for radar. Our technique is based on a phenomenon called resonance enhanced multi-photon ionization (REMPI), a very sensitive method used to detect trace molecules both in research laboratories and for such things as environmental monitoring and the analysis of coffee roasting.

In the standard REMPI process, a laser tuned to excite a particular energy transition in the target molecule is focused on one designated spot. If molecules of that kind are present, some will absorb a photon (or two, in the case of a two-photon transition), be excited to the higher energy level, and then absorb another one or two photons. When that happens, an electron is knocked out of the molecule, leaving it a positively charged ion. You can detect the presence of such ions either by seeing whether a current will pass through the gas or by running the gas through a mass spectrometer, which accelerates ions using an electric field and then bends their trajectories with a magnetic field, revealing their charge-to-mass ratios.



Our version, which we call radar REMPI, dispenses with the electrodes and mass spectrographs. Instead, we detect the charged particles using radar. The outgoing radio waves reflect off the electrically conductive region of ionization, just as if it were a metal particle, and return to the detector. We can achieve the same high sensitivity and spectral selectivity as with classical REMPI but at a distance. This approach serves as a complement to the air-laser method because it reveals the same target molecules in a completely different way. We have demonstrated its effectiveness by using the ultraviolet laser we employed to produce an air laser but tuned to a slightly different wavelength—one that excites nitric oxide through the absorption of a single photon. Once the nitric oxide is in that excited state, a second photon of the same wavelength can ionize the molecule. We used a very-low-power radar system—just 10 milliwatts—operating at 100 gigahertz and placed a few centimeters away from our sample, a blend of nitric oxide and air contained in a small glass vial, which kept the mixture controlled. The laser was focused on a very small volume within the vial, about 300 micrometers long and about 10 μm in diameter. Only the nitric oxide molecules in this tiny region were ionized.

The intensity of the return radar signal scaled with the concentration of the target molecule, all the way down to parts per million and below. We can even measure to better than the ambient 50 parts per billion concentration in room air. We began by placing the radar set just a few centimeters from the vial. Next we tried it a meter away—and then 10 meters away—and found that this system still worked very well. We expect that it'll function fine over some tens of meters—far enough away from a typical bomb to be safe. For those experiments we will use a higher power microwave, pulsed to coincide with the laser pulse.

Of course, the presence of nitric oxide doesn't prove there are explosives nearby. Nitric oxide is present in low concentrations even in clean air. Still, it does suggest the presence of nitrates, a common ingredient in explosives, and it is also the product of the laser-induced fragmentation of many other nitrogen-rich molecules found in explosives. We've already done some preliminary work that shows that we can distinguish such freshly made nitric oxide fragments from atmospheric nitric oxide molecules by their characteristic vibrations. Radar REMPI can also detect trace quantities of many other molecules of interest. This approach is good for standoff detection because of the high sensitivity of the radar process and its immunity to sunlight interference. And because the molecular selection (which is done with the laser) and the detection (which is done with the radar) are separate, you can transmit a very powerful radar signal without affecting the laser selectivity.

WE ARE CONFIDENT that the air laser and radar REMPI can each produce strong signals from trace elements that we can distinguish from background noise. Applying the techniques to the detection of IEDs will require much more work, because they have extremely low vapor pressures and are normally found outdoors, where wind and rain may obscure their presence. The system will need to operate at high repetition rates and with fast processing to scan large areas effectively. Also, because IEDs are frequently made from fertilizer, it will be difficult to distinguish them from organic waste.

Problems in the civilian world should, however, be much easier to tackle. Our two techniques could, for instance, be used to monitor air pollution, greenhouse gases, and gaseous leaks from chemical plants, and even for detecting the presence of natural gas. For these applications, all you have to do is detect gases whose concentration is in the parts per million, or even higher. And you often have to do the job in places inhospitable to humans—and dogs. ❏

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/laseried0212

+SPECIAL REPORT+

DREAM JOBS ✯ 2012

ENGINEERS DESIGN THINGS and solve problems. No surprise there—that's the textbook definition of an engineer.

But there's nothing textbook about the careers these 10 engineers have forged for themselves. They're educators, explorers, and entertainers, as well as builders and problem solvers. Nicole Richard, for example, is using Lego kits to fire up young minds all over the world with the possibilities of technology. Chieko Asakawa is making the Web accessible to the blind. Kevin Hardy is part of a team attempting to send a man to the bottom of the Mariana Trench, the deepest spot in the world's oceans. And Brent Bushnell is creating complicated machines with a simple purpose: to delight and enthrall.

Trying to visualize an engrossing career in technology? Problem solved.

BRENT BUSHNELL

IEEE Member AGE 33 WHAT HE DOES Conceives and builds colorful contraptions that entertain people on television, in Internet videos, and in real life. FOR WHOM Syyn Labs, Doppelgames, and "Extreme Makeover: Home Edition" WHERE HE DOES IT Los Angeles FUN FACTORS Gets to play with technology in novel ways; every project is different.

PHOTO: GREGG SEGAL

Rube Goldberg 2.0

Brent Bushnell has a whimsical take on real-world engineering

A HUNDRED YEARS after Rube Goldberg's cartoons of impossibly complex machines captured the public's imagination, another California-born engineer, Brent Bushnell, is spending his days designing and building bizarre and complex machines—and making money at it.

Bushnell is a lead engineer with Syyn Labs, a company he cofounded that mashes up technology, art, advertising, and entertainment, creating one-of-a-kind high-tech spectacles that draw crowds and attention to its clients. The company's greatest hits include the "car organ" built for a DieHard battery commercial, created from 24 cars with their horns tuned, all hooked up to one battery and a keyboard, and a Rube Goldberg machine built for the Google Science Fair, designed around classic science fair projects, including a hamster running on a wheel to generate electricity and a Tesla coil that ignites a toy rocket.

Bushnell is also the founder of Doppelgames, a venture-funded company that builds smartphone apps that are tethered to the real world. Is it tough juggling two jobs, especially ones as unusual as these? Apparently not. Bushnell recently added yet another job, signing with the "Extreme Makeover: Home Edition" television show as a resident geek. For Bushnell, this job is actually an outgrowth of job No. 1: This season, Syyn Labs is creating high-tech gizmos for the show's projects, and he helps build them and reveal them on camera.

The son of Nolan Bushnell, founder of video-game pioneer Atari (and the kiddie birthday-party destination Chuck E. Cheese's), Brent and his seven siblings grew up creating games, tinkering with electronics, and starting companies. Home was a sprawling turn-of-the-century mansion in upscale Woodside, Calif. There Brent and his younger brother Tyler took on a daunting engineering problem: creating a circuit diagram for the entire house. "It was a rat's nest. We had walkie-talkies, and we went through and pinged out the whole house, so you would know which breaker to go to if something blew." The boys were aged 6 and 8 at the time.

When Brent was 19 and a sophomore in the EE program at the University of Colorado at Boulder, disaster struck the family. Merrill Lynch waged an intense legal battle against Nolan that arose out of a dispute concerning venture capital funding in the '80s. The company eventually succeeded in seizing much of Nolan's personal property. The family was forced to sell the Woodside house and move into a modest rented house in Southern California.

"As hard as that was," Brent says, "I'm grateful for it. It made us better and stronger. Scar tissue is a good thing."

Growing up in a hyperentrepreneurial family with eight children does present its share of opportunities. Brent left college about halfway through to join his sister Alissa's Internet start-up in

OK GO: The Rube Goldberg machine built by Syyn Labs for the band blasts them with paint. *PHOTO: OK GO/SYYN LABS*

TOP: GREGG SEGAL

San Francisco. Once that was on track, he moved south to go back to school, this time at the University of California, Los Angeles, in computer science, while he and brother Tyler started a Web hosting company. Brent had every intent of finishing his degree, but in 2005, with just three classes to go, his father's latest start-up, uWink (think Chuck E. Cheese's for adults) needed him. Bushnell once again left school. (He says he'd really like to finish up his degree at some point.)

By late 2008 the company was in trouble. Its last restaurant closed in 2010. The collapse of uWink was a huge disappointment, but it couldn't have happened at a better time: He'd been spending the occasional evening working with friends at Syyn Labs, then called Mindshare Labs. The company, started in 2007 as a Tuesday night get-together for tech enthusiasts to drink and build cool stuff, had been more recreation than anything else. Then in 2008 the rock band OK Go hired the techies to build a machine that band members could "dance" with, whatever that meant. Syyn Labs came up with a contraption that filled a warehouse and used it to accompany a song with 4 minutes of frantic activity. The music video starring the machine, for the song "This Too Shall Pass," went on to garner nearly 40 million views on YouTube. Since then, the company has been in demand whenever art directors and designers envision something unusual, striking, and technically complex.

Syyn Labs today has more potential clients than it can handle. Typically, Bushnell has little warning of what he'll be working on next. And over at "Extreme Makeover," he rarely gets more than a week's notice about what problems he might be asked to solve. He thrives on the pace, Bushnell says, because he rarely has time to tire of one project before he's diving into another one.

Over at Synn Labs, in a converted paint factory a short walk from Bushnell's live-work space in a former Pabst Brewery just east of downtown Los Angeles, the workspace is littered with projects in progress or recently completed—intriguing flotsam like a partially smashed Chevy Sonic, a minigolf green, and an electronically controlled fire fountain. "It's hilarious stuff," Bushnell says. "It's hard to call what I do work, actually."

—TEKLA S. PERRY

[ONLINE EXCLUSIVE]

P2P POLITICS

Jascha Franklin-Hodge uses the Web to improve political campaigning

ONE EVENING in early 2008, Senators Ted Kennedy and Barack Obama met to talk shop. Obama, who was just about to announce his presidential bid, was looking for a company to create and manage his digital campaign, and Kennedy suggested a start-up called Blue State Digital. For Jascha Franklin-Hodge, the start-up's cofounder, this was the big break he'd been working toward for five years.

Obama's team soon signed Blue State Digital to build a website that could help get the candidate's message out and raise funds. Franklin-Hodge had been building such websites since he served as systems administrator for Howard Dean's U.S. presidential campaign in 2004. The young man had been inspired by the new ways Dean was using online networks to transform the electoral process—appealing directly to voters to connect, get involved in the campaign, and contribute funds. Although working for Dean—one of the first to embrace digital communication—meant leaving a lucrative job at AOL, it provided a huge opportunity for Franklin-Hodge to be a part of the political process and help define how the technology developed.

Dean eventually withdrew from the race, but Franklin-Hodge and his colleagues kept going. They incorporated Blue State Digital in 2004 and just a few years later were helping guide Obama to his groundbreaking win. Now Franklin-Hodge is focused on Obama's 2012 campaign. —*Marisa Plumb*

JASCHA FRANKLIN-HODGE

IEEE Member AGE 33 WHAT HE DOES Heads up the technology team for a company that builds websites for politicians, nonprofits, and businesses to get their messages out. FOR WHOM Blue State Digital WHERE HE DOES IT A converted factory in Boston FUN FACTORS Gets to advocate political ideas he believes in.

PHOTO: DAVID YELLEN

Read about Franklin-Hodge's efforts to use technology to support politicians at http://spectrum.ieee.org/franklinhodge0212.

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Sports Geek

Antoine Ravisé found his calling developing next-generation sports gear

ANTOINE RAVISÉ opens a secret door wedged between fire gear and bike tires at the back of a sports store in Villeneuve d'Ascq, a university town in the northern corner of France. A white industrial door shuts behind him as he waves an entry card to unlock the revolving glass door that separates him from a busy laboratory. Ravisé speed walks through the high-ceilinged workspace, hailing colleagues along the way. He arrives at a walled-off room, laces up a pair of running shoes, steps onto a stack of wood, and puts on a blindfold. "It's a surprise for my body," he calls out, just before stepping off the stack and landing on a pressure sensor embedded in the floor. He clearly delights in the work, running over to a computer after each step to save the data.

Ravisé is an R&D engineer for Oxylane, the product-development branch of the international sports chain Decathlon. Over the past four years, he has spent long hours performing tests—often on himself—in the name of better sports gear. This latest experiment is devised to show how he might determine whether shoes cushion a runner's footfalls better than bare feet. He's also shivered for 5 straight hours in a climate chamber to evaluate thermal apparel. He's taken to the Alps and the Pyrenees to check out GPS devices and tent lights. Closer to home, a 600-meter-long stretch of cement outside his office is a favorite place to assess running and cycling gear.

Bright-eyed and spiky-haired, Ravisé has come to Villeneuve d'Ascq to take advantage of the lab's pressure sensor. But he spends most of his time in an office in nearby Lille, where he develops and tests sports electronics for Oxylane's newest brand, Geonaute.

Ravisé's first love was sports. When he was 6 years old, he decided he wanted to be a professional athlete and spent the next six years training in gymnastics before discovering fencing in high school. But he also liked to tinker. When his grandfather gave him a small gasoline-powered Solex motor at age 14, Ravisé looked up directions on the Internet, disassembled the motor, reassembled it, and then attached it to his bicycle. Some modifications later, he had a moped that ran at up to 60 kilometers per hour.

For a long time, though, Ravisé's technical interests took a backseat to sports. After high school, he enrolled in an engineering school near Nice. But he found that he couldn't carve out enough time for fencing in the demanding academic schedule, so after a year he switched to physics at the University of Bordeaux. By a special arrangement with the university, he was allowed to reduce his class hours to keep up with his fencing. He trained hard: He swam laps in the morning, spent his lunch hours lifting weights or doing yoga, and squeezed in hours of fencing at the end of the day. He even found unpaid work as a sparring partner for the French women's Olympic team.

But in 2007, just before his last year at university, he tore a ligament in his knee during a competition. The setback, combined with the growing realization that professional fencing offered limited career

prospects, led Ravisé to rethink his aspirations.

There was no way he would give up athletics altogether, so instead he looked for a way to combine sports and research. He contacted surfing companies in southwest France, met people from Nike, and introduced himself by e-mail to about 20 people from Decathlon, a company that's best known for its sports stores but also develops a range of products in-house.

ANTOINE RAVISÉ

IEEE Member AGE 27 WHAT HE DOES Designs and tests sports electronics devices. FOR WHOM Oxylane WHERE HE DOES IT Lille, France FUN FACTORS Rides bikes, swims laps, and runs through the hills in pursuit of better sports equipment.

PHOTO: ANTOINE DOYEN

He was looking in part for a good project in order to complete a second degree in management. He ended up joining Decathlon's research training program, which assigned him to a project evaluating the comfort of sports clothes. He tested fabrics for permeability and used temperature and heart rate sensors to assess how well they worked when worn.

Just a month after graduation in 2008, Ravisé was hired full-time as the company's first test engineer specializing in electronics. One of his first tasks was to set up two device testing labs, one in Lille and the other in Shenzhen, in southeast China. His visits to China offered the opportunity for a personal research project: new food. Ravisé says he can't resist sampling snake, fish heads, and other dishes that are hard to come by in northern France. He has a container of chicken feet at home, which to his disappointment has largely been avoided by his friends.

Once he had the labs in operation, Ravisé dove into a project: a waterproof MP3 player for swimmers that also functions as a distance meter. The design specifications called for a device that could detect each time a swimmer turns around to start a new lap. So Ravisé and colleagues rigged up a few prototypes and tested them on a range of swimmers. He also hopped into the pool himself to test the gear. "Afterward we had a lot of data, and we had to find an equation [to fit it]," Ravisé says. One equation would have to work well for almost every swimmer. With some number crunching, the team eventually found a way to count laps using just one gyroscope, which helped keep costs down. The device hit the market at the end of 2010 and costs about €75, or around US $100.

These days, Ravisé is investigating ways to build devices that don't need battery power and instead harvest energy from the environment. He is also exploring flexible printed circuit technology that could allow electronic devices such as heart monitors to be embedded directly into clothing. A native of sunny southern France, he says he had to make some sacrifices for the job. "For example, I spend most of my time in the north of France," he quips, gesturing at a typically overcast sky. But he says he couldn't be happier he made the move. The weather certainly doesn't slow him down. After putting in a full day at the office, he hops into his Volkswagen with a trunk full of gear and speeds off to the gym.

—Rachel Courtland

[ONLINE EXCLUSIVE]

SOCIAL ENGINEER

José Edimilson Canaes bridges Brazil's digital divide

JOSÉ EDIMILSON CANAES enters a small classroom crammed with a dozen computers and as many kids. He walks around. "Let me see some photos," he says to a 12-year-old with curly hair and brown eyes. She shows him a series of PowerPoint slides she's creating, explaining that this morning's class focuses on problems the students found in their São Paulo community: open sewage ditches, littered streets, broken traffic lights. Later the group will prepare pamphlets and letters demanding that local representatives address the problems.

Canaes is the director of operations at the Center for Digital Inclusion, known as CDI, a nonprofit organization that establishes computer education programs in underprivileged and isolated parts of Brazil and 12 other nations. Its goal is to teach people not only basic computer skills but also how to use technology to solve problems in their own communities and make their lives better.

"You can see the sparkle in her eyes," Canaes says of the 12-year-old girl. "All she needs is a little push, and then she'll soar." *—Erico Guizzo*

Read more about Canaes's experiences at CDI at http://spectrum.ieee.org/canaes0212.

JOSÉ EDIMILSON CANAES

IEEE Member AGE 53 WHAT HE DOES Uses computer education to empower people. FOR WHOM Center for Digital Inclusion WHERE HE DOES IT Brazil and 12 other countries FUN FACTORS Travels to isolated and exotic locales establishing computer centers; gets to meet educators and students who are changing their communities.

PHOTO: PAULO FRIDMAN

Lego Queen

Nicole Richard uses Lego kits to inspire budding engineers

NICOLE RICHARD was never obsessed with Legos as a child, but the 34-year-old has clearly caught the bug now. Her desk is adorned with a skiing Lego Santa, a camel-riding Lego pirate girl, a Lego robot wearing a hula skirt, and a bin full of rare Lego parts—Yoda heads, crabs, wineglasses, mermaid tails, and hot dogs—culled from visits to Lego headquarters in Billund, Denmark. She might have a 12-year-old boy's dream job, she says, but it's become hers, too.

Richard manages the development of software for two popular Lego robotics systems. One is Mindstorms NXT, a kit with a 32-bit wireless microcontroller that's developed a devoted following among kids and robotics hobbyists since its introduction in 2006. The other is the Education WeDo Robotics Kit (WeDo for short), a construction set that introduces robotics and computing basics to children as young as 7. She's employed by National Instruments Corp., based in Austin, Texas, which uses its LabView graphical programming environment as the basis for the Lego software.

Richard joined National Instruments in 2000, right after she graduated from the University of Colorado at Boulder, with a degree in electrical and computer engineering. She cut her teeth at NI on a series of programming and managerial jobs. She enjoyed the work, but she says she really began to find her passion in 2007, when her boss approached her about working on the Lego software. Richard says she didn't think twice before accepting the offer—at the very least, she

NICOLE RICHARD

IEEE Member AGE 34
WHAT SHE DOES Manages the creation of software for Lego robotics kits. FOR WHOM National Instruments Corp. WHERE SHE DOES IT Austin, Texas FUN FACTORS Travels around the world to bring robotics kits to kids; gets to visit Lego's headquarters in Denmark and mine the company's coffers for rare pieces. PHOTO: MARY SLEDD

says, she was excited to get to work on a product with such wide appeal.

The switch turned out better than she could've imagined. Right after she began managing the Mindstorms software, Richard got the chance to help create the WeDo software, which lets users manipulate cartoonlike icons to create simple programs that can control motors and sensors. This was one of Richard's first opportunities to shepherd a product from inception through release. Even more important, she had the chance to see how her work was having an impact in classrooms thousands of miles away, in the United States and beyond.

And "beyond" includes Cambodia. In 2010, Promoting Education, emPowering Youth, a nonprofit group working to improve Cambodian schools, was looking for help with 10 donated WeDo kits. A representative from the organization asked if anyone at NI would be passing through the area and could show teachers how to use the kits. Richard had already been planning to visit Bali for a wedding, so on impulse, she added a week to her trip. In September, she and a friend made the 30-hour journey from Austin to Siem Reap, in northwestern Cambodia, and then on to the village of Chanleas Dai. There they trained teachers and spent a day with 18 students who came in eager to learn, despite the fact that it was the last day of their summer vacation. "It was overwhelmingly different there," Richard says. "These kids were motivated to learn unlike any kids I'd ever seen before. They don't take education for granted there at all."

Last year Richard traveled to Jharkhand, in eastern India, and spent a week conducting Lego workshops in a small orphanage there. Just as in Cambodia, she says, the kids took to the technology straight off. In just a few hours, even children who had never used a computer before were well on their way to building drumming robotic monkeys. Others were enthralled. "It was only after the [uninterruptible power supplies] lost all of their charge and the computers shut down that we could get any of them to leave," she says. "They're hungry for this stuff."

Richard wasn't sure whether her visits would have a lasting impact. But she kept in touch with the teachers at the Cambodian school, and she was thrilled to hear that they had started two robotics clubs. Demand for the clubs was so high that the teachers had to put an application process in place. Richard now hopes to replicate this kind of activity elsewhere; lately she's been working with nongovernmental organizations to set up engineering clubs in Peru and India. The ultimate goal, she says, is for the children to develop critical thinking, problem solving, and technical skills and use them in turn to help address some of the challenges their communities face.

Given Richard's belief in the transformative effects of technology, it's hard to believe that she herself wasn't always so focused on engineering as a career. Although her parents are both engineers, she says she had little sense of what an engineering career involved until she joined NI. Working with engineers to troubleshoot communication lines within Mars rover prototypes and configure strain gauges to measure the flex of snowboarding boots, she finally got a sense of what engineers do for a living. Then it took her a bit longer to find her calling.

"I chose to go into engineering because I knew I could make a good living at it, and I liked programming," Richard says. "It was only later that I became inspired by the opportunities it offers to really make an impact." She hopes her outreach efforts can help kindle a passion for engineering in others. "It took me a while to connect those dots for myself," she says. "Now I'm out trying to help kids make those connections for themselves more quickly."

—Rachel Courtland

[ONLINE EXCLUSIVE]

QUICK-DRAW ANIMATOR

Kevin Wang's software turns news stories into viral videos

THE ANIMATED VIDEOS went viral even before they had English subtitles. There was, for example, the one showing Tiger Woods's marital meltdown in gruesome detail. And then there was the one with the JetBlue flight attendant who quit his job by shouting obscenities over a plane's public-address system, grabbing a beer from the galley, and sliding down the plane's emergency chute. These bizarre Taiwanese animations re-created the dramatic moments that everyone so desperately wanted to see, and they hit the Web while the stories were still in the headlines. No wonder they were sensations.

What *is* a wonder is the way they were created, using a system developed by Kevin Wang. As director of the multimedia lab for Next Media Animation, an offshoot of a news company based in Taiwan and Hong Kong, Wang reinvented the process of computer animation and reduced production time from 2 weeks to 2 hours, so that on-the-fly animations could be published on the company's websites before the news got stale.

Accomplishing this required a completely new approach to animation, with a combination of tricks and shortcuts that no one had tried before. Wang called the assignment his own "mission impossible," but he was ready for it. Throughout his life, he has gravitated toward the professors and bosses who assigned the toughest work—and, if necessary, he has doled it out to himself. For example, he turned a mandatory stint in the Taiwanese military, when he served as the army librarian on an isolated island base, into a study course on 3-D animation. —*Eliza Strickland*

KEVIN WANG

IEEE Member AGE 48 WHAT HE DOES Builds computer animation systems used in news and entertainment programs. FOR WHOM Next Media Animation WHERE HE DOES IT Taipei, Taiwan FUN FACTORS Plays with cutting-edge animation tools; can take credit for viral videos about foolish celebrities.

PHOTO: GARRET M. CLARKE

Read more about Wang and the solution he found for Next Media Animation at http://spectrum.ieee.org/wang0212.

Going Deep

Kevin Hardy's creations plumb the depths of the Mariana Trench

KEVIN HARDY

IEEE Member AGE 58 WHAT HE DOES Builds seafloor landers that will go to the deepest trenches on Earth. FOR WHOM Virgin Oceanic WHERE HE DOES IT San Diego and over the Mariana Trench in the Pacific Ocean FUN FACTORS Adventure on the high seas—need we say more?

PHOTO: ROXIE J. CIRINO

WITH THE BOAT surging over ocean swells, a soaked and smudged Kevin Hardy reaches over the side and yanks a tether, freeing a 3-meter-long submersible. It sinks quickly into the waves—first the iron weight, then the long tubes that will collect water samples, and finally the bright orange spheres that protect its electronics. Hardy's latest oceanic probe is starting a 10.6-kilometer (6.6-mile) journey to the bottom of the Mariana Trench, the deepest spot on planet Earth. The probe will fall for 3 hours to reach that mysterious seafloor.

Exuberant and ruddy-faced, Hardy wipes the salty spray out of his eyes and shakes hands with the crew members. It has been a grueling day. Embarking from Guam in the early morning on a small former ferryboat, the team motored 130 km out to sea, rocked by high waves that caused a few of the scientists to go green around the edges. They reached a part of the trench called the Sirena Deep as the sun began to set and readied their equipment for the big plunge. The boat's depth finder, overwhelmed by the abyss beneath the hull, displays an absurd depth reading of only 8.5 meters.

The seafloor lander they're testing will play a role in a US $10 million mission that will send a human to the bottom of the Mariana Trench later this year. No one has been there since 1960, when a Swiss engineer and a U.S. Navy officer descended aboard the bathyscaphe *Trieste*. In the 52 years since then, only a few unmanned probes have been down to those pitch-dark deeps. But if all goes well, Chris Welsh, the cofounder of Virgin Oceanic, will soon become the third man to reach the nadir of the world. Four of Hardy's tough little landers are to accompany the Virgin Oceanic sub that Welsh will steer down to the ocean floor.

It will be the culmination of a mammoth engineering challenge. At the bottom, water will press on the sub with a force of 110 megapascals, or roughly the same pressure that would result from a large elephant standing on a postage stamp. Hardy's commands to his landers will be transmitted acoustically through more than 10 km of water. But that's all part of the fun for him—throughout his career he's always pushed to "go deep," as he puts it. "If there was a deeper place than the Mariana Trench, I'd try to go there too," he says. And the ferryboat is full of people who have caught Hardy's enthusiasm for the world's watery chasms. "I build teams as well as things," he says. "I love the part where you cross the finish line together."

Hardy has spent much of his life preparing for this challenge. He grew up in San Diego in the 1950s, part of a big, boisterous family. At age 7, he built his first marine vessel—a boat made of orange crates that used one of his little brother's cloth diapers for a sail. His plan was to go into marine or aerospace manufacturing, so at San Diego State University he majored in industrial technology manufacturing.

Between freshman and sophomore year, in the summer of 1972, Hardy knocked on doors at the Scripps Institution of Oceanography at the University of California, San Diego, until he found a job there. He ran errands and loaded supplies onto ships as a lowly lab helper, but during his lunch hours he'd wander the halls of Scripps, popping into labs to talk to people about their work.

Plenty of scientists found the ebullient 18-year-old charming, and one offered to take him out on a two-week research cruise. The expedition so thrilled Hardy that he kept volunteering for night watches aboard the

[ONLINE EXCLUSIVE]

AUTOMATION FOR ACROBATS

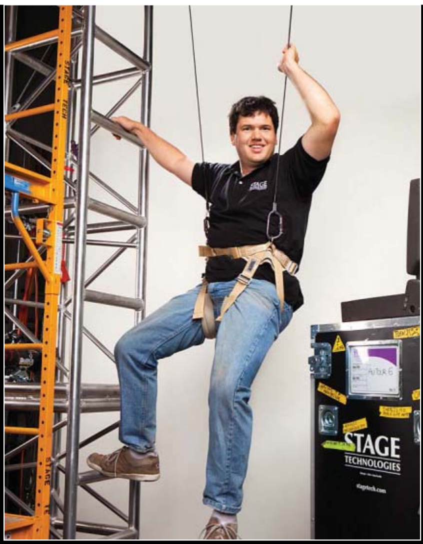
Phillip Toussaint's code keeps Cirque du Soleil and other extravaganzas moving

A GIANT STATUE of Elvis Presley, a 27 000-kilogram set incorporating seven trampolines, performers who fly through the air on computer-controlled cables—such are the elements that transform theatrical productions into magic. Behind the magic is technology, and behind that technology is Phillip Toussaint.

Toussaint is an automation engineer with Stage Technologies, a maker of hardware and software for automating spectacular set changes and gravity-defying flying effects for concerts, opera houses, and theater companies all over the world. A self-professed computer nerd, he says he always knew he wanted to be a programmer. Then in high school, he enrolled in a class on theater lighting to fulfill an arts requirement, and he became excited by the technical challenges of theater. At the University of Arizona, he majored in computer engineering and minored in theater arts.

Today, Toussaint writes the programs that guide the movement of machinery, scenery, and acrobatic performers, making sure each follows a precise path. *IEEE Spectrum* encountered him inside a dark crawl space in Las Vegas, surrounded by the motor controls, motorized trolleys, and whirring winches that move that massive construction of trampolines for Cirque du Soleil's production *Viva Elvis*. "There's no schooling that prepares you for [this] sort of project," he says.

—*Alaina G. Levine*



PHILLIP TOUSSAINT

IEEE Member AGE 26 WHAT HE DOES Writes the software that makes scenery—and sometimes actors—fly across the stages of Cirque du Soleil and other theatrical productions. FOR WHOM Stage Technologies WHERE HE DOES IT Las Vegas and at client sites around the world FUN FACTORS Travels around the globe creating magic for performers and audiences; meets the directors and sometimes the stars of today's hottest shows.

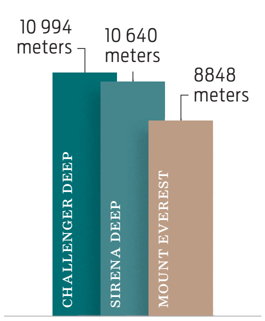
PHOTO: GREGG SEGAL

Go behind the scenes with Toussaint and Stage Technologies at http://spectrum.ieee.org/toussaint0212.

ship. "I stayed awake for three days straight," he remembers, "I didn't want to miss anything." One cruise led to the next, and when Hardy graduated college, Scripps offered him a job as an ocean engineer. He ended up working there for almost 40 years, building buoys studded with sensors and sediment samplers for Scripps's scientists.

Throughout his Scripps years he sought out the men who had been involved in the historic *Trieste* expedition of 1960. As he listened to their stories, he gradually resolved to go to the Mariana Trench himself. "At some point," says Hardy, "it became a consuming goal: 'I'm going. If it's me in a rowboat with my machine, I'm going to the trench.' "

Luckily enough, he met Chris Welsh, an accomplished sailor and adventure seeker, who founded Virgin Oceanic with Sir Richard Branson for the sole purpose of visiting the world's deepest trenches. In early 2011, Welsh hired Hardy as a consulting engineer to build the landers that will accompany Virgin Oceanic's sub to the ocean bottom. The timing was right for Hardy, as he had retired from Scripps in 2011 and was looking for new challenges.



Everest could drown in Mariana's deeps

In the grand Mariana Trench expedition planned for 2012, Hardy's landers will sink down before the sub, like the advance team for a head of state. They'll be equipped with lights, cameras, and equipment to take samples from the bottom. Welsh, who will pilot the one-man sub on the first dive, can then navigate between the landers, which will stake out spots of scientific interest. The team hopes to come back not only with a rip-roaring adventure story but also with samples of sediment, water, and maybe even tiny invertebrates from the landers—not to mention some great footage. "When the pilot gets down there, we can order the landers to turn on their lights and cameras to watch the sub glide in," Hardy says.

But at the moment, Hardy has more immediate concerns. On the ferryboat, floating on 10 km of water, he and his colleagues ping the descending lander and get a response: It's at 1400 meters and falling fast. Once the lander reaches bottom it will collect its water samples; then Hardy will release the anchor, returning the lander to the surface with its payload. He expects the lander to surface at 1:30 in the morning, Hardy says, cheerfully planning another night watch.

—Eliza Strickland

Web Guru for the Blind

Chieko Asakawa can't see your website, but she can make it better

CHIEKO ASAKAWA has just given the *IEEE Spectrum* website a once-over, and the verdict isn't good. Her software program has declared that the site is neither operable nor understandable, and it has decorated *Spectrum*'s home page with a series of red frowny faces. "I'm afraid it's pretty bad," she says regretfully, smiling to soften the blow.

Asakawa isn't talking about what the site looks like—for someone who navigates the site visually, it's a nicely organized wealth of information. But for Asakawa, who is blind, it's a mess.

She uses an audio Web browser that reads content aloud, and on *Spectrum*'s home page it bogs down in category headings and subheadings, taking minutes before it finally gets to an actual article headline. That's not unusual, says Asakawa; many of the Web's wonders are still inaccessible to the visually impaired. But Asakawa has done her best to change that through her work at the Tokyo branch of IBM Research, where she has devoted herself to improving blind people's access to computers and the Web for 27 years.

What began as a personal challenge grew gradually into a globe-trotting career, as a blind Osaka teenager became a cosmopolitan woman who knows the New York City subway system from top to bottom. In her plain, unornamented office, the elegant Asakawa toys with the string of pearls around her neck and starts her story at the beginning.

She was born with normal vision and harbored early dreams of becoming an Olympic athlete. But Asakawa's world began to darken at age 11, when she hit her eye on the side of a swimming pool, damaging her optic nerve. She was completely blind by 14,

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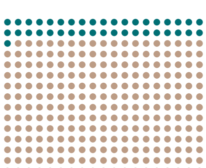
CHIEKO ASAKAWA

IEEE Member AGE 52 WHAT SHE DOES Develops software programs for visually impaired computer users. FOR WHOM IBM Research WHERE SHE DOES IT Tokyo FUN FACTORS Travels the world to meet collaborators; opens up online frontiers for herself and others; gets to tell hotshot Web designers how lousy their pages are.

PHOTO: MAKOTO ISHIDA



39 million people worldwide are blind; 246 million more are visually impaired

Source: World Health Organization

and her future seemed constrained. At that time in Japan, many blind people were routed into careers in massage or acupuncture. "I didn't want someone else to decide my job," says Asakawa. "So I made it my goal to find a new type of job as a blind person." After getting a bachelor's degree at Otemon Gakuin University, in Osaka, where she majored in English literature, she heard about a two-year computer course for the blind and signed up.

It was 1982, the twilight of mainframe computers and punch cards. Asakawa learned to program by mastering a torturous device called the Optacon, which used a camera to transmit the letters in a printed document, one by one, to a grid of tiny rods that formed the shape of each letter beneath her fingertips. She found the process excruciating, but she says there's a Japanese word for people like her: *makezugirai*. It means a stubborn character, or as Asakawa puts it, "someone who doesn't like to lose!" Sticking out the computer course led to a one-year position at IBM Research in Tokyo, which quickly evolved into a staff research job.

Times were already changing when Asakawa started at IBM in 1984: Personal computers were taking off, the first Braille printer was on the market, and an in-house IBM team had just developed a voice synthesizer that allowed Asakawa to read e-mail and write code much more easily. For her first IBM project she developed a digital Braille editor, which replaced clunky Braille typewriters with a modern word processor. Next she rolled out a network that allowed Braille libraries to upload and share documents and books (at a then dazzling but now quaint speed of 300 bits per second).

Asakawa's position on IBM's technical team gave her direct access to the personal computing revolution under way. And with each upheaval, Asakawa found a new challenge. When a colleague set up a system that allowed Asakawa to browse the Internet in the mid-1990s, she embarked on her mission to bring the Web to blind people everywhere.

By 1997 she had developed a plug-in that worked with the Netscape browser, mapping Web navigation commands to the computer keyboard's number pad and using text-to-speech technology to read out content. Computer stores around the world sold IBM's Home Page Reader, and Asakawa says its effect on the blind community was immediate, electric, and sometimes touching. During one training session for new users in Japan, she remembers a 70-year-old woman who asked for help searching for health insurance for the elderly. "She knew such information was available on the Web, but she couldn't get it by herself," says Asakawa.

Other browsers for the blind followed IBM's groundbreaking efforts, and Asakawa moved on to addressing a deeper problem: the fact that designers were unintentionally creating inaccessible websites. She and her team wrote a program called aDesigner—the software she used to reveal *Spectrum*'s flaws—to allow designers to experience a site as blind users do and to suggest ways to improve navigation for audio browsers.

Today Asakawa is a fellow at IBM, a poised and fashionable role model for women engineers, and a keen strategist for the company. In 2004, after earning a Ph.D. in engineering from the University of Tokyo, she began to think about how her research interests could mesh with IBM's global goals. While she still works on new projects for the blind, she has broadened her efforts to include Web accessibility tools for illiterate and aging populations. That last category is of particular importance in Japan, where 40 percent of the population will be over the age of 65 by 2055.

Asakawa is glad to be a proselytizer for Web accessibility, but she longs for a day when her missionary zeal won't be necessary. "Information access has become so critical for our daily lives," she says in her soft but forceful voice. "It's not a privilege; it's a human right."

—Eliza Strickland

[ONLINE EXCLUSIVE]

AVIONICS MAVEN

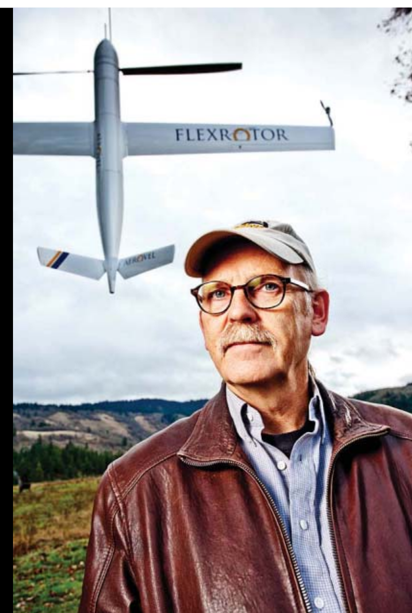
John Stafford is having a blast building an unmanned heliplane

WHEN JOHN STAFFORD was growing up in Altoona, Pa., in the 1960s, he loved tinkering with automobiles—and driving them fast. He imagined himself becoming the next Bruce McLaren, the famed New Zealander who was then building and racing Formula One cars. These days Stafford is helping to construct a composite-body hybrid-electric vehicle that's as sophisticated as any Formula One racer. But it isn't a car at all—it's an unmanned aerial vehicle (UAV) that takes off and lands like a helicopter but otherwise flies like a plane.

Stafford leads the avionics design team for UAV start-up Aerovel Corp., although he does mechanical work for the company as well, sometimes using the well-equipped machine shop in his home. Developing a vehicle that flies like both a helicopter and an airplane is no mean feat, and he and his fellow engineers are busily addressing the many challenges involved at their makeshift company headquarters in rural Washington state.

Stafford gravitated to Aerovel because of a fondness he'd developed for small, informal companies, where managerial tasks are few and the focus is on getting things done with your own two hands. For him, satisfaction comes from spending the workday tackling technical problems instead of managing subordinates or fussing with corporate bureaucracy, as he's had to do at some of his previous jobs.

—David Schneider



JOHN STAFFORD

IEEE Member AGE 57 WHAT HE DOES Leads avionics development. FOR WHOM Aerovel Corp. WHERE HE DOES IT White Salmon, Wash. FUN FACTORS Develops UAVs by strapping them to cars, flying them indoors—and yes, with conventional flight tests.

PHOTO: BRIAN SMALE

Read more about Stafford's career and his work on Aerovel's Flexrotor helicopter plane at http://spectrum.ieee.org/stafford0212.

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The Ultimate Switch

Continued from page 32

actually perform logic operations, and we had to get a better understanding of how competitive they might be against state-of-the-art CMOS.

One of the first designs we explored was the simple binary switch. You could build such a switch with just a square of graphene. If you draw an imaginary diagonal across the square, you create two triangles of graphene. Under each of these triangles you place a triangular wedge of conducting material—such as copper or heavily doped silicon—that can be either positively or negatively charged. These buried wedges act as gates, altering the electronic properties of the graphene above them. If both wedges have the same charge, the switch is on, and an electron coming from one side of the graphene square can move in a straight line from one side of the square to the other. But if opposite biases are applied, the two graphene regions will become oppositely doped, and nearly all the electrons will be reflected at the interface. Now the switch is off.

This simple device can be arranged in series to create a range of logic functions, including NOT, OR, and AND. According to our simulations, these devices should pass 1000 to 100 000 times as much current when they're on as when they're off, on par with CMOS and about 1000 times as good as graphene transistors. Because electrons move faster through the graphene, our calculations also suggest that logic made in this way could be 57 percent faster than CMOS, when power and area are held constant.

Raw speed is one thing, but these sorts of devices could also do things that traditional transistors can't do. With three buried gates and three electrodes for input and output, we reckon graphene switches can be made to perform a range of fairly complex logic functions by creating multiplexer devices. A multiplexer is usually used in communications applications to combine multiple inputs to make a single output signal. But the device's ability to handle multiple data streams also makes it a powerful way to make programmable logic.

In this case, the three buried gates and two electrodes on either side of the rectangular multiplexer device can all act as inputs. An electrode at the center of the device delivers the output. Electrons coming from electrodes on either end of the device may reach the electrode at the center, but only if the three gates beneath the device have the right voltages to allow the electrons through. This basic device can be reconfigured to support as many as eight different logic functions—everything from the simple inversion of a signal to more sophisticated constructions such as NOT (A and NOT B). By changing the voltage of the gates, the multiplexer can be made to switch between these functions in an instant.

That's a big departure from the way today's chips work. In CMOS circuits, a *p*-type transistor can't be converted to an *n*-type transistor or vice versa. As a result, you need more transistors to perform some of the more sophisticated logic operations. It takes at least eight transistors, for example, to perform an XOR function, an operation that could easily be accomplished with a single graphene multiplexer. That means less area on the chip and less power consumed. Considered another way, reconfigurable graphene logic can perform nearly three times as many calculations per second as a CMOS circuit, given the same amount of area and power.

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THAT WOULDN'T be too impressive if reconfigurable graphene logic remained in the realm of theory. But research into these devices has already begun to make its way from simulation to the laboratory.

In our preliminary studies of simple *p-n* junctions fabricated in the lab, we've shown that oppositely doped regions of graphene can be used to bend the paths of electrons. Varying the angle of a *p-n* junction with respect to an incoming beam of electrons can significantly alter the resistance of the device. This is an early proof of principle that we can create devices that can divert electrons.

We might also be able to create the electronic equivalent of an optical fiber. Early last year, a team at Harvard reported they had created a channel for electrons by applying different voltages to gates that were placed parallel to a graphene sheet. In their system, the electrons hit the sides of the graphene channel at glancing angles and experienced significant internal reflection.

The work suggests we could use graphene not only to make switches but also to guide electrons from one logic device to the next. These steering devices would be built the same way that logic devices are in a graphene sheet; the only difference between them would be the way voltages are applied to gates beneath the graphene sheet.

For now the biggest hurdle to bringing these new sorts of integrated circuits into production is the purity of the material. Electrons in today's graphene can move up to a micrometer before getting scattered by imperfections, such as corrugations in the surface of the material or grain boundaries between adjacent crystal patches. But electrons will likely need to be able to travel for 100 micrometers or even millimeters in graphene in order for it to be a viable logic material.

Fortunately, graphene fabrication has only been getting better since the material was first isolated. One of the first techniques used to make graphene was to push graphite across the surface of a silicon wafer, a process that could produce only imperfect, microscopic flakes. Now we have more precise methods that can produce fairly pure graphene on a large scale.

We can heat silicon carbide wafers, for example, to evaporate the silicon on the surface, leaving behind a layer of graphene. We can make even purer graphene sheets by growing the material using chemical vapor deposition and then using a layer of polymer to transfer the graphene to a wafer. This technique has met with great success. In December, a team at IBM used it to create the first graphene-based RF devices and amplifier circuits built on a 200-millimeter wafer, the biggest graphene layer with fully functional circuits that's been shown so far.

We have very good reason to anticipate that graphene quality will only continue to improve. With luck, we might see graphene-based reconfigurable logic prototypes within the next five years. For building logic capable of replacing CMOS circuits, it won't be a moment too soon. ❑

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/graphene0212

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Inria informatics mathematics

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the data

Engineers: What's in a Name?

IF YOU WERE LOOKING for a computer job on the Mark I, you might have described yourself as a *coder*, not a *programmer*, a term that wouldn't emerge until the 1950s. In the late '50s you could have added *computer operator* to the job hunt, but a decade later the computing community realized these jobs were not as easy as they seemed, so it created terms like *software engineer*. Other suggestions (possibly in jest) included *flow-charts-man*, *comptologist*, and even *turingineer*. More serious options included *informatician* or *datolotist*.

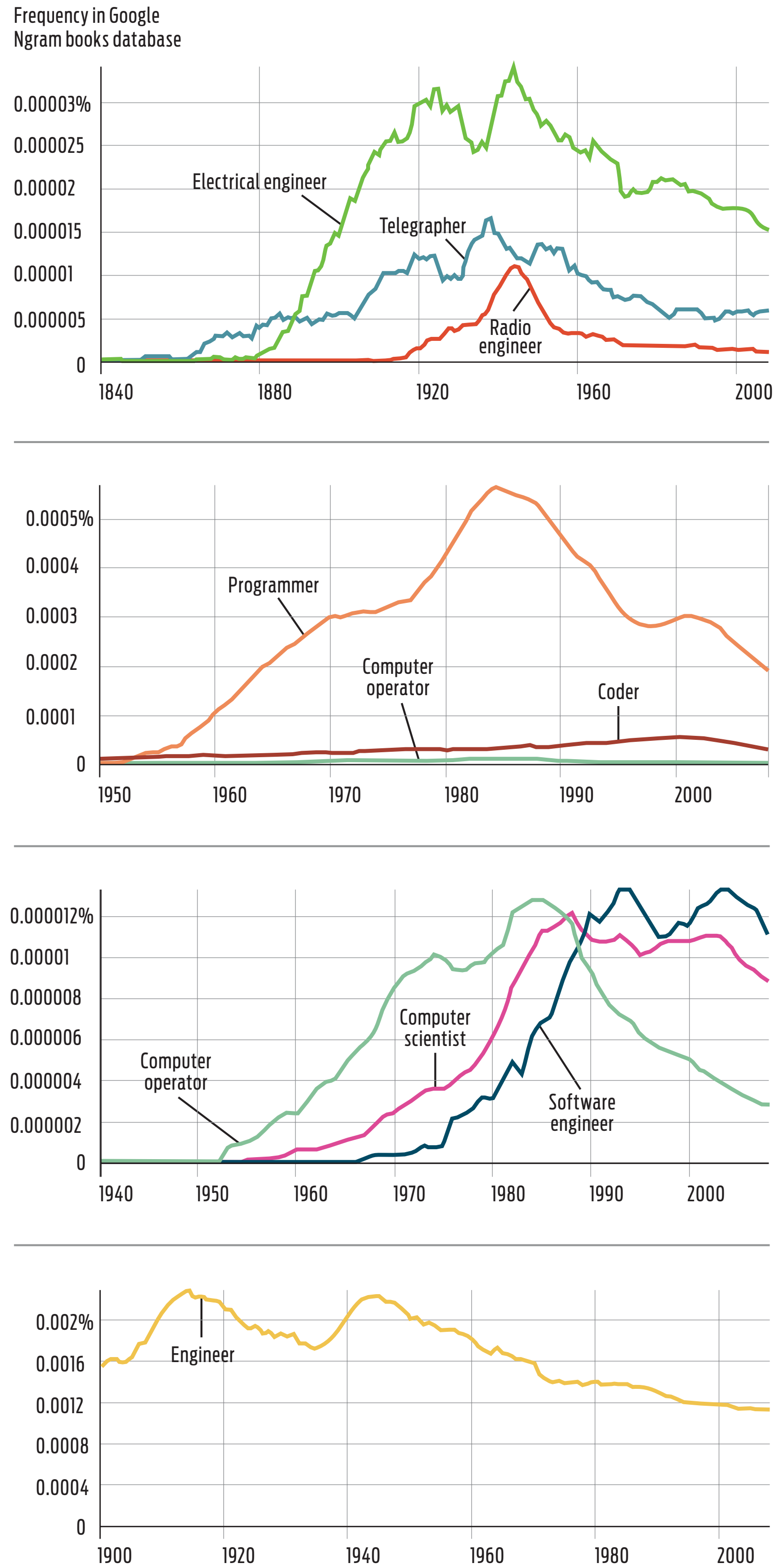
"It's not just word preference, it's identity," says University of Texas science historian Nathan Ensmenger. Computer operator positions were frequently filled by women, as were those of coder, keypunch operator, and computer (a term that used to refer to the person, not the machine). As the low-level jobs became automated, women gradually left what we now refer to as *computer science*, a term that was initially controversial, says Ensmenger. "Some thought you can't have a computer science any more than you can have a television science."

These trends can be verified in Google Ngram Viewer, a database of thousands of terms that combs through millions of digitized books. Ngram can't show how many people filled these positions, but it does show how frequently job titles were mentioned. Some terms, like *computer operator*, peaked in the early 1980s and dropped off when the position became automated. *Software engineer* spiked in the '90s during the dot-com boom and then dipped. The word *information*, as in *information architect* and *information specialist*, has become more popular. References to the lone word *engineer* increase around the world wars, in the early 1910s and early 1940s.

Radio engineer has come and virtually gone, evolving into more marketable titles like *electronics engineer* and *electrical engineer*, according to Matthew Wisniosky, a science historian at Virginia Tech—perhaps due in part to the 1963 merger of the Institute of Radio Engineers and the American Institute of Electrical Engineers that formed the IEEE.

And what about the jobs of the future? The industry may look for people who think more broadly about what computerization might mean for specific industries. "They don't have a great title for that yet," Ensmenger says.

—Ada Brunstein



SOURCE: GOOGLE NGRAM

Note: The *y*-axis represents the frequency of the indicated term in the entire Google Ngram database of 5.2 million books in a given year. The *x*- and *y*-axes differ in scale from graph to graph.

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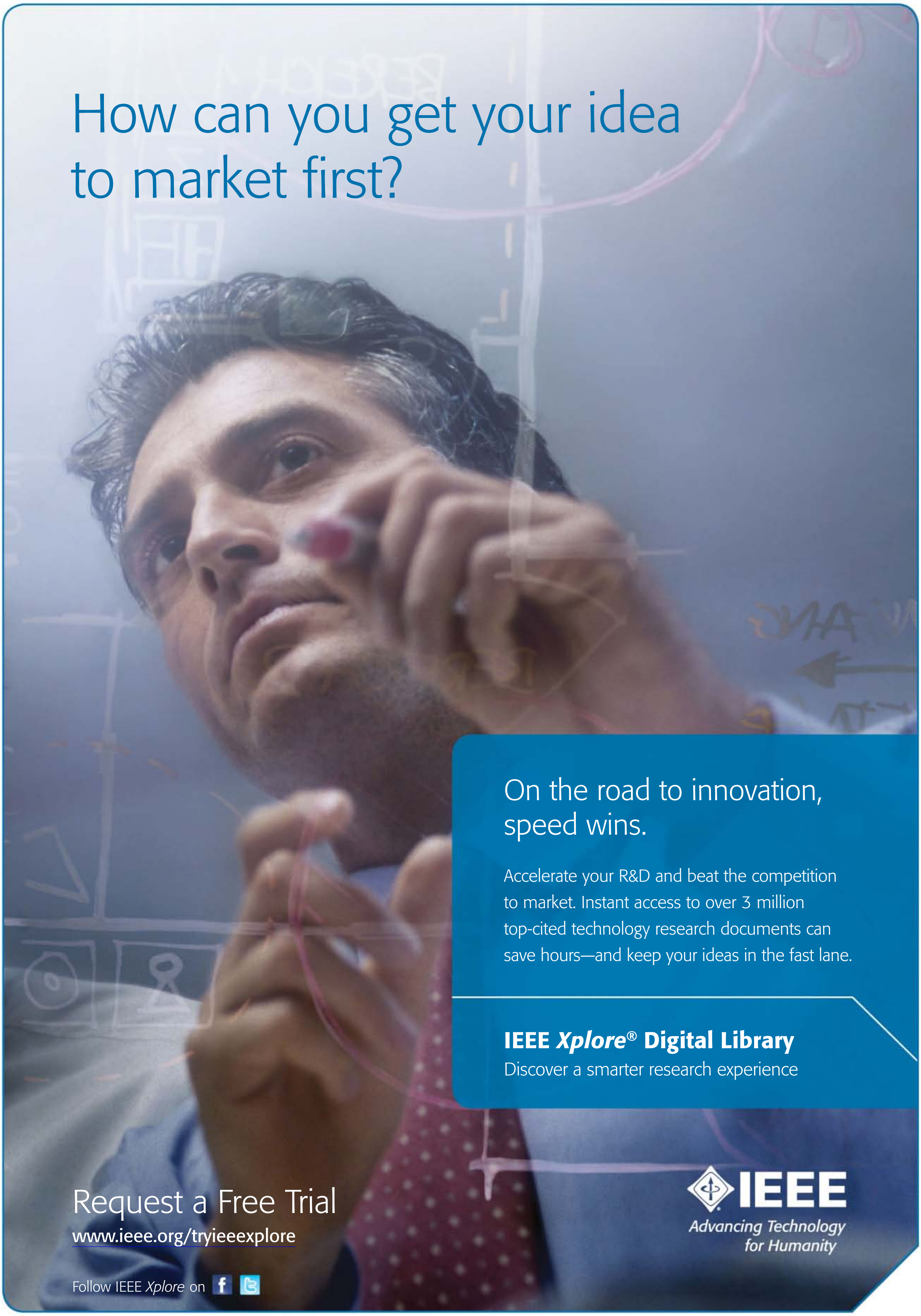

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