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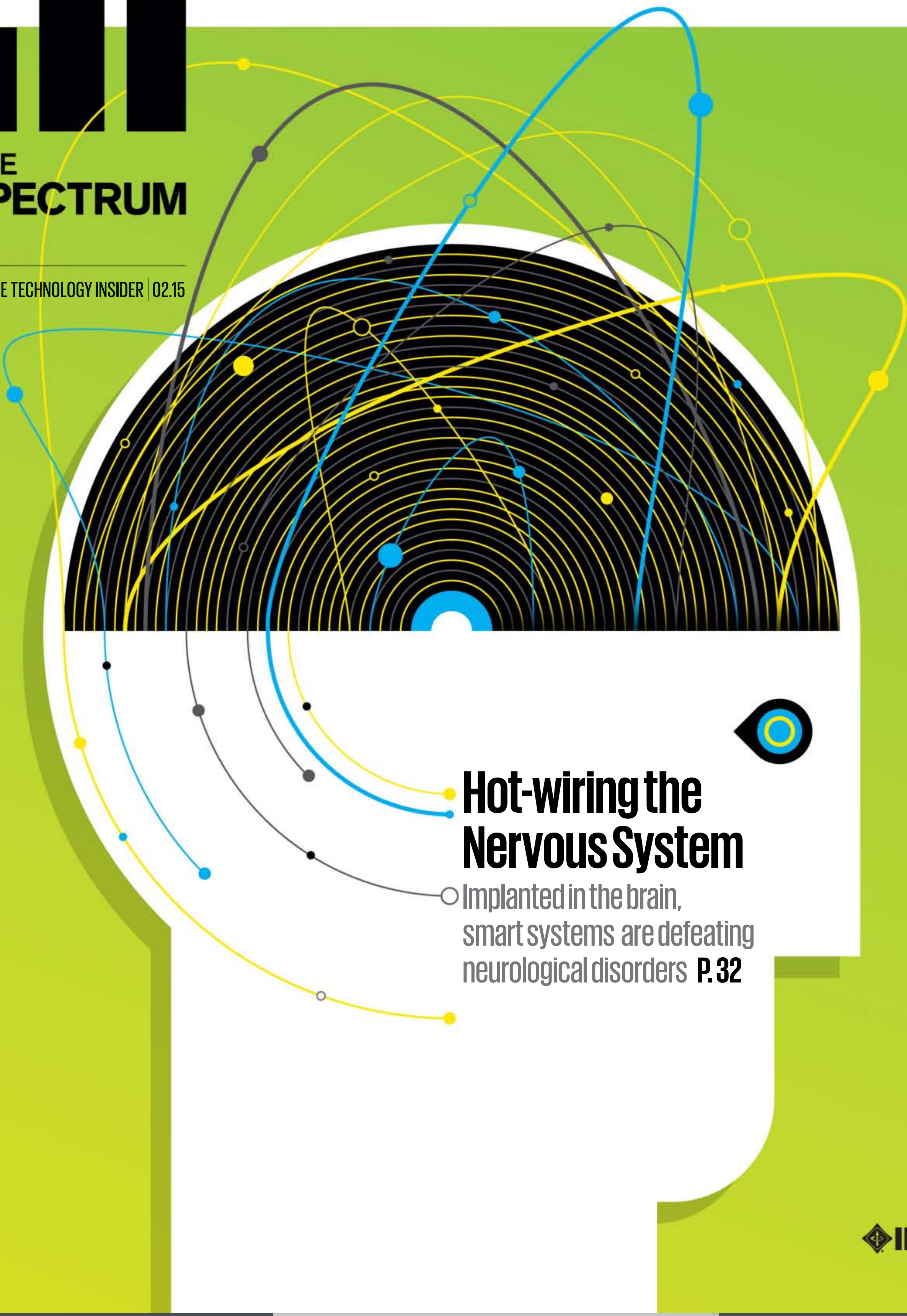

Hot-wiring the Nervous System

Implanted in the brain, smart systems are defeating neurological disorders **P. 32**

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PROP STYLIST: ROBIN FINLAY

On the Cover **Illustration for *IEEE Spectrum* by Carl De Torres**

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SPECIAL REPORT ON GLOBAL GROWTH Innovation is taking place in underserved and remote regions around the world, and IEEE is supporting these efforts. One IEEE program is helping local entrepreneurs in Africa start solar businesses that aim to eliminate harmful kerosene lamps, while another is working with India's young adults to teach them how to launch ventures in their communities.

BECOMING A SOCIAL ENTREPRENEUR Several IEEE members have founded their own social enterprises, which give back to the community while also making a profit. Read tips on how to do the same.

MEET THE IEEE GLOBAL OFFICERS Directors from the Europe and Asia offices share what technological advances are taking place in their parts of the world as well as IEEE's activities on the local scale.

FROM LEFT: BERNHARD LANG/GETTY IMAGES; W. WAYT GIBBS; CELIA GORMAN

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BACK STORY_

A Magazine Endures

EVEN THE FINEST PRINT MAGAZINE IS EPHEMERAL. It's read and possibly passed on to someone else. But sooner or later it's discarded.

So when the time came to illustrate historian Matthew Wisnioski's "The Birth of *Innovation*," about a prescient but short-lived 1960s technology and business magazine, we had a problem: Where could we find copies of the magazine?

By chance, a man named Michael F. Wolff had e-mailed us last summer about an article he'd read in *IEEE Spectrum*. Wolff, it turns out, was the second (and last) editor of *Innovation*, and he lives on Manhattan's Upper East Side, just a few subway stops from *Spectrum*'s midtown office. He offered to share his pristine and nearly complete set of *Innovation*, as well as promotional material, internal memos, and his recollections about how the magazine came to be and what it stood for.

Though *Innovation* lasted just over three years, Wolff likes to think the magazine captured the era's zeitgeist and presaged a heady time in technology publishing. Before *Innovation*, tech-focused magazines were usually wonky trade or academic titles. But after *Innovation* came some slicker, more mainstream fare, such as *Omni*, *Fast Company*, and *Wired*.

Spectrum was an upstart when *Innovation* began its short run. Following his magazine's demise, in fact, Wolff became a *Spectrum* contributing editor, writing about inventors and invention. He fondly recalls interviewing Intel cofounder Robert Noyce in the latter's unfinished swimming pool, for the 1976 feature "The Genesis of the Integrated Circuit."

With *Innovation*, Wolff says, "We felt we were doing something really different. *Spectrum* continues that editorial mission, of helping people understand the impact and the direction of technology." ■

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes an international and a North American edition, as indicated at the bottom of each page. 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, And Now This... is in *IEEE Spectrum*, Vol. 52, no. 2 (INT), February 2015, p. 60, or in *IEEE Spectrum*, Vol. 52, no. 2 (NA), February 2015, p. 68.

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PHOTOGRAPH BY Randi Klett

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Harry Campbell

Campbell is a Baltimore-based illustrator whose work has appeared in *The New York Times*, *Newsweek*, *PCWorld*, *Time*, and many other publications. For this issue's Numbers Don't Lie column [p. 28], he was asked to visually capture the entangled debate over shale gas. His illustration shows a complex network of pipes snaking underground through fractured stone. "It doesn't make [shale gas] look bad or good—just complicated," says Campbell. "Because the issue *is* complicated."

Tim Denison

Denison, a technical fellow at the medical device company Medtronic, writes in this issue about smart neural stimulators [p. 32] with coauthors Felice Sun, a clinical science consultant at NeuroPace, and Milton Morris, former vice president of R&D and currently a consultant for Cyberonics. Their companies may be competitors, but the authors were glad for the opportunity to work together. "The challenges for individuals with neurological disorders are more important than the rivalries between companies," says Denison.

Mitchell Lazarus

Lazarus has worked as an electrical engineer, psychology professor, education reformer, educational-TV developer, freelance writer, and, most recently, a telecommunications lawyer. A partner with Fletcher, Heald & Hildreth, he specializes in securing regulatory approvals for new technologies, some of which he describes in "Radar Everywhere" [p. 52], his fifth article for *IEEE Spectrum*. Lazarus writes about more than just electronics, however: He recently finished a book about the Manhattan Project.

Subhasish Mitra

An associate professor at Stanford University, Mitra works on building robust nanoscale integrated circuits and systems. Before joining Stanford, he was at Intel, where he solved a crucial problem in cost-effectively testing chips for defects. He sees a connection there to the hunt for malicious hardware, which he and his coauthors discuss in this issue [p. 46]. Whether a chip malfunctions because of manufacturing problems or a deliberate attack, he says, the result looks much the same: "It all comes down to trust."

Matthew Wisnioski

Wisnioski is an associate professor of science and technology and senior fellow of the Institute for Creativity, Arts, and Technology at Virginia Tech. In this issue he writes about the trailblazing 1960s tech magazine *Innovation* [p. 40]. "*Innovation* had this remarkably contemporary view of technology and society," Wisnioski says. Research into the magazine helped spark his latest book project, *Every American an Innovator*, which looks at the rise of the notion of innovation expertise.

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VOLKER MÖHRKE/CORBIS

Forecasting Tomorrow's Technology Today

As it's been said, prediction is very difficult, especially about the future

EARLY IN 2014, *IEEE SPECTRUM* TEAMED UP with SciCast, the "Bayesian combinatorial prediction market" group based at George Mason University, in Fairfax, Va. And when our January Top Tech 2015 issue hit the Web, *IEEE Spectrum* added something new to a few of its articles: the opportunity for readers to participate in *IEEE Spectrum* SciCast forecasting and match wits with experts by making their own predictions about the future of technology.

SciCast founders Robin Hanson, Kathryn Laskey, and Charles Twardy built the system to allow large numbers of forecasters (some 10,000 have signed on so far) to collectively prognosticate on technological progress. Initial support for SciCast came from the U.S. Intelligence Research Projects Activity.

The publication of our annual prediction issue seemed an ideal time to introduce *Spectrum* readers to SciCast. So, for example: Rachel Courtland's piece, "The XPrize's Lunar Deadline Drifts," reported that the Google Lunar XPrize team had extended the prize deadline to 31 December 2016. On SciCast, we ask two questions: "When will a spacecraft land on the moon and fulfill the requirements of the US $20 million Google Lunar XPrize Grand Prize?" and "Which team competing as of December 2014 will win the Google Lunar XPrize before December 31st, 2016?"

Considering Erico Guizzo's "A Robot in the Family," we ask, "When will an in-home robot–costing less than $100,000 and capable of performing at least three household chores–be available to the general public?" At press time, SciCast predictors say there's a 61 percent probability that automated maids will arrive before 2022 does.

The term "prediction market" sounds exotic; the thing itself isn't. To see one at work, look no further than the pari-mutuel tote board at almost any horse track. In pari-mutuel betting, of course, the odds offered are basically the ratio of the total amount bet on all horses to the amount wagered on one particular nag. The process is dynamic, as bettor-forecasters factor group consensus into their own calculations.

Prediction markets can seem spectacularly prescient, as the Dublin-based Web trading exchange Intrade showed with its spot-on forecasting of Barack Obama's U.S. presidential victory in 2012. At Intrade, however, members put up actual cash to buy "contracts" on specific event outcomes, which caused big problems with the U.S. Commodity Futures Trading Commission, leading to the company's demise.

SciCast forecasters invest points, not cash. And if the augurs augur well, they win more points, bragging rights, and sometimes more tangible prizes offered by SciCast and its sponsors. And, in a change from most prediction markets, SciCast allows direct bets on a variety of different outcomes and permits bettors to invest points to assign a specific probability to any outcome.

We've already learned that it can be surprisingly difficult to formulate questions broad enough to be interesting, detailed enough to be valuable, and precise enough to allow referees to clearly see the outcome and award points.

It reminds me of Deep Thought, the city-size "stupendous super computer" of Douglas Adams's *Hitchhiker's Guide to the Galaxy*. It cogitated for 7.5 million years to answer the Ultimate Question of Life, the Universe, and Everything...and finally, somewhat diffidently, coughed up the answer: "Forty-two."

The answer, Deep Thought assured its dismayed hereditary programmer-priests, is correct. The problem was that the question was poorly defined. They begged the machine to give them the right question.

"Deep Thought pondered for a moment. 'Tricky,' he said."

Indeed.

Join us at SciCast. Registration is free but is required to set up a trading account. Select "IEEE Spectrum" under "Topics" in the left-hand menu. And let the world know what you think.

—DOUGLAS McCORMICK

Douglas McCormick, principal of Runestone Associates, is a science and technology writer and editor, *IEEE Spectrum*'s webinar host, and its test and measurement blogger.

NEWS

3 GW: APPROXIMATE INSTALLED ROOFTOP SOLAR IN CALIFORNIA

BERNHARD LANG/GETTY IMAGES

HOW ROOFTOP SOLAR CAN STABILIZE THE GRID

Following Germany's lead, California gives advanced inverters a bigger role in the grid

Rooftop solar power systems are picking up a second job on the distribution grids that deliver electricity to California homes and businesses. Right now, their photovoltaic panels just generate electricity (meeting about 1 percent of the state's consumption), but within a few months some systems will also start moonlighting as junior grid regulators—a role that could keep them busy even after the sun goes down.

While the development in California is the result of a state-specific standard, approved by the California Public Utilities Commission (CPUC) in December, it is also part of a global movement: Germany, Japan, and other countries where solar is booming are implementing a similar change to empower rooftop solar installations to regulate voltage levels and perform other grid-support tasks.

Solar's expanding role is the result of upgraded inverters—the power electronics that link distributed generators such as rooftop photovoltaics to the grid. The inverters convert direct

ROOFTOPS FOR RELIABILITY: Germany is using smart inverters to give solar a role in stabilizing the grid. California is following its example.

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INTELLIGENT INVERTERS ARRIVE: Smart inverters can add or subtract reactive power to maintain line voltage. They also allow more rooftop solar arrays to share a power line.

SMA AMERICA AND RADIANCE SOLAR

current from PV panels into a wave of alternating current that is synchronized with the AC grid. Inverters can also synthesize reactive power—AC whose current wave leads or lags the voltage wave—which grid operators worldwide use to control line voltage. Adding reactive power with leading current boosts AC line voltage. Subtracting reactive power (by adding power with lagging current) pulls AC voltage down.

The new inverter standards mark a big change for equipment that utilities have viewed largely as a nuisance. Standards have hitherto required solar inverters to shut down at the first hint of line trouble, in order to protect workers from unanticipated currents. "Traditionally, we've been looking for these devices to trip off with any hiccup on the distribution system. Now they are becoming a resource," says Robert Sherick, principal manager for advanced technology at utility Southern California Edison.

Utilities must adapt because maintaining power quality gets harder with rising levels of distributed generation. German grid operators were among the first to experience this when solar started booming there a decade ago. At times of low power demand, high solar output drove up voltage levels, explains Bernhard Ernst, grid integration director for inverter manufacturer SMA Solar Technology, based in Niestetal, Germany. Such situations prompted utilities to freeze PV installations on certain lines.

Germany's smart-inverter requirements, established three years ago, solved the problem by requiring inverters to start subtracting reactive power when output from their PV arrays exceeds 50 percent of capacity. This counterbalances the voltage-boosting impact of the solar power generation.

Compared with upgrading distribution feeders with thicker cables, smart inverters were a cheaper way to enable continued growth of PV systems, Ernst says. "We can install 40 percent more PV capacity on the same line with this functionality," he adds.

Germany also mandated improved performance during grid emergencies. In the event that excess supply causes AC frequency to exceed Europe's 50-hertz standard by more than 0.2 Hz, inverters must now electronically trim output from PV panels instead of shutting down. Frequency deviations are rare on Europe's "electrically stiff" continental grid, but German regulators—worried about the destabilizing effect if PV systems turn off en masse—mandated an inverter upgrade costing owners and installers approximately US $300 million.

California's standard, developed through a collaborative process that began in 2013, pushes the envelope for smart inverters. Though solar causes few problems for California utilities today, rooftop PV is growing fast—by more than 40 percent per year in San Diego Gas & Electric's territory. The state's smart-inverter standard starts with Germany's requirements and then asks inverters to be smarter still.

> Smart inverters allow the connection of 40 percent more photovoltaic capacity to a power line

Consider voltage regulation. California's smart inverters will, like Germany's, counterbalance PV's direct impact on grid voltage. But they will also dynamically regulate voltage. If a smart inverter detects voltage exceeding 1 percent of normal, it will absorb additional reactive power. And if line voltage drops below normal—as can occur when passing clouds suddenly squelch PV power—the smart inverters will bolster it by injecting reactive power.

In essence, the inverters act like tiny versions of the flexible AC transmission systems (FACTS) equipment installed in utility substations to manage flows on high-voltage power lines. And this act could ultimately be a full-time gig. At night, when their PV panels are silent, the inverters can keep running on grid power.

Michael Turner, principal engineer for San Diego Gas & Electric, says solar installers will be encouraged to start using smart inverters within a few months. He also anticipates firmware upgrades by manufacturers that will give existing inverters the advanced functions required by the standard.

Meanwhile, efforts are under way to incorporate California's upgrades into the IEEE 1547 standard governing distributed power devices, which would accelerate smart-inverter use across the United States.

Frances Cleveland, president of Boulder Creek, Calif.-based Xanthus Consulting International and the CPUC's technical consultant on smart inverters, notes that even California's standard is not mandatory until mid-2016. The idea, she says, is to give utilities time to work out the optimal settings for inverters on their systems. One potential issue they will be watching for is feedback between multiple smart inverters trying to dynamically adjust voltage on the same line–with some inverters absorbing the reactive power that others produce.

Coordinated, real-time control of inverters could solve that problem, and California's smart-inverter collaboration is already working on standardizing the communications links between smart inverters and grid operators to make real-time control possible.

Southern California Edison's Sherick says distributed inverters could be a fully integrated component of utilities' distribution control systems within five years. By then, the CPUC hopes to have addressed another question with the potential to divide the hitherto collaborating smart-inverter developers: whether inverter owners should be compensated for providing grid-regulation services. –PETER FAIRLEY

NEWS

CARBON NANOTUBES, STUFFED AND STACKED

A Stanford team's carbon nanotube transistors have record-setting current densities and can be incorporated into 3-D circuits

In 2013, a team at Stanford reported that it had arranged arrays of tiny, atom-thick cylinders to create an entirely new machine: the world's very first carbon nanotube computer. With a clock speed of just 1 kilohertz and fewer than 200 transistors, it didn't stand a chance of competing with today's silicon-based processors.

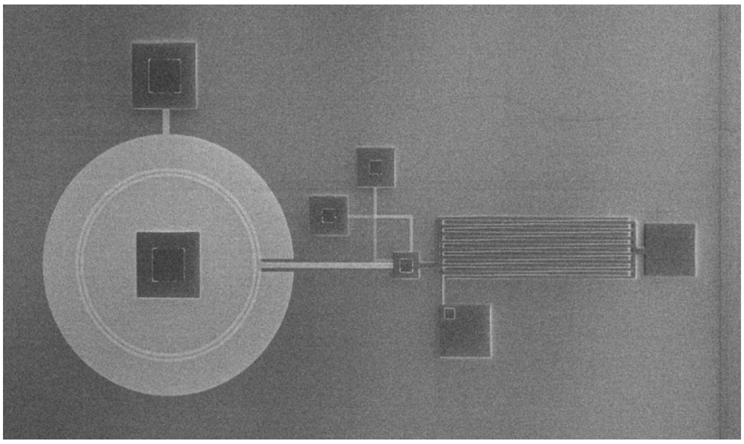
Now, the gap between silicon and carbon nanotubes is starting to narrow. In two papers, presented in December at the IEEE International Electron Devices Meeting in San Francisco, the same team has shown they can make carbon nanotube transistors with current densities and other properties that rival similarly sized silicon transistors. Graduate student Max Shulaker also reported that the team could build carbon nanotube transistors directly on top of silicon circuits.

"Now that we have this nanotube that's on par with conventional silicon," says H.-S. Philip Wong, who led the work along with Shulaker's advisor, Subhasish Mitra, "we can think about building high-performance systems."

Unlike its two-dimensional cousin, graphene, the carbon nanotube can be a natural semiconductor, and it's long been eyed as a potential material for speedy and energy-efficient switches.

In practice, however, creating transistors with enough carbon nanotubes to carry a sizable amount of current has proved a bit tricky. Growing carbon nanotubes results in a mix of metallic and semiconducting forms, which is undesirable, and the number of nanotubes must be made quite uniform from transistor to transistor in order to get any power and performance benefits.

In prior work, the Stanford team solved the metallic-nanotube problem by



LAYERS UPON LAYERS: A carbon nanotube transistor, memory cells, and a silicon transistor are built on different layers of a monolithic integrated circuit.

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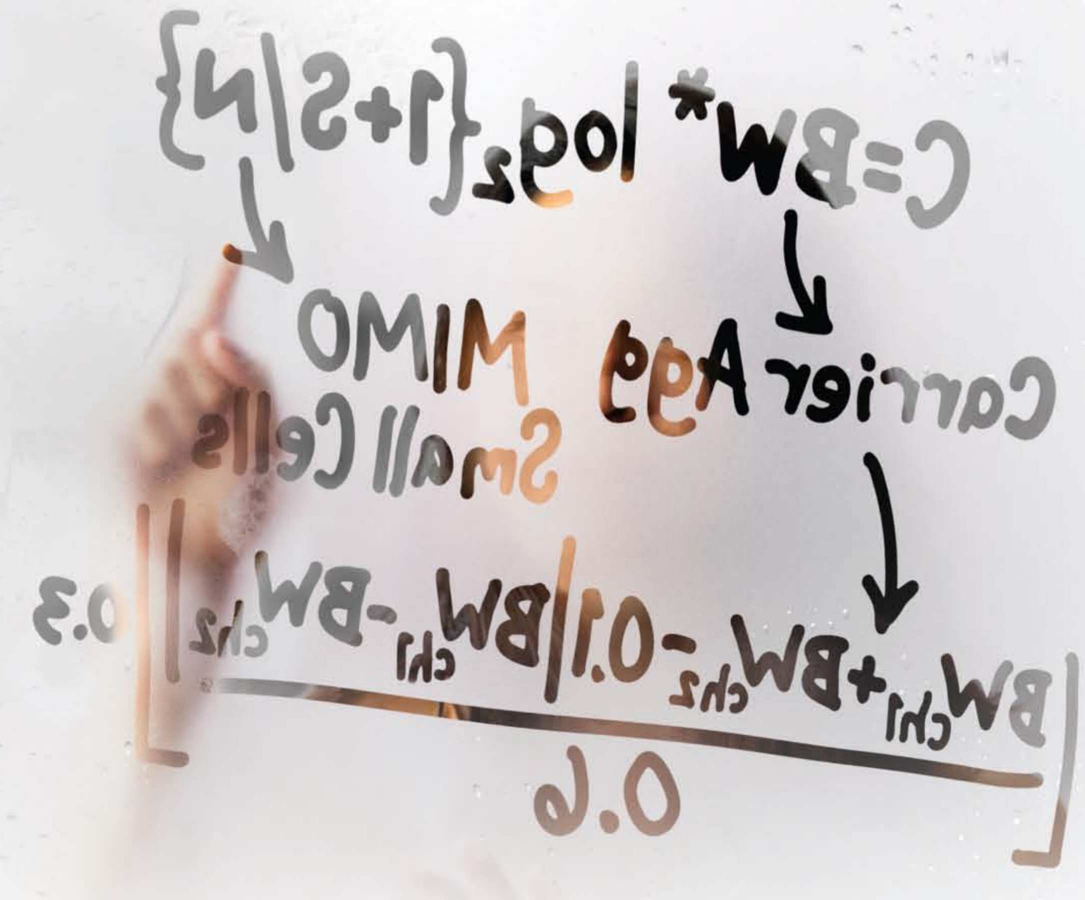

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designing circuits that could vaporize metallic tubes, leaving only the semiconducting ones behind. Now they've refined the fabrication process to boost the density of carbon nanotubes while preserving the level of uniformity.

Their fabrication process begins with quartz, on which the carbon nanotubes are grown. A layer of gold is deposited on top and then peeled away with thermal tape, taking the nanotubes with them. The nanotubes can then be transferred to the target surface, where the thermal tape is eased off and the gold chemically removed, leaving an array of parallel carbon nanotubes on the surface.

One transfer yields around eight nanotubes per micrometer, as measured perpendicular to the direction that current would flow across the devices. But in this latest work, the team showed they could repeat this deposition process more than a dozen times by laying down a gluelike polymer before each successive deposition of carbon nanotubes. The polymer prevented the carbon nanotubes from sticking to one another and becoming a spaghetti-like mess when exposed to the liquid used to etch away the gold. It also helped smooth the surface for the next layer of nanotubes.

With this approach, the team was able to make transistors with an average density of 100 carbon nanotubes per micrometer, giving a current density of up to 122 microamperes per micrometer.

This is neither the highest density of carbon nanotubes nor the highest current density that's been achieved. In 2013, a team based at IBM's Thomas J. Watson Research Center, in Yorktown Heights, N.Y., reported that a suspension of carbon nanotubes in oil could be used to produce more than 500 carbon nanotubes per micrometer and similar current densities.

But in the IBM experiment there were metallic carbon nanotubes in the mix, which conduct current even when a transistor is supposed to be off. This may have contributed to a fairly low ratio of on-current to off-current, which, in the shortest IBM transistors, maxed out at around 600:1, Shulaker estimates. The Stanford team's ratio is around 6,000, an indicator that only a small amount of current is leaking through the devices when they're supposed to be off. (Designers typically aim for an on/off ratio of about 10,000 for the CMOS devices used in smartphone and computer processors.)

To prove the approach's compatibility with silicon, the Stanford team used the multiple-transfer strategy to create a "monolithic" 3-D integrated circuit. A monolithic IC is made in one fell swoop on a single silicon substrate by building layers of devices one on top of the other, with dense metal wiring connecting them.

The team built a crossbar switch—a circuit that can be used to connect different inputs and outputs—out of a layer of silicon, two layers of resistive RAM, and then a layer of carbon nanotube transistors. They were able to build the stack of circuits without raising temperatures above 400 °C, which could damage the transistors.

"These guys are masters of stacking," says Sung Kyu Lim, who works on monolithic 3-D design at Georgia Tech. Although researchers at CEA-Leti, in France, have stacked logic on top of logic, Lim says this is the first demonstration he's seen of memory and logic stacked together in a monolithic fashion: "They're the first one demonstrating that this is possible," he says. The combination of logic and memory could dramatically reduce the time and energy needed to move information inside a computer.

But bringing carbon nanotube ICs into mass production could still be a ways off, Lim notes. The current-carrying channels in the Stanford team's carbon nanotube transistors are 400 nanometers long, about 10 times the size of state-of-the-art devices. "You want the devices to be smaller and the circuits to be larger," Lim says.

The next step is indeed building speedier circuits with shorter-channel transistors, Wong says. And it should be possible; previous work at IBM has shown carbon nanotube transistors with channel lengths smaller than 10 nm. But Wong says there are hurdles that must still be overcome on the road to high-performance circuits. First on his list are the metal contacts that connect to the nanotubes, which, like the contacts in other devices, balloon in resistance as they get smaller. Still, he has high hopes: "Having a technology that can compete with silicon in an academic setting would be tremendously exciting."

—RACHEL COURTLAND

AVERTING SPACE DOOM

Orbital debris could become a serious concern. How will we deal with it?

We are closer than ever to witnessing the "Kessler syndrome," a scenario proposed in 1978 by NASA scientist Donald Kessler in which the high density of objects and debris in low Earth orbit creates a cascade of collisions that renders space travel and satellite use impossible for decades. However, how close we really are is a matter of debate.

The United States Space Surveillance Network, operated by the Air Force, estimates there are more than 500,000 pieces of debris larger than 1 centimeter orbiting Earth today, including 21,000 pieces larger than 10 cm that are actively tracked. And that's ignoring the millions of smaller bits that are also up there. The average speed at which space junk would collide with a satellite is approximately 10 kilometers per second, meaning collisions with debris as small as 0.2 millimeters can still do damage.

Next month, engineers will gather at the 2015 IEEE Aerospace Conference, in Big Sky, Mont., to figure out what the real dangers are and what, if anything,

SPACE-JUNK SIFTER: Lockheed Martin is building a US $914 million system, called Space Fence, to better track orbital debris.

LOCKHEED MARTIN

we can do about them. The organizers of the conference's session on space debris, Kaushik Iyer and Doug Mehoke from Johns Hopkins Applied Physics Laboratory, are themselves cautious about ringing the alarm bells.

"Space is a very, very big place," says Iyer. "When you do the probability analysis of when spacecraft will collide with debris and how much damage will occur, generally you see that it's an extremely unlikely event."

To deal with space junk today, space agencies use ground-based radar to track debris larger than 10 cm and supply that information to the owners and operators of satellites that may be in the way. Those people can choose whether or not to carry out collision-avoidance maneuvers–if they have that capability. Jer Chyi Liou, NASA's chief scientist for orbital debris, argues that the biggest concern is posed by small pieces of debris, which cannot now be tracked but can still destroy a satellite.

Apart from disasters like the 2009 Iridium-Kosmos satellite collision, we haven't seen anything calamitous happen yet. Raymond Sedwick, an aerospace engineer at the University of Maryland's Center for Orbital Debris Education and Research, thinks what is being done right now is effective for the most part, but he recognizes a growing concern that will have to be dealt with soon. "Some may argue that it's already here or that it's still decades away, but if you let it go until then, it might be too late," he says.

According to Iyer, we are years away from really changing our approach to orbital debris. Most proposals have focused on three areas: improving protective measures, removing debris already in orbit (remediation), and preventing further accumulation of orbital junk (mitigation). Here's a quick look at some of the technologies that may help. –NEEL V. PATEL

PROTECTION

WHAT: **Tracking systems and collision avoidance**

HOW: The U.S. Air Force is replacing its current tracking system with one that Lockheed Martin is building for US $914 million. Dubbed Space Fence, it will use an array of S-band radars spread around the world to track debris as small as 2 to 3 centimeters.

EXPERTS SAY: Technologies like Space Fence will help, "but it's not the solution," says Donald Kessler, a retired NASA space debris expert. Little satellites are vulnerable to even smaller, undetectable objects as tiny as a millimeter. While Space Fence will be able to track more debris, Raymond Sedwick, an aerospace engineer at the University of Maryland, notes it will not really do so with any greater precision than the tracking done now. Kessler also says improved tracking will not keep two nonfunctioning satellites from colliding.

WHAT: **Increased shielding**

HOW: The most well known form of improved shielding is the Whipple shield, a thin outer bumper placed a certain distance away from the spacecraft. The bumper wall can shock the incoming particle and cause it to disintegrate during impact, leading to a distribution of momentum and allowing the spacecraft's hull to better withstand the impact. Whipple shields are used in many different configurations on the International Space Station. They're effective in protecting spacecraft from roughly centimeter-size pieces of debris racing at 3 to 18 kilometers per second.

EXPERTS SAY: Increased shielding like Whipple shields makes a craft heavier and bulkier, raising both production and launch costs, notes Kessler. Unless there is some extremely expensive equipment on board, manufacturers are likely to opt against it.

REMEDIATION

WHAT: **Lasers**

HOW: High-powered lasers–fired either from the ground or from space–could slow down debris until it's unable to maintain orbit and burns up in the atmosphere. A 1990s NASA project called Orion explored this possibility, but international agreements banning the use of lasers in space prevented any real testing.

EXPERTS SAY: Sedwick says such a system might work well for smaller debris, but like most other scientists, he believes the whole idea is still not technologically practical, let alone economically feasible. Another concern is that a laser could unintentionally break a piece of debris into several pieces, generating more junk.

WHAT: **"Catchers" or "tugs"**

HOW: The idea is to use spacecraft to physically relocate space junk, either to lower-altitude orbits where debris would burn up in the atmosphere or to higher-altitude "graveyard" orbits. A spacecraft could use a claw or harpoon to tether debris and tug it away. That's the concept behind Nantucket, Mass.-based Busek Co.'s proposed Orbital Debris Remover (Order) spacecraft.

EXPERTS SAY: Sedwick believes such systems might work but would be too costly. Also, any spin on the debris would make capture and tugging difficult. What's more, these proposed tethers would also be several kilometers long and could easily collide with something.

MITIGATION

WHAT: **Increased enforcement of the "25-year rule"**

HOW: The 25-year rule argues that any satellite launched into space must not be allowed to stay in low Earth orbit more than 25 years past the completion of its mission. Owners and operators of satellites need to make plans to send the spacecraft out of orbit–most likely by reserving enough propellant for the job.

EXPERTS SAY: Jer Chyi Liou, NASA's chief scientist for orbital debris, believes that this is the "most cost-effective and most efficient plan for dealing with orbital debris and the first line of defense against generating more debris in the future."

NEWS

ALL-NATURAL ELECTRONICS

Materials scientists are coming up with ways to make circuits from paper, beeswax, DNA, and other biological materials

The United Nations estimates that people throw away about 50 million metric tons of electronics every year. One way to lessen the problem, some scientists say, may be to use biological materials–including plant dyes and DNA–to build devices that are biodegradable and biocompatible.

"We have to be ashamed" of the amount of e-waste humanity produces, Mihai Irimia-Vladu told a symposium on organic bioelectronics at the December meeting of the Materials Research Society, in Boston. Irimia-Vladu, a materials scientist at Joanneum Research in Weiz, Austria, has used cellulose as a dielectric layer in an inverter circuit and shellac as a dielectric in organic field-effect transistors. Many other biological materials could be transformed into suitable dielectrics, he says, including aloe, silk, and egg whites. Beeswax and carnauba wax–derived from a species of palm tree–could make dielectrics that are also hydrophobic, which might be useful in some applications, Irimia-Vladu says.

Using biological materials to build electronics would be environmentally friendly, he says, in part because their ability to biodegrade would lead to less trash piling up. Additionally, such materials could be nontoxic, unlike some of their inorganic counterparts, and they could take less energy to produce. He imagines building OFETs in hard gelatin capsules or on caramelized sugar for biomedical applications. Another researcher, Marc in het Panhuis, head of the soft materials group at the University of Wollongong, in Australia, is working on conductive, 3D-printable gelatins that could be used to make circuits for sensors that could be swallowed.

And it's not just conductors and insulators that can be made using biodegradable substances. "There are natural materials that have semiconductor properties," Irimia-Vladu says. He's done research showing that both indigo, a plant-based dye, and Tyrian purple, a dye originally derived from snails, have charge-carrier transport properties that make them promising for high-performance circuits.

Other researchers are turning to an even more basic level of biology in the search for electronic materials. Andrew Steckl, director of the Nanoelectronics Laboratory at the University of Cincinnati, has been working on organic LEDs that use DNA as an electron-blocking layer to decrease the devices' power consumption. Eliot Gomez, a Ph.D. student in Steckl's lab, told the meeting that Steckl's group has now gone one step further. They've integrated thin films made of the nucleic acids that make up DNA–adenine, guanine, cytosine, and thymine, as well as uracil, used in RNA–into OLEDs. The advantage of using individual nucleic acids rather than the entire DNA molecule is that different acids have different electronic properties. Guanine and adenine, for example, are better at transporting holes and blocking electrons, while the opposite is true for the other three.

Gomez says that OLEDs using these nucleic acids for the electron-blocking layer had efficiencies of up to 76 candelas per ampere and luminance of 130,000 candelas per square meter, as compared with 31 cd/A and 100,000 cd/m^2 for their standard devices.

Gomez's hope is to make an all-natural OLED, but it's a tall order. "The OLED structure has multiple layers with very demanding requirements," he says. "We need a lot more natural materials at our disposal."

Researchers at Åbo Akademi University, in Turku, Finland, are developing environmentally friendly components for printing logic circuits on paper. Fredrik Pettersson, an Åbo Akademi Ph.D. student, told the meeting that they've replaced an ionic liquid in a new kind of transistor with a mixture of choline chloride (a nutrient) and organic compounds such as urea, glycol, or vitamin C.

The transistor still uses a less environmentally benign organic semiconductor. But the group has found a way to minimize the amount of semiconductor needed. They do this by mixing it with an insulator and allowing the semiconductor and insulator to separate during coating, so that they wind up with the insulator on the paper and a thin layer of semiconductor on top. Because the insulator prevents contaminants in the paper from leaching into the semiconductor and degrading its performance, they can use less semiconductor material and, as a bonus, get transistors that switch much faster and require less current. The group made a NOR gate and a 1-bit memory cell with such a transistor, Pettersson said. The Finland-based researchers have also made paper-based supercapacitors.

Pettersson hasn't studied whether the new, more benign transistor biodegrades. But that might not be necessary. There can be various definitions of "environmentally friendly electronics," points out Joanneum Research's Irimia-Vladu. "There are different shades of green," he says. –NEIL SAVAGE

CORBIS

PHOTOGRAPH BY Adam Warzawa/Corbis

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THE WORLD IN A BOX

A JOURNEY OF A thousand miles begins with a single step. But now researchers at Gdańsk University of Technology, in Poland, have created a virtual cave that will let users take thousands of steps across computer-generated worlds without leaving the room. The cave, formally known as the Immersed Spatial Visualization Laboratory, is a roughly 40-cubic-meter space whose walls and ceiling–and most of the floor–are made of an acrylic on which high-res 3-D images are projected. What makes this installation different from all other virtual-reality setups is a transparent sphere mounted in the floor that rotates in all directions when the user walks. Sensors track the sphere's motion, using that information to adjust what the user sees over the course of an adventure.

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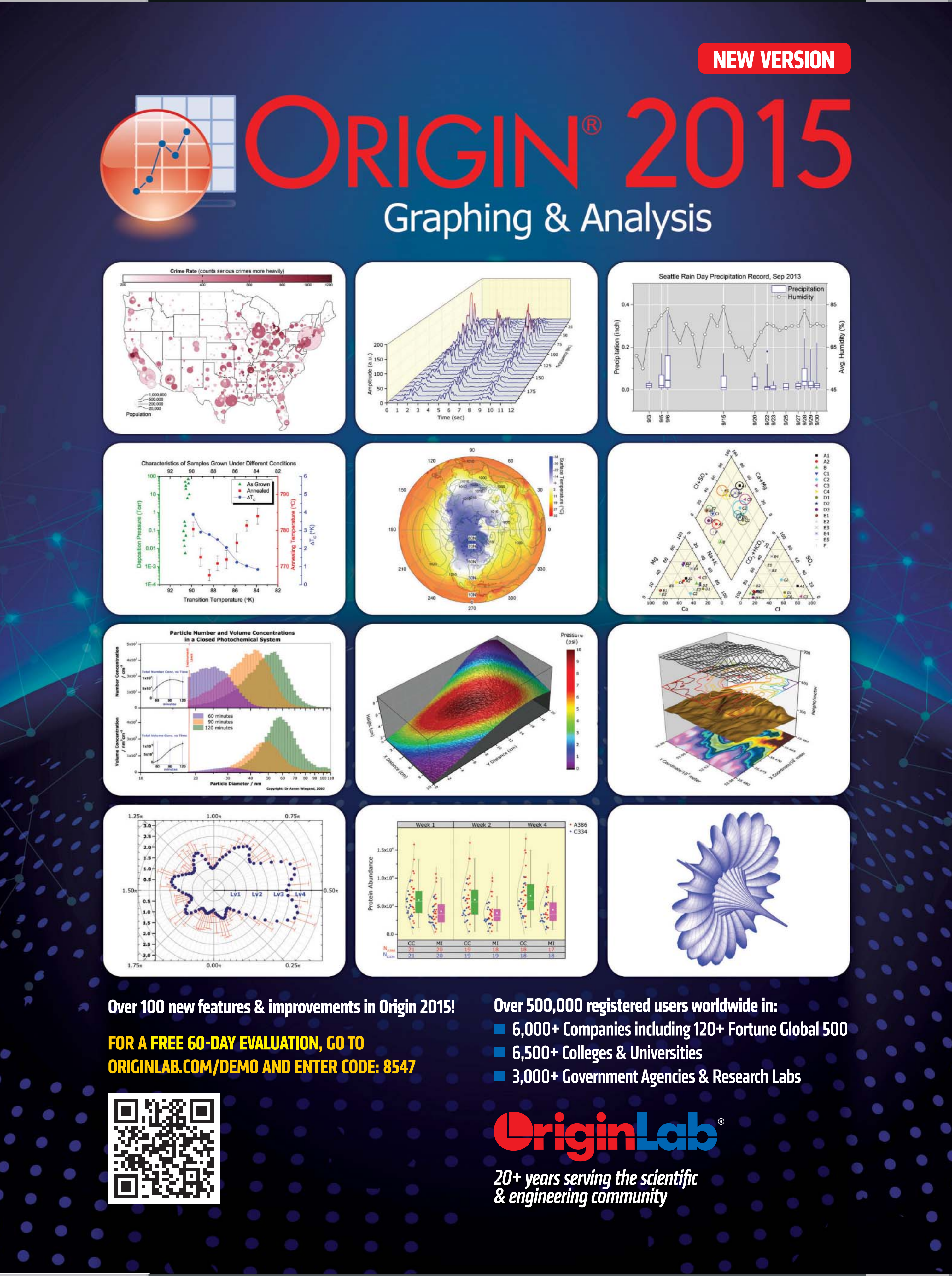
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RESOURCES

1983: THE YEAR THE MIDI STANDARD FOR DIGITAL INSTRUMENTS WAS PUBLISHED

W. WAYT GIBBS

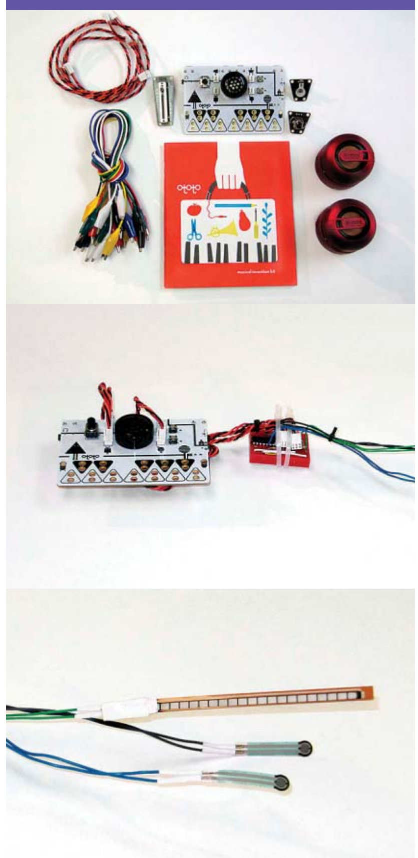
MUSIC FROM THE MUNDANE

THE OTOTO BOARD CAN TURN ANYTHING INTO A MUSICAL INSTRUMENT

The Ototo board is an invention for musical innovators; it is to would-be creators of playable instruments what a prototyping board is to circuit builders. The board makes it easy to connect both everyday objects and a wide range of analog sensors to a music synthesizer. Any vaguely conductive surface (metallic duct tape, the skin of a fruit, and so forth) becomes a touch sensor once wired to one of 12 large pads on the board, which correspond to one octave of notes. Additional sensors can be plugged into any one of the four headers, which provide 5 volts, a ground, and a voltage-sensing input. The inputs from these can alter the pitch, amplitude, and timbre of sounds. There's a built-in speaker, and a stereo headphone jack can send sounds to an amplifier. • But the most powerful feature of the Ototo—what really elevates it from toy to tool—is that when you connect it to a computer via the board's Micro-USB port, it functions as a musical instrument digital interface (MIDI) controller. This means it translates both key touches and analog sensor values into a stream of commands for software instruments. MIDI is the universal language of digital musical instruments, and it was this feature I was most eager to explore. In particular, I was wondering whether it could help me play a beautiful violin romance by Antonin Dvořák, even though I've never had a lesson. • Yuri Suzuki and Mark McKeague, the creators of the Ototo (which was developed along with Naomi Elliott and Joseph Pleass), are cofounders of the London design firm Dentaku, and the board reflects their artistic interest in encouraging people to interact with

RESOURCES_HANDS ON

MUSIC MAKER



THE OTOTO KIT comes with the Ototo board and a few basic sensors and connectors to which I added speakers [top]. To build an inflection hand controller, I wired up an op-amp to the Ototo board [center] that boosted the signals from two additional force sensors and one flex sensor [bottom], which I placed in a glove.

W. WAYT GIBBS (3)

sound and music in new ways. The video that they and their friends made to demonstrate the first prototypes of the Ototo early last year showed instruments made from cardboard, vegetables, and bowls of water. It's cool stuff, if not practical for serious music making.

Nevertheless, the demo video stimulated enough buzz that Dentaku's Kickstarter campaign raised more than £73,000 (US $115,000). By November of last year, the Ototo had been added (along with the Arduino) to the permanent collection of the Museum of Modern Art (MOMA) in New York City, which also began selling Ototo kits in its store for $145, including a set of cables and three sensors—a photocell, a small slider, and a rotary potentiometer. Dentaku quickly sold out of its sensors for force, touch, and breath, which are arguably more useful for a musician. So I bought a MOMA kit and supplemented it by ordering some additional sensors from Sparkfun Electronics.

When the kit arrived, I hooked the board up to some fruit and discovered a big limitation: Its sound chip generates just one tone at a time. You can tap out a melody, but you can't play a chord. I hoped that the MIDI output might help me get around this drawback.

To test the Ototo's multinote potential, my son and I quickly cobbled together an electric guitar of sorts (both my son and the guitar are pictured on the previous page). We cut the shape from a piece of thick plastic poster board. I mounted the rotary potentiometer sensor on the "headstock"—the part that would hold the strings—to use for tuning. The slider sensor fit into a slit on the neck, and I positioned it so that I could work it with my thumb to vary the tremolo. I put the photocell on the other side of the neck at a place where I could cover it with my index finger to act as a whammy bar. Next, I glued strips of aluminum foil to the strumming area of the body to create touch-sensitive activators for individual notes. Finally, I ran bolts through these strips to the back, where I mounted the Ototo board and all the cables.

For an hour's worth of construction, it looked pretty good. All that remained was to figure out how to get authentic, grungy power chords out of it. I bought Apple's MainStage program ($30) for my MacBook, which can map incoming MIDI commands from the Ototo sensors to the controls on a synthetic instrument (the actual synthesis is done by program called Kontakt 5, which has a wide range of high-quality synthetic instruments in its library). I plugged the Ototo into my laptop, selected a heavy-metal guitar voice, and configured MainStage to make use of the sensor data. Then I connected the computer to an amp and cranked up the volume.

It was the moment of truth. I tapped two notes from the first chord. Both sounded at once. As I jammed through the song, I wiggled the whammy bar and added a dash of tremolo to the wailing highs. It wasn't like playing a real guitar, of course, but it was fairly awesome nonetheless.

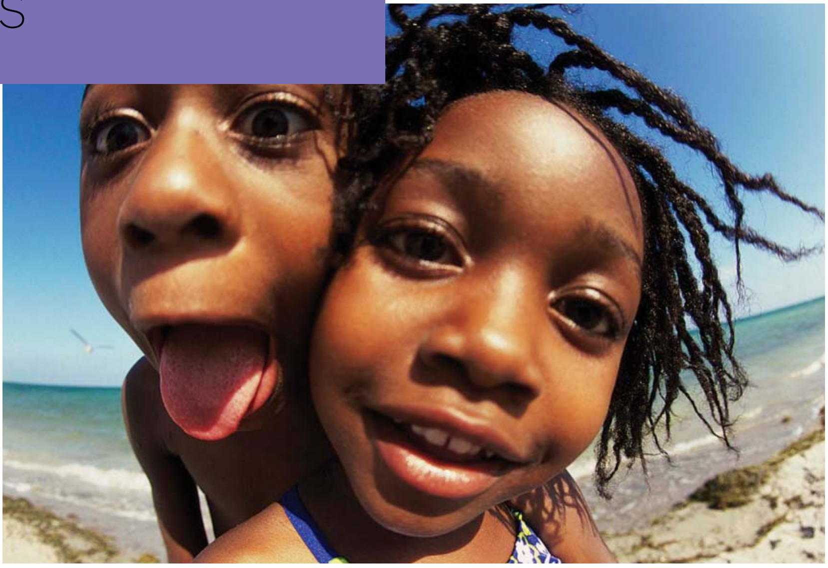
Ersatz instruments are fine, but the real promise of this technology is to inspire the creation of wholly new tools for musical expression. To that end, I'd been working on Dvořák's Romance in F Minor for violin and piano, which is a lovely piece to play but unsatisfying without the violin part of the duet. I had tried playing and recording the violin half using a software instrument and my digital piano keyboard, but the playback sounded too mechanical. The keyboard couldn't transmit the inflections that a human player would impart to a violin. Could I use the Ototo to turn my left hand into an inflection controller?

Taking a small protoboard and an LM324 quad op-amp, I wired the flex sensor and two force sensors that I'd purchased from Sparkfun (for about $40) to sensor cables that came with the Ototo. Then I plugged the board into my laptop and mapped the sensor outputs to control the dynamic level, vibrato style, and speed of the virtual violin. I put the flex and force sensors into the fingers of a glove, which I wore on my left hand. As I played the notes of the violin part on my keyboard with my right hand, I bent my left hand to play pianissimos and flattened it to hit fortes. I pressed down with my fingers to add urgency and intensity to sustained solo notes. What had sounded like a canned performance came alive with emotion.

Granted, strapping a protoboard to your wrist and playing while chained by nine wires to a circuit board is hardly an elegant approach. But as sensors, microcontrollers, and Bluetooth transceivers continue to fall in cost, it's not hard to imagine making a wireless controller glove that brings a real sense of touch and muscularity to digital instruments. **—W. WAYT GIBBS**

RESOURCES_TOOLS

WRANGLING DIGITAL PICTURES
FREE AND CHEAP TOOLS FOR ORGANIZING LARGE BATCHES OF IMAGES



GETTY IMAGES

With a digital camera—or even a smartphone—it's all too easy to take dozens or even hundreds of pictures on a vacation or at a family event. Once you've taken them, though, managing these photos can be overwhelming.

Proprietary picture management tools like Adobe Lightroom, Adobe Bridge, Adobe Elements, ACD Systems' ACDSee, and Apple's Aperture are available, but their complexity can be daunting. And even reasonable purchase and upgrade prices or low monthly fees add up over time. If you just want to organize image files and perhaps do some light editing, these tools are overkill. Fortunately, there are free or very-low-cost utilities that can do everything you want—and many come with your computer's operating system.

Based on my own experiences over the past year, here are my suggestions. Specific recommendations are primarily for users of Windows 7 and higher, but much of the advice will apply to other platforms.

Organization should begin when you first move files from your camera onto your computer. You should be sorting them into directories—ideally by event, but even just broadly defined dates, for example "FEB 2015 Photos," will help. In most cases, to sort photos appropriately you'll want to be able to see each picture. Modern operating systems' file managers can typically provide preview images in the place of traditional file icons. If the thumbnail or icon image in the left-hand side of your file manager isn't sufficient, the image displayed in the file manager's preview pane should do. At this stage you should be able to sort photos and cull obviously bad shots (those that are completely out of focus, and so on).

Next, it's time to do some basic editing. During this pass, you may also further refine the "keep/don't keep" sort, as you look at each image more closely. I use Google's free Picasa tool, which is available for Windows and OS X. With Picasa I can, for example, crop and rotate photos and eliminate red-eye.

The real keys to organizing your photos so you can find things later are a good naming system and paying attention to captions, tags, and other metadata that's stored along with the image data in the file. To add captions and tags, it's possible to access and edit each file's metadata directly from Window's File Explorer—by selecting and right-clicking one or more files, selecting Properties, and within Properties selecting Details. But Picasa also allows you to edit this information. And there are third-party dedicated metadata editors available. While I haven't yet tried any, Patrick H. Corrigan, in his comprehensive and informative book *Data Protection for Photographers*, recommends ExifTool and ExifTool GUI.

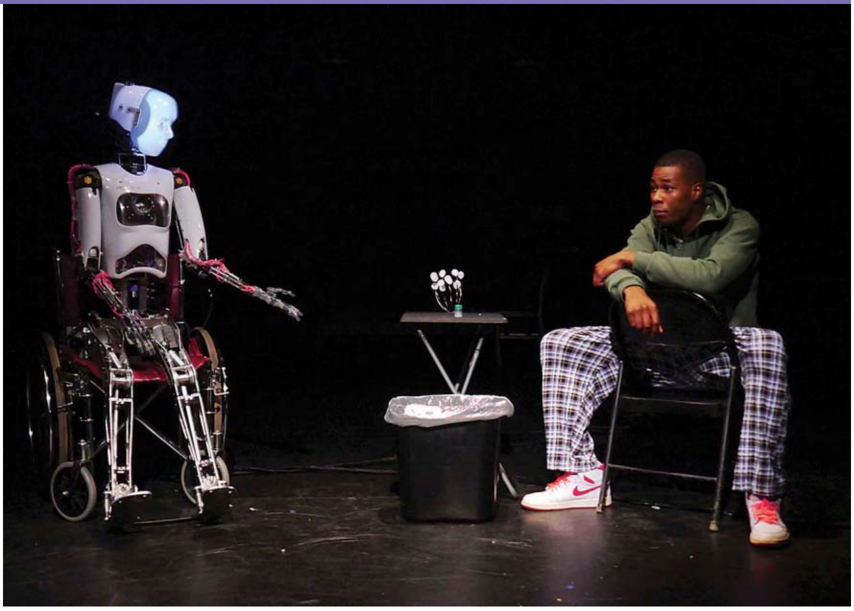
I'm a firm believer in self-documenting file names. The file names created by cameras are sequential numbers—good for chronological sorting but not for much else. A good file name will make it easy for you (and others) to search and identify images simply by looking at the file names. My practice is to prepend "about-the-batch" info at the beginning of a file name and append "about-this-image" info after the file name. Windows, sadly, doesn't have an adequate bulk-rename feature. However, there's at least one good free (donationware) utility, Bulk Rename Utility, and it even integrates into the File Manager menu. The user interface looks complicated and overwhelming, but to date I've needed to use only Bulk Rename's "Add Prefix" option.

If you plan on sharing your images, you may choose to add a watermark, such as your logo or a copyright notice, directly to the image. Watermarking won't prevent people from stealing copies; the purpose is to let people know who took the picture. Picasa's Export to Folder command includes a text field for specifying a watermark. The online service Watermark will let you do fancier watermarks, using fonts, symbols, color, and position.

Acquiring and getting the hang of these tools may take you an hour or two. But the payoff will be the ability to wrangle hundreds of photos in a remarkably modest amount of time. **—DANIEL DERN**

RESOURCES_REVIEW

REVIEW: *THE UNCANNY VALLEY* A PLAY BY FRANCESCA TALENTI FOR TWO HUMANS AND A ROBOT



DO ANDROIDS DREAM OF EQUITY CARDS? Alphonse Nicholson played human test subject Edwin [right] opposite the RoboThespian [left].

The RoboThespian, a human-size robot developed by Engineered Arts, based in Penryn, England, often works as a museum guide. It has also done some very stiff stand-up comedy and a slightly less stiff rendition of "Singin' in the Rain."

But these are largely solo performances. In July, it did something more unusual: It performed alongside two humans in a play called *The Uncanny Valley*, which made its New York City premiere at the Brick Theater in Brooklyn. (Clearly, robots are in the zeitgeist, as another production called *Uncanny Valley* played in New York around the same time; its robot character was portrayed by a human actor.) Both plays are named after the distressing psychological gray zone that people experience when faced by a robot or avatar that looks and acts enough like a human to be creepy, but not enough to be convincing.

The Uncanny Valley is set in a university laboratory. The RoboThespian plays Dummy, a research robot connected to a vast computer bank. Dummy works with a human research subject named Edwin. Every time Edwin visits the lab, he sniffs a vial and dons a sensor-laden skullcap. Each odor triggers memories and emotions, which Dummy absorbs, and gradually, the robot's voice and face start to resemble Edwin's. Dummy tells Edwin that the researchers in charge are working on a lifelike avatar, with biosynthetic skin and realistic facial expressions. Soon, Edwin is telling Dummy that someone who looks just like Edwin is walking around town, going to his job, and talking with his friends. In no time at all, it's looking like Edwin will be replaced.

Although the robot stayed seated throughout the play and was rather limited in its body language, it didn't seem stiff—most likely because the performance relied heavily on human beings. With the help of a US $50,000 grant from the University of North Carolina at Chapel Hill, creator and director Francesca Talenti and telepresence researchers at the university pieced together RoboThespian's performance from a combination of motion-capture data, voice recordings, and video of actors' faces. An internal rear projector was used to cast this video onto the interior of the RoboThespian's translucent white mask.

The motions, sounds, and video were divvied up into segments that were triggered during the play by a "puppeteer" on an offstage laptop. In some longer segments, the robot would perform without intervention, and it was up to the actor playing Edwin to make sure he timed his lines properly. "The actor had to be very consistent in order to not trip up the robot," Talenti says.

Despite the RoboThespian's voice and face becoming more like Edwin's, the play never really gets close to the depths of the uncanny valley. RoboThespian never really leaves the obviously mechanical side: There's only so much you can do with a spindly-looking roboskeleton that hisses seemingly every time its pneumatic actuators engage.

That said, Dummy does start to seem more human over the course of the play: It experiments with jokes; it gushes about its pet cat. At times, the robot's distorted, video-projected face makes it seem as if there's someone inside the robot, trying to escape. I got that feeling especially toward the end, when Dummy realizes the research project has done Edwin harm. The thought causes the robot pain, and it cries out in anguish in Edwin's voice.

This isn't what usually happens in science fiction when a robot becomes as smart as we are. And it raises a troubling possibility as the play nears a resolution. Has a new, sentient being been brought into the world? Or is the machine just playing out an empty model of human behavior? It's the Turing test with life-and-death stakes—and a conundrum we hopefully won't have to tackle for a long time to come. **—RACHEL COURTLAND**

KATHY PERKINS

PROFILE: CYPHY WORKS
TETHERED DRONES PROVIDE AN EXTRA PAIR OF EYES

DRONE ON A STRING: CyPhy's tactical drones can fly for long durations by using a tether to provide communications and power to the vehicle.

CYPHY WORKS

Combat and emergency response involves split-second decisions. The decisions could be better informed if soldiers or first responders could get a look inside buildings or over ridges before venturing forward. To give them that capability, start-up CyPhy Works is making tethered aerial drones that can fly for hours and stream high-quality video.

Based in Danvers, Mass., the company wants to put its drones in the hands of every soldier, police officer, and emergency responder. "Our systems are about saving lives," says Matt England, CyPhy Works' vice president of military systems.

Drones typically have their own batteries and computers and use radio communication. CyPhy Works' drones rely instead on a microfilament that tethers the flying robot to a computer and small battery pack carried by the user. The hairlike filament includes a fiber-optic cable, and it unspools from a small bobbin on the robot, so it doesn't restrict the drone, England says. And unlike a radio frequency link, the cable connection can't be jammed or monitored by an enemy.

The drones can send back a high-definition video feed and communicate with users even when they're deep inside a building, says founder and CEO Helen Greiner. Greiner is the cofounder and past chair of iRobot, which brought robotics into the mainstream with its Roomba vacuum. She approached England in 2008 with her idea for a tethered aerial robot. England was about to retire after a 30-year military career, during which he was instrumental in deploying unmanned systems for the U.S. Army. He identified the combat problems the robots could solve and joined the company. CyPhy Works publicly unveiled its two aircraft in 2012.

The first is a 140-centimeter-long quadrotor vehicle designed to hover in place up to 150 meters high. In addition to providing live video, it can be set up as a wireless communication relay for soldiers spread out in the field. These robots would be ideal for use at remote combat outposts in the mountains of Iraq and Afghanistan, England says. As of press time, CyPhy Works planned to deliver test units to the U.S. Army by the end of January of this year.

The other craft is an 18-centimeter-wide, 80-gram hexacopter that soldiers can easily slip into their pockets or packs. Unlike most UAVs, the pocket flyer is designed for enclosed spaces, because fighting increasingly takes place in urban environments, England says. It is also ideal for rescue workers inspecting confined spaces. In September 2014, the U.S. Air Force awarded CyPhy Works a contract for the pocket flyers for search-and-rescue missions in collapsed buildings.

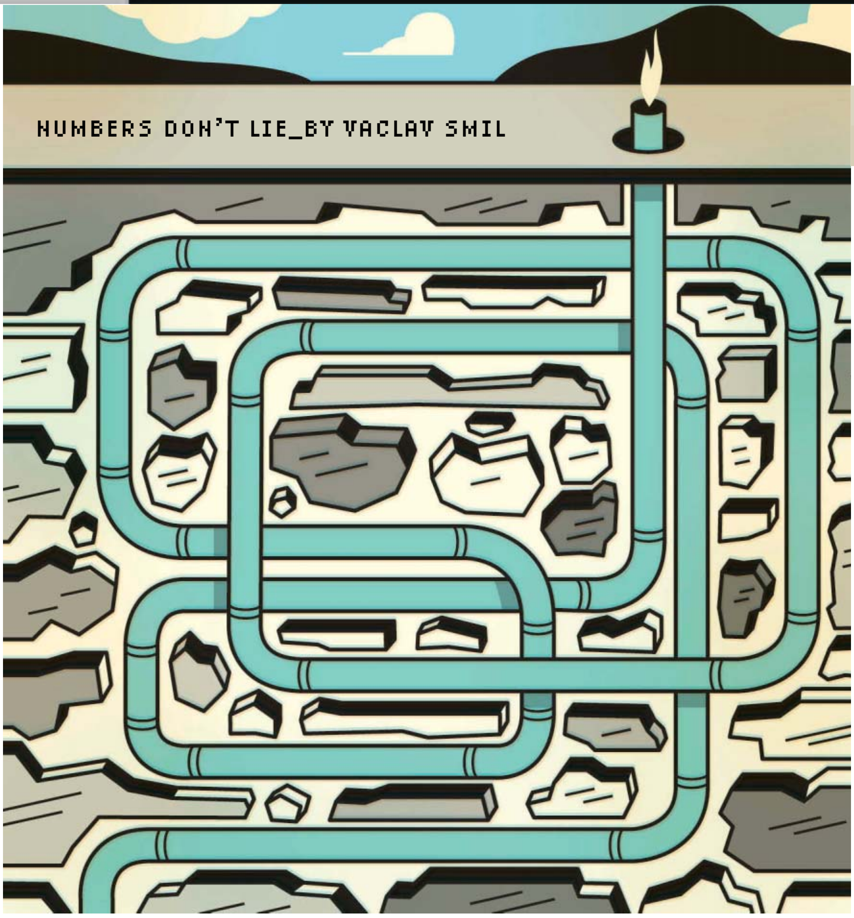
"The best robot is the one you have with you," Greiner says in an oft-repeated sentiment. "That's exactly what this robot will be. It'll be what you have when you're in a dangerous situation."

After initially focusing on the military market, Greiner plans to tackle the bigger, civilian market. She says the larger aerial reconnaissance robots could act like personal satellites for monitoring and security at fuel refineries and industrial plants, as well as bridges and other infrastructure.

Bilal Zuberi, a partner at Lux Capital, which has invested over $5 million in CyPhy Works, says the company's tethered approach is needed because batteries will not evolve anytime soon. But technology factored second in Zuberi's investment decision. "It's team first," he says. "Helen's work and successes show she is a real engineering entrepreneur who has lived in and out of the robotics world." The market for CyPhy Works' drones could be huge, he adds. "It [just] doesn't exist yet."

—PRACHI PATEL

Company: CyPhy Works **Founded:** 2008 **Headquarters:** Danvers, Mass. **Founder:** Helen Greiner **Funding:** Undisclosed **Employees:** Undisclosed **Website:** http://cyphyworks.com



IT'S TOO SOON TO JUDGE SHALE GAS

SHALE GAS—THAT IS, natural gas from shale deposits—may seem at first glance a huge, indisputable success for the United States. In 2007 it accounted for just 8 percent of the gas extracted; by 2013 its share had risen to nearly 40 percent. As a result, in 2009 the United States became the world's largest producer of this, the cleanest of all fossil fuels. This surge has led to two far-reaching decouplings of price: between those of natural gas and crude oil, and between those of natural gas in North America and in Eurasia. • Before 2008, the energy-weighted price of crude oil in the United States used to fluctuate at between one and two times that of natural gas. By 2013, that ratio had risen nearly to 5. In 2008, wholesale gas prices in the United States were just marginally lower than in Europe and only about 20 percent lower than in Japan. But by 2013 Europeans were paying nearly three times as much as Americans, and the Japanese nearly 4.5 times • No wonder foreign chemical companies have shown a lot of interest in building their new capacities in the United States. By 2013 nearly half of the US $100 billion in planned petrochemical investment had come from abroad. And the U.S. regulatory authorities have received nearly 40 applications to export natural gas in liquefied form. • Yet even so, it would be best to reserve judgment on fracking, the technology that made it possible, for at least a decade or so. That's because it always takes time to assess the durability and impacts of new ways of supplying energy. • Consider the problem of production over the long term. Freshly fractured shale layers yield a lot of gas, but by the end of the first year, the output of U.S. shale gas wells declines by at least 60 percent and by as much as 80 percent.

To keep the gas flowing, companies must drill new wells, each at a cost of between $3 million and $6 million. For some producers that may be either barely profitable, or too high, at today's natural gas prices.

Hence an inevitable question: How long will the recent surge of output—shale gas volume is up 5.5-fold between 2007 and 2013—and the resulting low gas prices last?

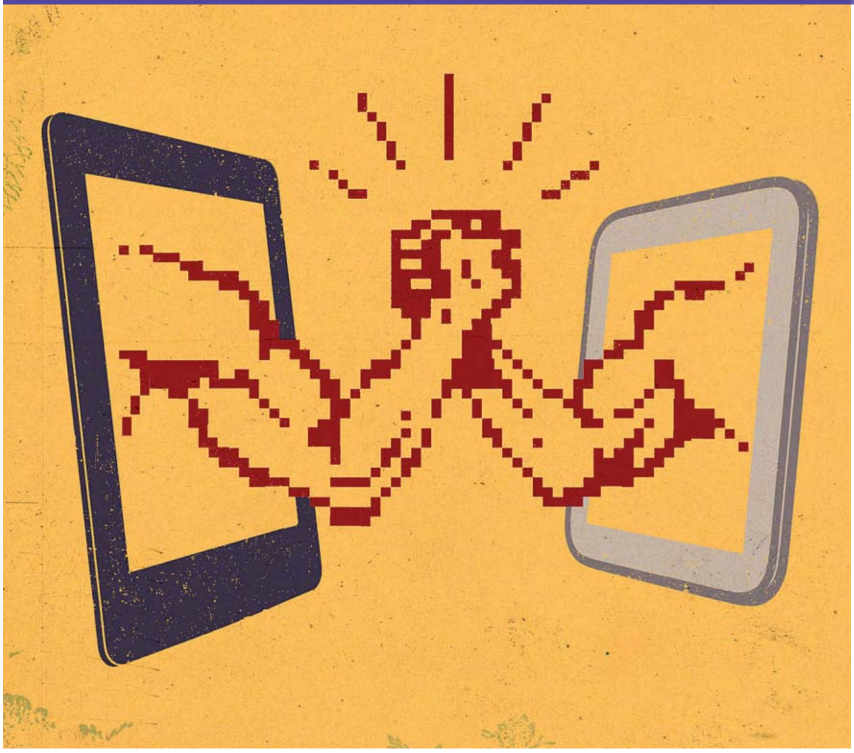
On a global strategic scale, will U.S. shale gas, exported as liquefied natural gas (LNG), ever make a difference? Will it, for instance, greatly diminish Europe's dependence on Russian gas? And even if the nearly 40 projects to export American LNG could make profits at today's prices, wouldn't rival producers in Russia, Qatar, and Australia just lower their prices in response?

Reserves of shale gas are enormous on all continents, but few basins offer such favorable recovery conditions and such low production costs as do the best half-dozen basins in the United States. Most important, many gas-rich basins have no ready access to the large volumes of water needed for fracking. This is particularly true in China, the country that has perhaps the world's largest shale gas resources and which would benefit most from their development.

Then there are the environmental aspects. Fracking can pollute air and water, and the one great environmental advantage of gas—burning it releases less carbon dioxide than burning oil products and coal—disappears if too much natural gas escapes during drilling and fracking. Natural gas is mostly methane, and every molecule of methane traps more than 20 times as much of Earth's infrared radiation as does a molecule of carbon dioxide.

Exaggerated claims and promises are rife in energy affairs, and that is why we must remain cautious. Shale gas has already transformed the U.S. energy balance, and it promises to change the global energy economy, but we cannot yet say how long this transformation will continue, nor can we predict its final economic, strategic, and environmental effects. ■

ILLUSTRATION BY Harry Campbell



THE LANGUAGE OF E-BOOKS

Remember the Internet Explorer vs. Netscape "browser wars" back in 1995 or so? That's where e-book formats are today. *—Jani Patokallio*

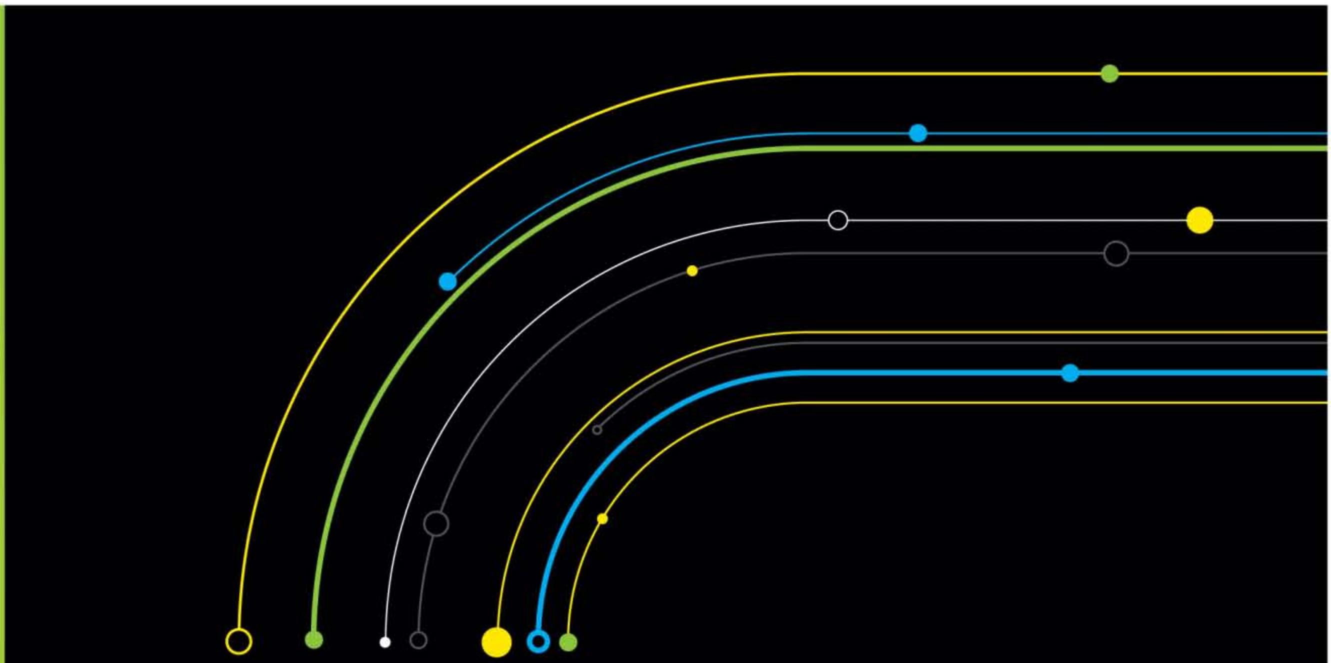
SEPTEMBER 14, 2000, is a date which will live in, well, "nonfamy," if I may be permitted such a neologism. That day, Microsoft released Windows Millennium Edition, its most forgettable operating system. It was also the day I posted the entry **p-book** to my Word Spy site, along with the following prognostication: "Within a few years, using the word 'book' without any kind of modifier will be confusing because people won't know if you're talking about a book printed on paper or one that's printed on electrons (so to speak). So I predict that 'p-book'...will become a common noun that will help us distinguish between the paper and electronic formats." • For a while it looked like I couldn't have been more wrong. The number of citations for "p-book" (as well as "pbook") in the Nexis media database went from 20 in 2000 and 19 in 2001 to just 1 in 2003 and 2 in 2004. But as e-books have become more popular, the word *p-book* has been showing renewed signs of life, with 20 citations in 2010, 24 in 2011, and 28 in 2012. • Language prediction is a mug's game, but it's certain that **digital books** (as opposed to printed **analog books**) are here to stay. Sales of e-books (also known as **ebooks** or **eBooks**; there is much hand-wringing in the industry over the correct spelling) have slowed down recently, but they remain the fastest growing (or, for some companies, the *only* growing) segment of the publishing industry. The past few years have seen a steady increase in the number of writers–amateurs as well as professionals–who are getting into **digital publishing** (or **e-publishing**). For many writers, breaking into **DIY publishing** is a simple matter of saving a word processing document as a PDF, then putting up that file on a website along with a PayPal donation form.

But for serious publishers, authors, and **writerpreneurs**, getting **e-published** means dealing with the arcane world of e-book formats. The most common of these by far are EPUB and Mobi. EPUB (the books themselves are often called **ePubs**) is based on Web technologies (the latest specification, EPUB 3, is derived from HTML5 and CSS3) and is used by Apple iBooks, Adobe Digital Editions, and the **e-readers** Nook (from Barnes & Noble) and Kobo. Mobi (short for Mobipocket) is the e-book format used by older Amazon Kindle devices (and these e-books are sometimes called **mobis**), with the newer Kindle Fires using a file type called Kindle Format 8 (KF8).

EPUB and Mobi (as well as KF8) are known as **package** formats because although they are distributed as a single file, the file is actually an archive that contains multiple items. These formats are riddled with inconsistencies and incompatibilities between different manufacturers (and even different devices from the same manufacturer). Sorting out problems involves tackling an acronym- and abbreviation-filled technology (OPS! OPF! OCF! WTF?). So it's no surprise there's a thriving ecosystem of **self-publishing providers** offering to help authors get their e-books to market. These include **formatters** (who take your plain text and give it an e-book shine), **converters** (experts at the finicky task of converting digital books from one format to another), and **aggregators** (companies that offer a full range of e-book services, including editing, cover design, and marketing strategies). Some even handle **POD** (print on demand: turning the e-book into a p-book).

E-book publishing is a bit of a mess, with some folks saying it will die off in the near future, choked by proprietary technologies, vendor lock-in, and overly restrictive digital rights management. But the success of EPUB and Mobi is undeniable. With apologies to Winston Churchill, it would appear that these standards are the worst forms of e-books, except for all the other forms that have been tried. ■

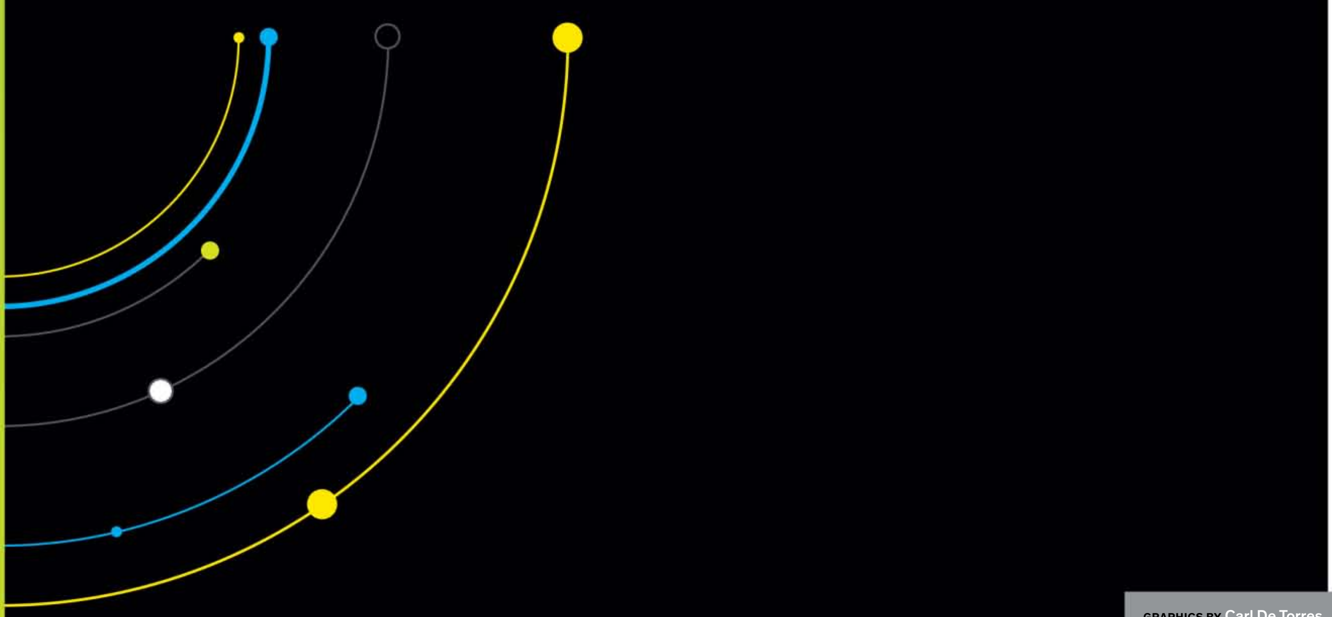
ILLUSTRATION BY Richard Mia



Building a Bionic Nervous System

Smart neural stimulators sense and respond to the body's fluctuations

By Tim Denison, Milton Morris & Felice Sun



GRAPHICS BY Carl De Torres

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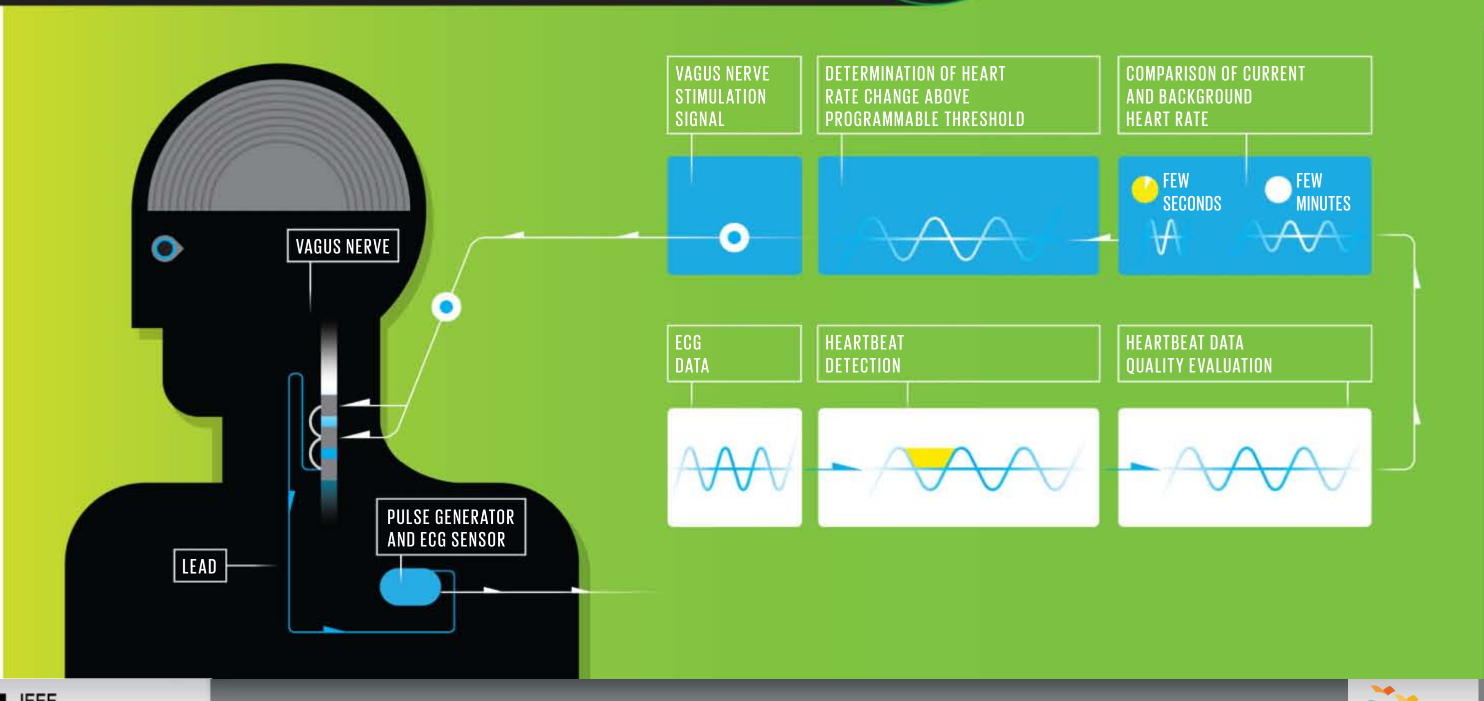
IT'S AN ELECTRIFYING TIME TO BE IN NEUROSCIENCE. Using implanted devices that send pulses of electricity through the nervous system, physicians are learning how to influence the neural systems that control people's bodies and minds. These devices give neurologists new ways to treat patients with a wide range of disorders, including epilepsy, chronic pain, depression, and Parkinson's disease. So far, these stimulators have been one-way devices that deliver a steady sequence of pulses to the nervous system but can't react to changes in the patient's body. Now, at last, medical device companies are coming out with dynamic neural stimulators that have a bit of "brain" themselves. These smart systems can detect changes in a physiological signal and then respond by delivering a therapy or adjusting the patient's treatment in real time.

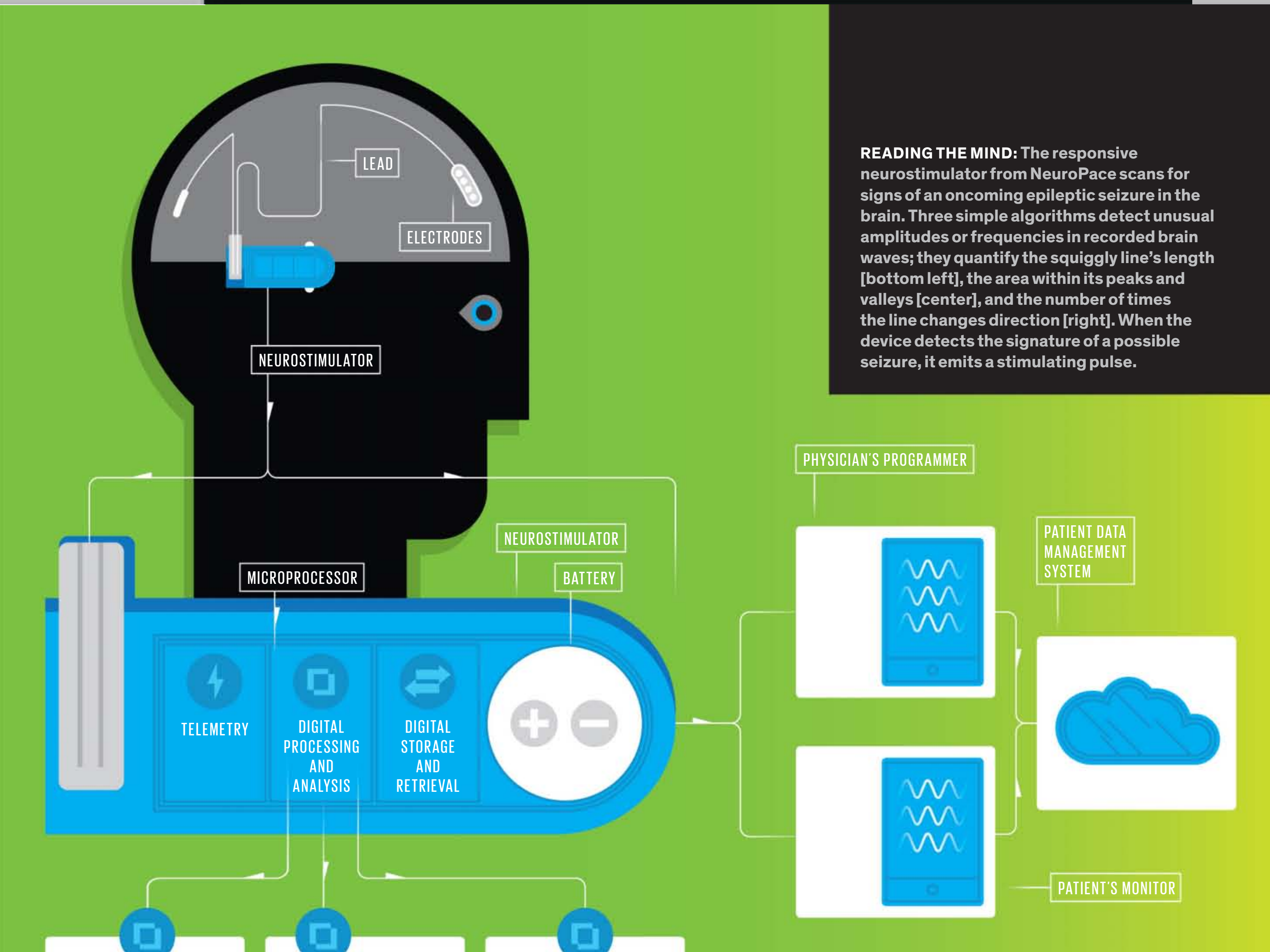
The three of us work for companies on this technological frontier, building devices that take advantage of developments in low-power implantable sensors and embedded signal processing. In this article we'll describe three devices that respond to the flux of biology within the body. Because these devices rely on data related to the processes they influence, we call them "closed-loop" systems, but you could also call them the next step in a bionic model of medicine. In this new paradigm, engineered systems composed of chips, wires, and batteries can replace or supplement biological systems that malfunction.

AN EPILEPTIC SEIZURE starts with a storm of abnormal electrical activity in the brain. In the most common adult form of the disorder, this activity begins in one or two specific brain regions and can then spread to other parts of the brain, causing disturbances in movement, sensation, mood, and mental function. During a severe seizure, a person may have convulsions and lose consciousness. It's a terrible and disruptive condition, and it's fairly common: The World Health Organization estimates that about 50 million people around the world have epilepsy.

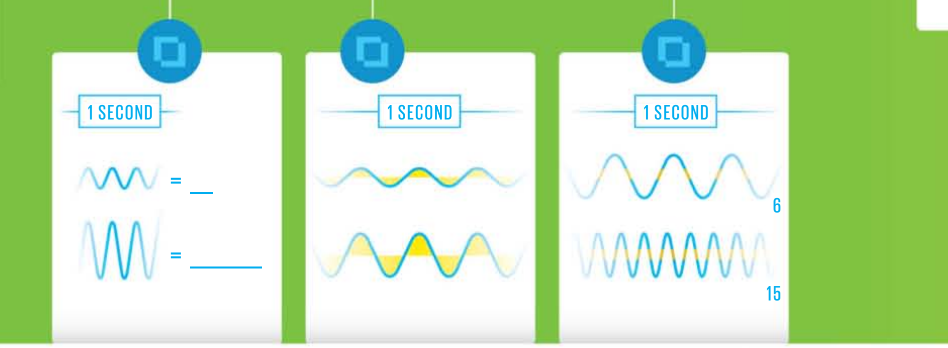
The majority of patients find their seizures can be controlled with antiepileptic drugs. For 30 to 40 percent of patients, however, these drugs don't do the job. Neurosurgeons sometimes resort to cutting away the pieces of brain tissue where the seizures originate, but in the past decade or so they've had another alternative: They can implant neurostimulators. These stimulators send pulses of electricity through the nervous system in an

READING THE HEART: The newest vagus nerve stimulator from Cyberonics looks for an abruptly elevated heart rate, which can herald an epileptic seizure. The device measures the heart's electrical activity with an electrocardiograph (ECG) sensor and extracts heartbeat signals. It compares the last few seconds of data with the prior few minutes of data to differentiate sudden spikes from gradual increases. Then it delivers a pulse of electricity through electrodes wrapped around the vagus nerve.





READING THE MIND: The responsive neurostimulator from NeuroPace scans for signs of an oncoming epileptic seizure in the brain. Three simple algorithms detect unusual amplitudes or frequencies in recorded brain waves; they quantify the squiggly line's length [bottom left], the area within its peaks and valleys [center], and the number of times the line changes direction [right]. When the device detects the signature of a possible seizure, it emits a stimulating pulse.



attempt to prevent the electrical storms from commencing. An "open-loop" device, which stimulates the brain but can't detect or respond to changing conditions, has been available since 1997. But the technology took a big step forward recently when NeuroPace, the Mountain View, Calif., company where one of us (Sun) works, invented a closed-loop device for epilepsy. This responsive neurostimulator (the RNS System), which received approval from the U.S. Food and Drug Administration in 2013, both records information and delivers stimulation directly to the brain.

With the NeuroPace RNS System, the surgeon implants a slim device that houses the microprocessor and a battery into a small cavity in the skull. The device is connected to one or two leads that the surgeon carefully inserts into the brain; depending on where the seizures originate, the surgeon may place the leads on the surface of the cortex or implant them deep in the gray matter. Each lead has four electrodes that record the brain's electrical activity and also deliver the stimulating pulses.

Here's the beauty of this system: It works in the background, continuously sensing the electrical activity in the brain and delivering stimulation in response to specific patterns of activity that have been flagged by the physician. With just a few simple algorithms, doctors can configure the device to detect the electrical patterns—different in each patient—that indicate the onset of a seizure. These patterns are represented in the squiggly lines of an electrocorticogram and are composed of signals with unusual frequencies and amplitudes. When the device identifies one of these patterns, it triggers a stimulating pulse within tens of milliseconds. Doctors can also change the detection parameters over time if conditions change in the patient's brain.

Patients may receive thousands of stimulations per day. However, with each burst lasting only a tenth of a second or so, the total stimulation time usually adds up to just a few minutes a day. Moreover, the brain doesn't have pain receptors, so

INFOGRAPHICS BY Carl De Torres

LIFE AS A BIONIC WOMAN
A BRAIN IMPLANT OFFERS RELIEF TO AN EPILEPSY PATIENT

Chelsey Loeb says she's still getting used to her new cyborg life. In November, neurosurgeons implanted a stimulator in her brain to treat her intractable epilepsy, and doctors turned on the device a few weeks later. She can't feel the electrodes that routinely send pulses of electricity into her left temporal lobe, but she often thinks about her new internal hardware: "It's like I have an iPod in my head," she says with a smile. One night, when she heard a mysterious beep in her darkened bedroom, her first thought was, "Did my head just beep?"

It hadn't. Loeb's responsive neurostimulator (RNS System), described in the accompanying article, does its work quietly. The device constantly records the electrical activity in specific areas of Loeb's brain, scans for the signature of an approaching epileptic seizure, and then triggers a burst of stimulation. The idea is to interrupt the abnormal activity before it can spread across her brain and interfere with her movements, mood, memory, and cognition.

The 26-year-old Loeb has been on medication to control her seizures since age 15. (Disclosure: Loeb's father, Matthew Loeb, was formerly an IEEE staff executive.) Last summer the efficacy of those pills began to decline. Almost every day was interrupted by a seizure, in which she'd seem to zone out, become incoherent, and then regain awareness with no memory of what had occurred. These blank spaces were alarming. For example: What had happened in those few minutes after she started to feel strange at a pharmacy counter and before she came to her senses next to a dumpster in a parking lot? Loeb had to give up her driver's license, and she took a disability leave from her job as a preschool teacher in Paterson, N.J.

In search of a solution, Loeb came to the epilepsy center at New York University Langone Medical Center. Doctors there recommended the new NeuroPace RNS System, which had been on the market for about a year. Loeb's case required two surgeries. First, surgeons draped temporary electrodes over the surface of her

patients typically aren't aware of the stimulation. This busy device doesn't always stop the patient's seizures altogether, but the NeuroPace clinical trial showed that patients implanted with the RNS System experienced an average 38 percent reduction in seizures within five months. And the frequency of seizures dropped further over the ensuing years, with the majority of patients experiencing a 50 percent or greater reduction in seizures by the two-year mark.

The technology has only just begun to help patients with epilepsy–256 people received implants during the clinical trials, and nearly 100 people have received commercial implants since then. But this modest start could be the beginning of a much broader research effort. Now that NeuroPace has figured out how to record and respond to the symptoms of one neurological disorder, the company may be able to build dynamic brain implants for others, perhaps helping people with movement disorders or mood disorders like depression.

THERE'S ANOTHER WAY to head off an epileptic seizure with electricity. The Houston-based medical device company

BRAIN UPGRADE: Chelsey Loeb [far left, with her parents] hopes her new brain implant will control her epileptic seizures. First, surgeons placed temporary electrodes in Loeb's brain so doctors could monitor the electrical patterns associated with her seizures over the course of several days [left]. Then surgeons implanted the responsive neurostimulator [right], which emits pulses of electricity when it detects signs of a seizure. Once a day Loeb uses a wand [far right] to extract device data, which is sent to her medical team.

brain. For five days, she sat in a hospital bed with wires emerging from her head while doctors monitored the electrical patterns in her brain. "I wasn't allowed to walk around at all," she says. "I was literally plugged in." Once the doctors had observed the pattern associated with her seizures, they implanted the neurostimulator in her cranium and guided its electrodes to the spots in her brain where her seizures begin.

NYU neurosurgeon Werner Doyle is a pioneer of this technology; Loeb was the 17th patient he outfitted with a commercial neurostimulator. Doyle says the device takes advantage of the brain's remarkable self-organizing ability. "If you shut the brain down and then turn it on again, which we can do with anesthesia, it reboots itself back to normal," he says. "That's what the RNS does, but locally rather than globally." And if the brain is an operating system, he says, the malfunctioning part of an epileptic brain is an application that freezes. "The RNS reboots the application so you can use it again."

Loeb has recovered well from the surgery. She's had a few seizures since the procedure, but most have been minor, lasting just a few seconds and not interfering with her speech or memory. The device continuously records the electrical activity in her brain, and when Loeb feels a seizure, she swipes a magnet past her head to mark that moment in the data stream and flag it for examination. At her checkups, her doctors analyze the data and tweak stimulation parameters. "They're figuring it out," Loeb says. "Their goal is to have me be 100 percent seizure-free."

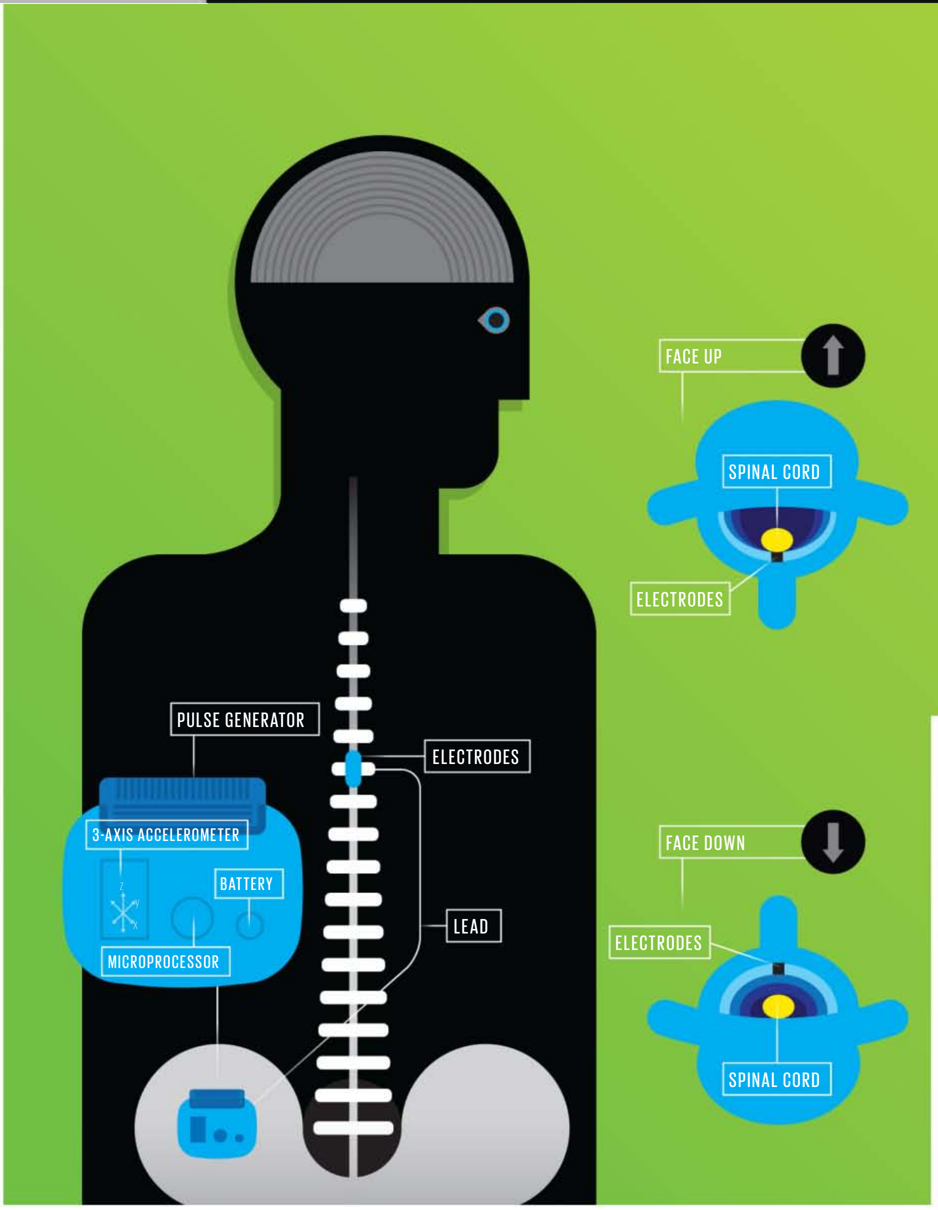
The doctors' work won't just benefit Loeb. As her doctors learn how to better control her seizures with pulses of electricity, they'll also be learning about the neural circuits that govern the human body. Doyle hopes that every time he implants electrodes into an epilepsy patient's brain, he'll get better at integrating the stimulator into the nervous system. "The more this device becomes like the brain, the better it will work," says Doyle. "That's the future." ***—Eliza Strickland***

Cyberonics, where one of us (Morris) works, invented a device that stimulates the vagus nerve, which extends from the brain to the colon. Back in 1997, the company received FDA approval for the first version of the product, an open-loop vagus nerve stimulator (VNS).

For that basic VNS Therapy system, a surgeon implants a pulse generator in the chest and tunnels a lead up to the neck, where two spiral electrodes are wrapped around the vagus nerve. Typically, two weeks after the implantation procedure the pulse generator is programmed to deliver electrical stimulation pulses to the nerve, which sends them on to the brain. About 80,000 patients worldwide have received such implants.

The current open-loop system also allows on-demand stimulation, a freedom that comes in handy for those patients who can sometimes tell when they're about to have seizures. Such premonitions are called auras, and they manifest themselves as illusions such as shimmering lights or strange smells. Thus warned, a patient can pick up the device's external magnet, which looks something like a pager, and pass it over the implanted pulse generator to trigger

PHOTOGRAPHS BY Matt Loeb



READING THE BODY: Medtronic's latest spinal cord stimulator adjusts its treatment for chronic pain according to the patient's body position, which is registered by a three-axis accelerometer. For example, in a patient lying face up [top], gravity pulls the spinal cord closer to the electrodes; the device then reduces stimulation to avoid unwanted sensations. Conversely, the device increases stimulation for a face-down patient [bottom] to ensure adequate treatment when the distance between the spinal cord and electrodes is greater.

a stimulation burst. In this way, patients who experience auras can prevent some seizures entirely and reduce the severity of many others.

Not all patients get auras, however, and not all can place the magnet over the pulse generator in time. Many people have seizures when they're sleeping or just waking up, and some people's seizures are accompanied by mental disturbances or unconsciousness. That's why Cyberonics set out to create an automated version of the device–one that is always on alert, so the patient doesn't have to be.

The company's closed-loop AspireSR neurostimulator builds on the fact that seizures affect the neural circuits regulating the heartbeat; this means patients' hearts begin to race as their seizures commence. So the new system's implanted pulse generator includes a sensor that records an electrocardiogram (ECG), a readout of the heart's electrical activity. This detection system has a big practical advantage: By looking for signs of seizures in the heart, this system treats epilepsy without invasive brain surgery.

While the sensor's position in the chest is advantageous from a procedural perspective, electrical signals from the heart can be difficult to work with, as they can be obscured by signals generated by the muscles as the body moves. To compensate, the detection algorithm constantly monitors the quality of the signal; there are a number of checks that must be passed before the algorithm deems an electrical signal to be a valid heartbeat worth including in its calculations.

The next challenge is determining whether a heart is beating faster because of a seizure or from another cause entirely, like exercise, an argument, or an exciting football game. False positives aren't a major concern, because the stimulation pulses are rarely perceptible to patients. At most, if the current is very high they might feel tingling in their throats or experience hoarseness. Too many false positives could tax the battery, however, which is intended to last four to seven years, depending on the programmed settings. So to detect a truly abnormal spike in heart rate, the algorithm compares the last few seconds of ECG signals with the last few minutes' signals to calculate the relative change. If a person's heart rate increases gradually as she starts to jog, for example, the threshold for triggering an electric pulse will go up. Likewise, as a person's heart rate slowly decreases as he drifts off to sleep, the threshold will go down.

Cyberonics first conducted a study to compare the AspireSR's detection of seizures against the current gold standard: visual inspection of graphs of the brain's electrical activity (electroencephalograms, or EEGs). The system caught 80 percent of the seizures and did so quickly, in an average of 6 seconds. Subsequent clinical trials showed real therapeutic benefit. As with the brain stimulation system for epilepsy, the Cyberonics system doesn't prevent all seizures, but in about 65 percent of patients the number of seizures was reduced by half.

The prior generation of VNS devices stimulated the vagus nerve in 30-second bursts about 11 times per hour. Cyberonics found in its clinical trial that when the new closed-loop device was set to its highest level of sensitivity, it added only a few extra stimulations to that total. Even if some of those additional pulses were the result of false positives, this seems acceptable. Vagus nerve stimulation doesn't have the side effects associated with anti-epileptic drugs, such as sluggishness and cognitive fog. In fact, patients using VNS therapy have reported feeling happier than usual and mentally sharper.

The AspireSR went on the market in Europe last year; it is awaiting FDA approval in the United States. Meanwhile, in the lab, engineers are continuing to refine the algorithms to detect more seizures with fewer false positives. They're also considering adding a notification function, so that the first sign of a seizure would trigger an alert for a caregiver.

TO BE USEFUL in a closed-loop system, a sensor needn't always detect the electrical signals that flicker through the brain or heart; sensors can also pick up physiological signals such as those generated by movement and activity. Medtronic, where another of us (Denison) works, has developed one such system that uses a three-axis accelerometer as its sensor, bootstrapping off the technology in your smartphone.

People who suffer from chronic pain usually try drug regimens or surgery to alleviate their symptoms, but in some patients these approaches don't work. So in the 1980s Medtronic came out with its first spinal cord stimulation (SCS) system, in which a pulse generator is implanted in the abdomen or above the buttock and leads are routed to the spinal canal inside the vertebrae. The system's electrodes send an electric pulse up the nerve fibers that carry sensory information from the painful body part to the brain, generally producing a mild sensation called paresthesia–the tingling feeling of an arm or leg falling asleep. This stimulation to the brain is thought to interfere with the pain signal that the nerve fibers would otherwise transmit.

Today's conventional SCS systems provide patients with remote controls to adjust stimulation if necessary and to maintain the desired levels of pain relief with limited side effects. For example, many patients find that changing body position alters the stimulator's effect on their spinal cords, which can cause unwanted sensations. To understand this phenomenon, visualize a patient lying on his back; in that position, gravity pulls his spinal cord down closer to the electrodes, causing the current to activate more nerve fibers. The patient may then feel a jolt, or the tingling sensation may spread through more of his body. Conversely, if the patient lies on his stomach, the distance between the electrodes and the spinal cord increases, and because fewer nerve fibers receive the masking stimulation signal, the pain may return.

To address this issue, Medtronic set out to develop a closed-loop device that automatically adjusts stimulation intensity according to the patient's position. While the best option might be a sensor that directly measures the distance between the electrode and the spinal cord using ultrasound or optical sensors, these technologies aren't yet practical for a small implanted device.

A simple three-axis accelerometer, however, can provide an indirect gauge of distance: Its inertial measurements indicate the body's position in real time, letting the device adjust stimulation as needed. For this purpose, Medtronic engineers adapted a type of microelectromechanical system accelerometer found in cellphones and other consumer products, which wouldn't draw too much power and drain the device's battery. The battery is rechargeable–the patient just holds an induction paddle over the implanted device–but it would be inconvenient if the patient had to recharge often.

In Medtronic's adaptive SCS device, the implanted pulse generator contains both the accelerometer and a microprocessor, which runs an algorithm that classifies the person's position and determines the appropriate stimulation. To calibrate the device initially, the patient assumes a series of postures (lying supine, prone, on the right and left sides, and standing up). The doctors can then map the data from each position to a stimulation level, with the aim of activating a constant volume of nerve tissue as the patient goes about the routines of daily life. The system also adapts over time by incorporating manual adjustments made by the patient into the automatic control algorithm.

Regulators in the United States and Europe approved this system, called the Restore Neurostimulator, a few years ago. The next generation of spinal cord stimulators from Medtronic may include other sensors as well–perhaps some that detect heart rate or signals from the central nervous system. As these implanted devices get smarter about what's going on in a patient's body, they should be able to deliver therapy that is more customized and precise.

AS WE SEE IT, the goal of all these closed-loop systems is to let doctors take their expert knowledge–their ability to evaluate a patient's condition and adjust therapy accordingly–and embed it in an implanted device. These dynamic systems have a number of potential benefits: They may react faster than current devices, provide more tailored therapy to individuals, and free up clinicians' time.

These smart devices may have something to teach doctors as well. As the stimulators provide therapeutic effects, they also provide data about how physiological states relate to clinical outcomes. From this new information, scientists and engineers hope to learn more about how the nervous system works, how it is affected by disease, and how to design better treatments. Sometimes, it seems, the way to move forward in science is to follow a loop. ■

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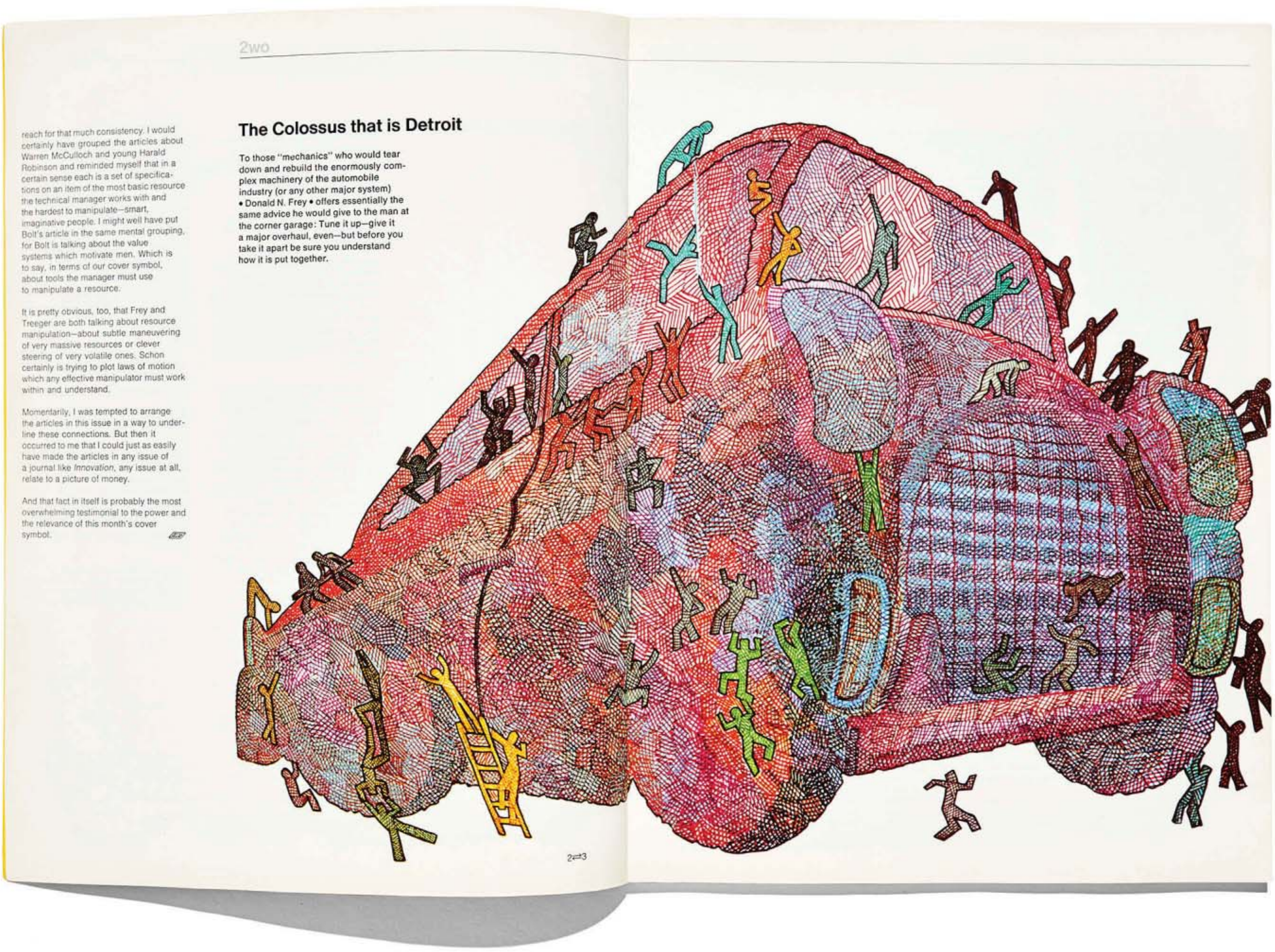
The Birth of *Innovation*

TODAY'S TECHNOCULTURE OF ENTREPRENEURSHIP AND CREATIVE PROBLEM SOLVING OWES MUCH TO THIS 1960S MAGAZINE

By **MATTHEW WISNIOSKI**

PHOTOGRAPHS BY Ben Alsop

***INNOVATION*'S** use of provocative graphics and design mirrored its lively coverage of technology and business. Subscribers also had direct access to experts via conference calls, workshops, and lab visits.



IN JANUARY 1970, two hundred technology managers met at a secluded mansion in Glen Cove, Long Island. Their mission: to learn what it takes to be an innovator. From the comfort of their rooms, executives from the likes of AT&T, Honeywell, IBM, and 3M talked shop via closed-circuit television and telephone with leading entrepreneurs, science administrators, and academics, who paced the stage of an intimate theater as they wove parables about how their lives were changed by the "accelerating rush of innovation." Each evening, the speakers again held court in the bar, where attendees were encouraged to "seize the chance to ask the speaker just how an idea he has presented applies to your particular situation." • The workshop, for which participants paid the equivalent of US $3,000 today, was the brainchild of a new media start-up called Technology Communication. The weekend event captured the club-like exclusivity, expert insight, and collective self-help for revolutionary times that the new venture sought to embrace.

Revolution, no doubt, was on attendees' minds. As corporate managers, they were being forced to reinvent themselves and their companies for an exciting but unsettling age. In the previous two years, they had witnessed the Apollo moon landing, fierce anti-Vietnam War protests, sweeping environmental regulations, landmark civil rights legislation, the exponential growth of the microelectronics industry, and the bold emergence of international competition. Technology Communication chronicled all of these episodes in its monthly magazine, *Innovation*, and expanded on them in events like the Long Island gathering. The start-up was selling a foothold for survival in a world in which industry, academe, government, and civil society were in chaotic flux. Rather than simply read about strategies for staying afloat, participants sought to exchange ideas firsthand on how to ride the waves of change.

Today, of course, innovation is everywhere: As professionals, we're continually reminded that we live in an innovation economy requiring self-styled careers of the sort trumpeted in executive-education programs, TED talks, and self-help best sellers. No mere buzzword, "innovation" generates excitement about working on the front lines of the future—as well as suspicion about the motives of those uttering this management-speak. And we reserve the superlative title of "innovator" for those bright few who have transcended the traditional labels of "engineer," "scientist," or "inventor."

This perspective did not always exist. Indeed, it owes a substantial debt to the people behind *Innovation*, whose rise and fall coincides with the birth of a new way of talking about innovation and a new ideal of what makes an innovator.

TECHNOLOGY COMMUNICATION WAS founded in 1969 to capitalize on the confluence of these world-changing forces. It was a partnership between the publisher William Maass and the journalist Robert Colborn, in consultation with a Bell Telephone Laboratories research director named Jack Morton. The company placed ads in the *Wall Street Journal* and *Scientific American* inviting readers to become members of a new community: the Innovation Group. The group, the ads declared, would be "a set of men very important to this country"—and in 1969 nearly all technologists were men—who shared an art without "teachers or precedents or tradition." Together, the group's members would address the promises and perils of technology while also turning a profit and enjoying meaningful and creative lives.

The Innovation Group's advisors, most of whom starred at the Long Island workshop, lived up to this lofty billing. They included 3M vice president of research and development Robert Adams; former U.S. congressman and architect of the U.S. Office of Technology Assessment Emilio Daddario; Fairchild Semiconductor chairman C. Lester Hogan; engineer and influential policymaker J. Herbert Hollomon; NEC founder Koji Kobayashi; and the eminent psychologist Donald Marquis, who founded the technology management program at MIT's Sloan School.

Accordingly, *Innovation* was intended not as an end in itself but rather as a catalyst—a "vehicle for initiating a process of interaction," a company ad declared. Designed by the renowned Madison Avenue firm Chermayeff & Geismar, the magazine's colorful and clean style blended modernism with countercultural flourishes. It carried no advertising, a point of pride for the editorial staff. The choice of topics cut across disciplines and industries. Issue 6, which came out in October 1969, included articles about the automobile industry's struggles to adapt to postindustrialism, the role of artists at NASA, a tribute to cybernetics expert Warren McCulloch, and a theoretical analysis of the diffusion of innovation. Informal interviews with contributors and a breezy, conversational tone made even the most esoteric subject seem accessible and familiar.

An annual membership fee of $75 (or slightly more for those outside the United States) included a subscription to *Innovation*, a newsletter, telephone conference calls with authors, a membership database, and invitations to in-person events like the Long Island meeting. Later, the company would offer subscriptions to the magazine for $35, making it one of the most expensive magazines on the planet. The group received additional funding from a venture capital group within what is now Citigroup.

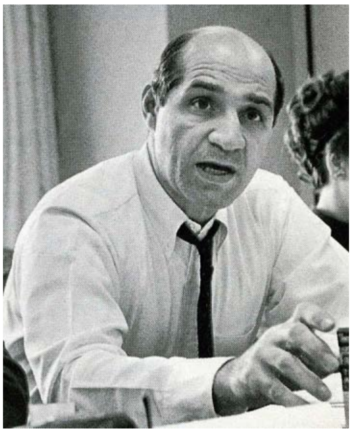
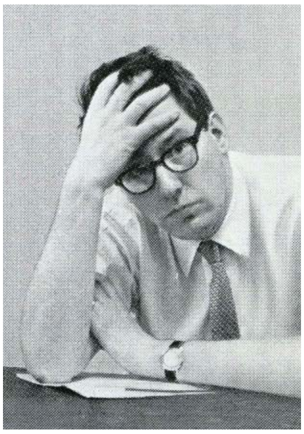
***INNOVATION*'S BOLD DESIGN,** by Chermayeff & Geismar, was apparent from the cover of the first issue, in May 1969 [above]. A prescient article on how to fix the U.S. auto industry [left] ran in the October 1969 issue.

The Innovation Group's unique approach was actually a refinement of its founders' vision, which they had been honing for the better part of a decade. That vision was a product of the post-Sputnik era, in which a rising chorus of stakeholders called for better science communication, improved primary and secondary education, more human portrayals of scientists, and new means for professionals to combat information overload.

In 1961, Maass, a vice president at the trade publisher Conover-Mast, launched *International Science and Technology* as a general-interest magazine for scientists and engineers. More cutting edge than *Scientific American* and less technical than *Science*, *IST* was distributed free of charge to 120,000 scientists and engineers. Funding came from corporate advertising, with scientific statesmen like Ernst Weber, the IEEE's soon-to-be first president, lending the publication some authoritative heft.

Maass—whom a reporter at the Long Island workshop described as a "supercharged, crackling blur of a man"—assembled an exceptional team of scientifically trained journalists. Most notable was *IST* senior editor Colborn, who'd just spent a decade as managing editor of *Business Week*. A civil engineering graduate of Dartmouth, he was also the author of a 1958 nuclear-disaster novel, *The Future Like a Bride,* about the inner life of a physicist-administrator.

IST offered a then-unique focus on the infrastructure of science. In addition to carrying interviews with Nobel Prize winners, the magazine worked with research managers and industrial scientists to describe and analyze what they did. These features publicized research and development as an "innovation process," an interpretation then percolating


MEN OF *INNOVATION* [clockwise from top left]: An Innovation Group "active seminar"; Congressman Emilio Daddario, an advisor to the group; Michael F. Wolff, *Innovation*'s second (and last) editor; Bell Labs research manager Jack Morton [gesturing], another key advisor; founding editor Richard Colborn [left] and publisher William Maass, who together forged *Innovation*'s unique business model and outlook; and staff writer Nilo Lindgren.

among economists and management experts.

A 1964 article of this sort, "From Research to Technology," altered the trajectories of both its author, Jack Morton, and the *IST* staff. The Bell Labs manager explained how he had guided the transistor from laboratory to market, and how the experience had opened the door to a general systems theory of innovation. In 1966, he followed up with "The Microelectronics Dilemma," which charted the decentralized expansion of microelectronics companies and the incessant creative destruction it generated. To "survive and grow in a new era of technology," Morton wrote, required mastery of the "people-process of innovation."

On 1 January 1969, Colborn, Maass, and much of the *IST* staff abandoned traditional publishing to form Technology Communication. Society was undergoing an epochal shift, they believed. The Innovation Group would be a network in tune with this Heraclitian age, and *Innovation's* staff would be its facilitators.

THREE OVERLAPPING AIMS GUIDED THE INNOVATION GROUP. First, it was a social network for managerial innovators to engage with their like-minded peers. Second, the core "product" the group was cultivating was new forms of innovation expertise—that is, the knowledge and practices members would need to achieve success in a volatile world. Third, the group was defining the cultural contours of a new kind of interdisciplinary professional—the change manager.

In its unusual approach to selling magazines, Technology Communication created a social technology that it hoped would spawn local innovation groups across the world. A kind of proto-LinkedIn, *Innovation* was intended as a space for sharing problems, putting seemingly disparate ideas on an equal plane, and aiding entrepreneurs in their pursuits. *Innovation* was no mere periodical: The July 1969 issue, for instance, offered members a direct phone line to venture capitalists Georges Doriot and Arthur Rock.

As the Innovation Group grew, it extended the boundaries of print media in search of new ways to connect people and ideas. In the September 1971 issue, for example, *Innovation* published one of the earliest profiles of computer visionary Douglas Engelbart. Members could sign up for a seminar with Engelbart in his laboratory at the Stanford

INNOVATION

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Research Institute, in Menlo Park, Calif. There they could try out the augmentation system made famous by his 1968 public demonstration, in which he debuted a number of groundbreaking technologies, including the computer mouse.

In January 1972, Technology Communication expanded its electronic services by partnering with another start-up called TeleSession Corp. Founded in 1970 by marketing expert Ron Richards and psychologist George Silverman, TeleSession started as a late-night telephone-based chat group, where strangers could discuss common interests. The Innovation Group used the TeleSession switchboards to build virtual workshops around its articles. Branding itself as "the first magazine with an interactive feedback system," *Innovation* boasted that economist Milton Friedman dialed into TeleSession from his summer cabin and deemed the experience more valuable than a face-to-face meeting.

Beyond networking opportunities, the Innovation Group's main attraction was access to innovation-related expertise. Practitioner-theorists of group psychology, economics, systems engineering, philosophy, and landscape architecture shared their work and insights in the pages of the magazine. *Innovation*'s editors outlined remedies for lumbering corporations, environmental degradation, and various urban ills. Selected articles were later collected in edited books through a partnership with the American Management Association.

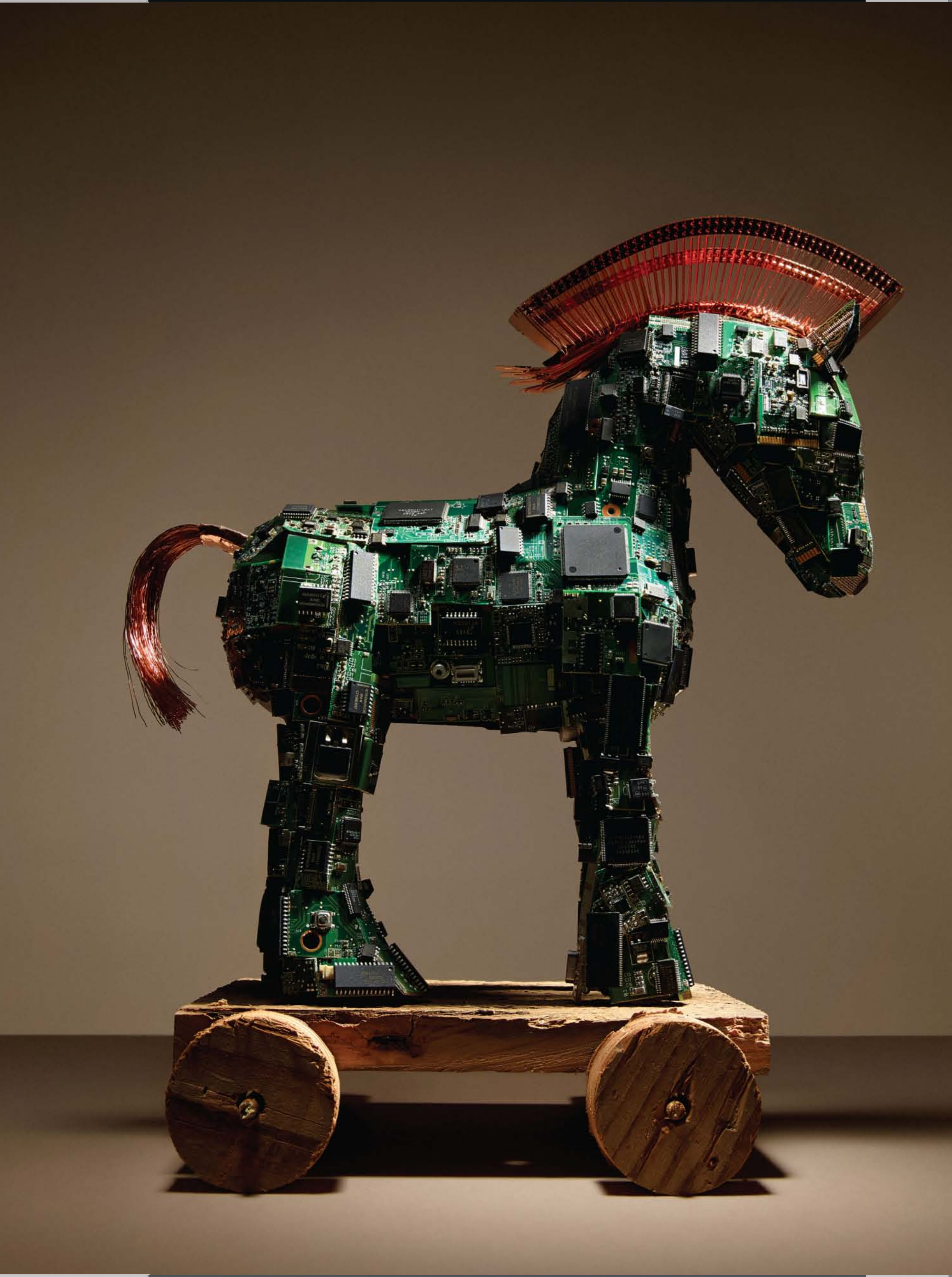
The editors were also fascinated with the rise of social movements, covering, for example, MIT's 1969 anti-Vietnam War work stoppage. The radicals, contributors argued, had the right attitude toward novelty and had discovered powerful forms of decentralized organization. (The MIT work-stoppage article was written by a Harvard-educated journalist named Charles Horman, who worked at *Innovation* from its founding until mid-1970; later, while report- | CONTINUED ON PAGE 60

Management Information Systems: It's All In The Tailoring

And Now, the Creative Corporation

Toward the Decentralized Intellectual Workshop

ARTICLES OF INFLUENCE: *Innovation*'s coverage of technology and management included a piece on management information systems [top], an essay on the "creative corporation" [center], and a profile of computer pioneer Douglas Engelbart [bottom].



THE TROJAN-PROOF CHIP

A FEW ADJUSTMENTS COULD PROTECT CHIPS FROM MALICIOUS CIRCUITRY

BY SUBHASISH MITRA, H.-S. PHILIP WONG & SIMON WONG

LONG AGO, THE STORY GOES, Greek soldiers tried for 10 years to conquer the city of Troy. Eventually, they departed, leaving behind a large wooden horse, apparently as a gift. The Trojans pulled the beautiful tribute inside. Later, a group of Greek soldiers slipped out of the horse and opened the gates for their compatriots, who easily sacked the sleeping city.

Nowadays, some 3,000 years on, a Trojan is a seemingly innocuous piece of software that actually contains malicious code. Security companies are constantly developing new tests to check for these threats. But there is another variety of Trojan—the "hardware Trojan"—that has only started to gain attention, and it could prove much harder to thwart.

A hardware Trojan is exactly what it sounds like: a small change to an integrated circuit that can disturb chip operation. With the right design, a clever attacker can alter a chip so that it fails at a crucial time or generates false signals. Or the attacker can add a backdoor that can sniff out encryption keys or passwords or transmit internal chip data to the outside world.

There's good reason to be concerned. In 2007, a Syrian radar failed to warn of an incoming air strike; a backdoor built into the system's chips was rumored to be responsible. Other serious allegations of added circuits have been made. And there has been an explosion in reports of counterfeit chips, raising

PHOTOGRAPHS BY Adam Voorhes

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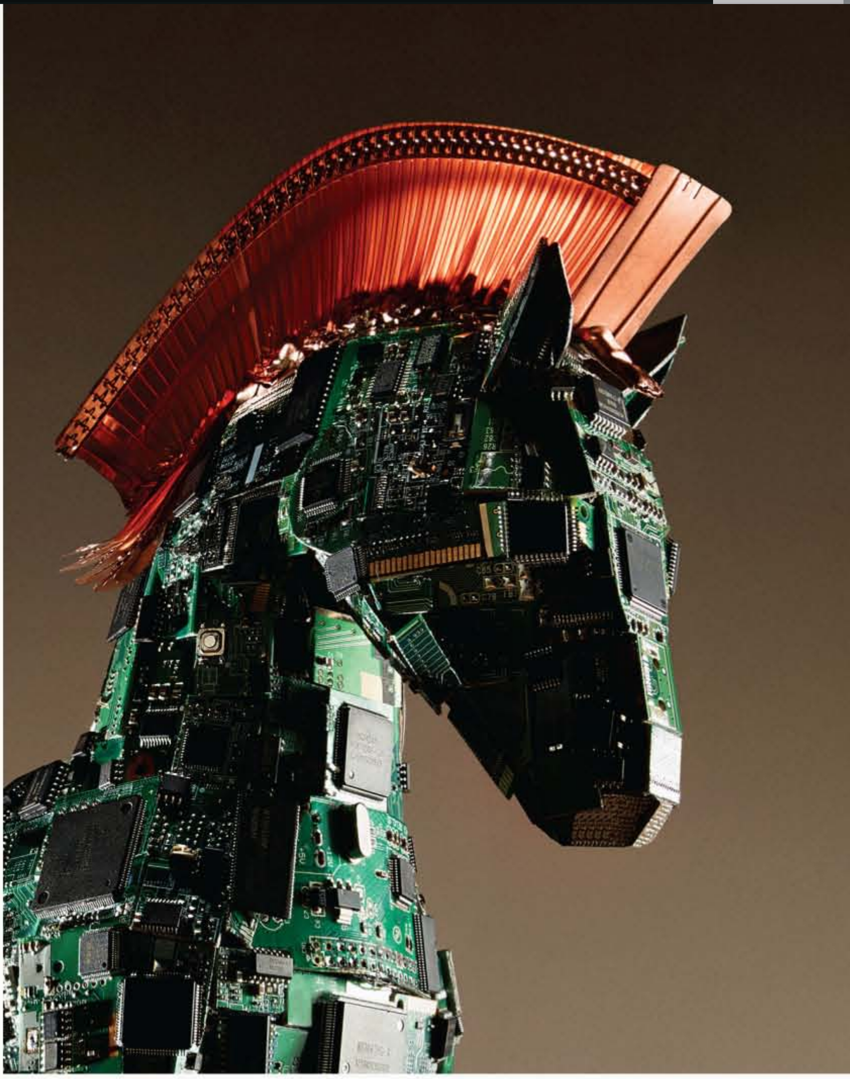
questions about just how much the global supply chain for integrated circuits can be trusted.

If any such episode has led to calamity, the role of the Trojan has been kept secret. Indeed, if any potentially threatening hardware Trojans have been found, the news hasn't yet been made public. But clearly, in the right place a compromised chip could scuttle antimissile defenses, open up our personal data to the world, or down a power plant or even a large section of a power grid.

A lot of research is still being devoted to understanding the scope of the problem. But solutions are already starting to emerge. In 2011, the United States' Intelligence Advanced Research Projects Activity (IARPA) started a new program to explore ways to make trusted chips. As part of that program, our team at Stanford University, along with other research groups, is working on fundamental changes to the way integrated circuits are designed and manufactured.

Today we try to protect against hardware Trojans by keeping careful tabs on where chips are made, limiting the opportunity for mischief by limiting who is authorized to make a chip. But if this research succeeds, it could make it practical for anyone to design and build a chip wherever they like and trust that it hasn't been tampered with. More radically, our research could open up ways to let you use a chip even if there is a Trojan inside.



PROP STYLIST: ROBIN FINLAY

Today's chips are so complex and costly to design and build that it's very difficult for a single company to create them without outside help. One company might conceive and market an integrated circuit, but other companies often make critical contributions to pinning down the design. Still others may have a hand in manufacturing, packaging, and distributing the chips.

With so many cooks in the kitchen, there are multiple opportunities to meddle with the hardware. A natural place to start is at the very beginning, when a chip is being designed. Today, that's done using sophisticated computer-aided-design software. These CAD tools are created by specialized companies that often work closely with chipmakers. The tools frequently contain millions of lines of code, and they change quickly: New algorithms are added almost continuously to help design faster, lower-power circuits. In principle, among the many thousands or perhaps millions of lines of code, it is easy to slip in a few extra ones to modify a hardware design. And there are multiple places it could be done. For one thing, routine circuit blocks, such as the accelerators used to crunch numbers for encryption and decryption, are often designed by third parties.

The other obvious time for an integrated circuit to be altered is during manufacturing. This was less of a concern decades ago, when chip manufacturing was more affordable and companies could make their own chips in their own fabrication plants, or fabs. But nowadays a new chip fab can cost upwards of US $10 billion, and research and development costs keep increasing. Because of this very high up-front cost, most chipmakers now rely on a handful of outside foundry services, based in China, South Korea, Taiwan, and the United States, among other countries, that specialize in implementing silicon designs. Although there is no reason to suspect that any of these foundries may be adding malicious hardware, it's impossible to exclude the possibility that they might make undesirable adjustments to the designs, potentially altering an entire batch of chips or a subset of them.

The U.S. Department of Defense is of course well aware of these vulnerabilities. To help address them, its Trusted Foundry program has accredited foundries, along with other links in the supply chain. The set of foundries allowed to work on these "trusted" chips is generally restricted to those in the United States. This limits access to the most advanced chips; many trusted U.S. foundry services have not been able to keep up their investments and are producing chips that are 10 years or more behind the current state-of-the-art manufacturing process. What's more, the DOD program is focused on military chips for applications such as weapons and avionics. The integrated circuits used in such vital nonmilitary applications as medical computer systems and nuclear power plants are often made overseas and aren't subject to the same level of supply chain scrutiny.

Ideally, what we'd like is a simple, quick, and cheap way to find out if a chip has a hardware Trojan inside. What would we be looking for? Researchers are still sorting out what kinds of hardware Trojan attacks are possible. But it's already clear they can be hard to detect.

In one experiment, conducted in 2008 at the University of Illinois at Urbana-Champaign, researchers designed a small backdoor circuit that gave access to privileged regions of chip memory. The Trojan could be used to change the process identification number of malicious software, allowing attackers to perform any operation and access any data they wish. Incorporating this Trojan added fewer than 1,000 transistors to the 1.8 million already on the chip, an increase of just 0.05 percent. And such tiny tweaks are likely to be par for the course: It doesn't take much additional circuitry to wreak havoc on a chip. In fact, it might not require any added circuitry. Recent research suggests that even slight adjustments to the electrical properties of existing transistors in a design could compromise security.

TODAY'S INTEGRATED CIRCUITS ARE INTERNATIONAL CREATURES. BUT TRUST ISN'T SOMETHING THAT'S BUILT IN FROM THE START

How would you find changes to the circuitry? You might think you could simply take a finished chip and look at it under a microscope. It's easy to imagine doing that back in the early 1970s, when Intel debuted its 4004 microprocessor. The 4004 had about 2,300 transistors, each measuring an optical microscope-friendly 10 micrometers or so. But today's integrated circuits are in another realm entirely. They can easily have billions of transistors, each well less than a hundredth the size of those in the 4004. While it's possible to scrutinize them with an electron microscope, the process is destructive. To get to the transistor level, you have to chemically remove or mechanically polish away the layers of metal that have been added on top of the transistors to wire everything together.

A straightforward solution to this problem is to destructively examine a representative sample of chips; if they're free of Trojans, you might conclude that all the untested chips in the batch are as well. But there is no guarantee that's the case; an attacker may have targeted only a subset of the chips in question.

So researchers are exploring other tests. One idea is to send different inputs into various circuits and then compare the resulting output data or the time it takes for information to move through the circuits, for example, to what you'd expect to see if the chip were operating normally. This sort of quality check can be performed after the chip is manufactured, and it could potentially detect a Trojan. But it's not the sort of thing that can be used to continuously monitor chip operation, so it wouldn't help you detect an alteration that's designed to be activated months or years down the line.

Researchers at IBM's Thomas J. Watson Research Center, in Yorktown Heights, N.Y., have been investigating a way to detect such intermittent Trojans. In this approach, a handful of chips are selected from the batch. They're put through their paces so that a "fingerprint" can be created based on such characteristics as power consumption, temperature, and electromagnetic emission. The idea is that a Trojan may have an effect on these fingerprint parameters, also called side-channel outputs, even if the Trojan isn't actively performing an attack. Statistical analysis can then be used to identify outliers. Or the fingerprinted chips can be dismantled and examined under an electron microscope to make sure they have no Trojans. If they pass that test, the fingerprints can be used to gauge the health of the rest of the chips in the batch. A mismatch in one or more of the fingerprints indicates the presence of a Trojan.

This technique has drawbacks of its own. For instance, it can't detect small circuit alterations, such as the addition of a single "exclusive OR" gate built with a handful of transistors. That's because even healthy chips display variations in the physical dimensions of their transistors and metal wiring. These variations in turn alter electrical and thermal properties from transistor to transistor. The resulting noise could easily swamp the signal created by a tiny Trojan.

Imaging could help see those smaller Trojans, and some researchers haven't given up on the idea. In 2011, a group led by Michael Bajura of the University of Southern California's Information Sciences Institute reported a way to image chips without tearing them apart. Instead of using an electron microscope, which can image only surfaces, the team directed X-rays at various angles through a chip. By stitching the resulting 2-D projections together, they could create a high-resolution 3-D rendering of the chip. This X-ray microscope could resolve details down to about 30 nanometers, which should reveal any added circuitry in even the most advanced chips used today. But unfortunately, the radiation can still cause damage, and a lot of work and time is needed to find departures from the chip's original design among what can easily be more than a billion transistors.

These sorts of challenges have led the U.S. government to consider a drastic measure—a change to the chipmaking process itself. The idea, called split manufacturing, is to literally split the manufacturing of chips into two steps. First, a state-of-the-art foundry would make, at the "front end of line," the smallest chip features: the layer of transistors, followed by the first (or perhaps a few) of the most finely detailed layers of metal wiring needed to connect them. In the second step, the chip would be shipped to a vetted, trusted foundry to be completed. This less advanced foundry would finish up the connections on the chip's back end—the chip's less fine layers of metal wiring and, ultimately, its connections to the outside world.

The idea is that if only the first few layers of a chip are made at an untrusted foundry, the chip will look like little more than a sea of arbitrarily connected transistors, and it will be impossible for foundry workers to know much about how the chip works. That incomprehension would in turn make it very hard for an aspiring attacker to devise a Trojan that would escape detection.

In principle, split manufacturing could be the best of both worlds: It would let a chipmaker take advantage of the advanced manufacturing capabilities of an untrusted foundry without disclosing everything about the chip. With that thinking in mind, IARPA established a new program in 2011 called Trusted Integrated Chips, dedicated to finding ways of exploiting split manufacturing.

The IARPA program was specifically designed to address the threat of Trojans added in foundries. But we've actually devised an approach that expands on split manufacturing and that we think could be a complete solution to the problem—one that would address the possibility not only of Trojans introduced at the foundry but also of Trojans introduced at the design stage, a problem that split manufacturing alone can't solve.

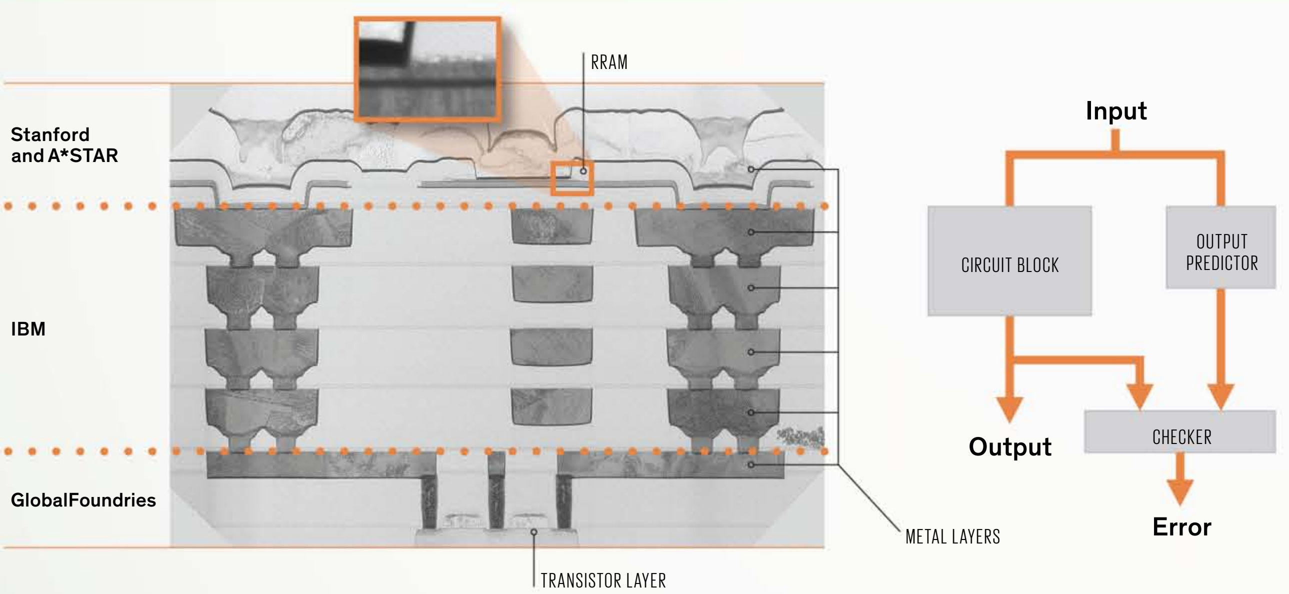
There will be a cost for such protection, of course, and it will be in the number of transistors. At a basic level, our approach is to build new circuitry on each chip that can monitor it on an ongoing basis, even after it's been purchased and installed. This circuitry performs a task called concurrent error detection, which has been used for years in fault-tolerant computing to detect hardware-related errors and boost the reliability of high-performance computers.

Concurrent error detection works on chunks, or blocks, of circuits on a chip. The trick to good error-checking design is to find an economical way to prove a block is operating correctly. This feat is typically accomplished by designing circuitry that runs alongside the block. The circuitry takes a computational shortcut, performing calculations on the input data to a block. If properly designed, it will generate results with the same properties as the output of that block when it's operating normally.

For example, one widely used check is the parity function, which tells you whether a computation has produced an even or odd number of 1s over a given interval. If the results of the parity function performed on the output of the checker circuitry and the one performed on the output of the circuit block match, there is a good chance that the circuit block is error-free. If there's a mismatch, it suggests something has gone awry.

This scheme works well for detecting random errors, but it could be circumvented with a carefully designed Trojan. For example, a clever attacker who knows a parity check is being used to protect the block could devise a circuit that would flip multiple bits in the output so that the number of 1s generated is preserved, masking the presence of the Trojan.

To prevent this deception, we've devised two ways to hide the functionality of the checker. The first is to change the checker design. We've devised a variation on the parity function, which we call randomized parity. An ordinary parity function might



SPLITTING THE CHECK

A cross section of a 130-nanometer test chip [left] shows the transistor layer at the bottom and six layers of metal interconnections built on top. The transistor and first metal layer were fabricated in Singapore by GlobalFoundries, the second through fifth layers were made by IBM in the United States, and the chip was finished by Stanford and the Agency for Science, Technology and Research (A*STAR). Checker circuitry that can hunt for abnormal operation is split among transistors in the transistor layer and resistive RAM (RRAM) switches that are sandwiched between the fifth and sixth layers of metal. These switches can be configured after the chip is made. As shown at right, the checker circuitry works by comparing characteristic information on a circuit block's output with similar information that is predicted and calculated directly by the checker circuitry.

A*STAR INSTITUTE OF MICROELECTRONICS AND STANFORD UNIVERSITY take 10 bits and count the number of 1s among them. In our approach, each checker circuit is configured to take a random sample of those 10, sampling perhaps only the second, fifth, seventh, and eighth bits in each group. The checker's sampling setting is chosen at random when the chip is being designed. And crucially, the configuration of the checker circuitry can be designed independently from the rest of the chip, which should help limit tampering at the design stage.

The second part of our approach is to obfuscate the function of the checker circuitry at the fab by building some of the connections with programmable switches that are set only after the chip is finished. That way, it won't be clear to the group fabricating the chip how the checker circuitry is designed, making it very hard to devise a workaround.

We build these switches using a form of memory called resistive RAM (RRAM). An RRAM cell consists of an insulating layer sandwiched between two layers of metal. With the right choice of insulating material, RRAM can be made to switch between states of high and low resistance with a fairly small voltage, and it will keep that state even if there's no power, which means it can act as configurable wiring. We can break and complete circuits as needed by applying a voltage.

Programmable switches themselves aren't new; many of the chips you find in TV set-top boxes, cars, and medical equipment are made with field-programmable gate arrays (FPGAs), standardized circuits that have their functionality programmed in transistor-based memory cells after they leave the assembly line. But RRAM is more attractive for this application, in part because it's compact. We've shown that if FPGA memory is made with cells containing one transistor and two RRAM devices instead of the typical six-transistor form, the area of a chip can be reduced by 40 percent and its energy consumption by 28 percent. What's more, unlike traditional, transistor-based memory, RRAM can be placed among the metal connections above the active layer of transistors on a chip, and it can be inserted at whatever stage in the manufacturing of metal layers you like, even if you choose not to pursue split manufacturing.

We launched our project in 2012. In the very first phase, as a proof of concept, we manufactured our chip designs through the IARPA program, using 0.13-micrometer technology. The transistors and transistor-based checker circuitry, along with the first metal layer, were made at a GlobalFoundries fab in Singapore. Other metal layers were added at an IBM-built plant in Burlington, Vt. We then built the RRAM and last metal layer.

The process produced a handful of accelerators, built to perform data compression, and FPGAs. Graduate student Tony Wu and other members of our laboratory installed these chips on a circuit board attached to a computer in order to run tests and emulate attacks. They showed that the checker circuitry we'd built in the accelerator to run alongside the compression process took up just 1 percent of the area of the chip and did not slow it down at all. And they emulated a variety of different Trojan attacks on the chip by altering the outputs of various circuit blocks. The chip's checker circuitry could detect some 99.9998 percent of 10 million emulated hardware attacks.

This approach can detect Trojans that directly alter the operation of a circuit. It can even spot "replay" attacks. These are perpetrated by recording valid circuit block outputs and then reemitting them during an attack to give the appearance that everything is operating normally. But the checker circuits do have limitations. They can pick up data that's transmitted through the normal input-output channels of a chip. But they can't detect a Trojan that passively extracts information and then wirelessly transmits it to a third party through added radio-frequency circuitry. We're just now starting to explore protections against such an attack.

POST YOUR COMMENTS at http://spectrum.ieee.org/trojan0215

Even if split manufacturing isn't used, our checker-circuit design approach and the programmable RRAM will help make it difficult for a potential attacker to devise a hardware attack. But we think that whatever strategy is used to protect against changes—even one that combines split manufacturing, testing, and destructive imaging—it will be very hard to definitively rule out the possibility that a chip contains a hardware Trojan before it's sent on its way. Small circuits are simply too easy to hide.

Because our checker circuitry is designed to monitor a chip continuously, it will be able to watch for an attack, but it won't be able to prevent it from happening. So a key challenge now is to figure out what to do if one of these circuits detects a Trojan attack in the field. Will a simple reboot suffice, pushing off the next attempted attack for months or even years? Can we add circuitry for chip recovery, borrowing error-correcting techniques such as checkpoints to save data at critical intervals? Should we plan on building more redundancy into critical control systems to protect against the possibility of a Trojan, adding more chips to our equipment in case one has a fault?

These are questions that will become more relevant as hardware Trojan protection technology matures. We're now in the second phase of the IARPA project, which is targeting the more advanced, 28-nanometer manufacturing process, one step away from today's most advanced chips. We can start considering how the semiconductor ecosystem might be changed to make the chip supply chain more secure. Split manufacturing could help, but it could also significantly add to the cost of chips and the logistical complexity of the process. It may be that incentives and regulations will be needed to convince chip companies and foundries to adopt it.

Tackling the threat of a hardware Trojan will require tough calls and a sea change in the way we approach chip manufacturing. It could also mean we have to redefine what we mean by trust. But with the right approach, we could make attacks rare and relatively benign—and ensure that the most famous Trojan horse story remains ancient history. ■

The authors would like to thank IARPA for its support, Farzan Fallah for his early work on this article, and our students and postdocs at Stanford and our collaborators at A*STAR's Institute of Microelectronics, in Singapore, for their vital contributions to this research.

Radar Everywhere

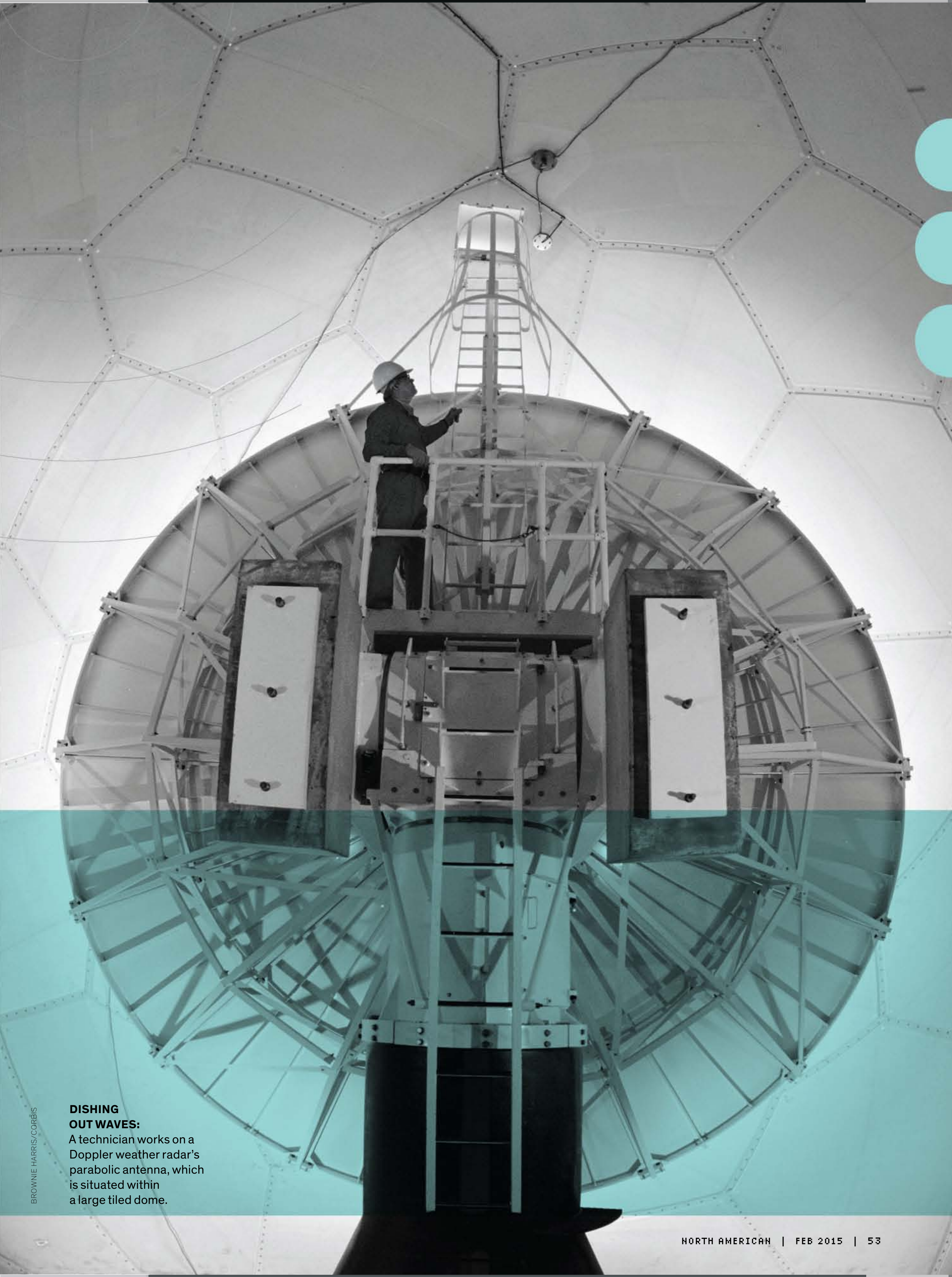
REGULATORS NEED TO KEEP UP WITH THE PROLIFERATION OF DIFFERENT KINDS OF RADAR · BY MITCHELL LAZARUS

During the 1930s, with Europe preparing for war, the British government badly needed a way to detect the approach of enemy aircraft. It got one, thanks to a bookish-looking engineer named Robert Watson-Watt, who devised and successfully tested a primitive radar system in 1935. By the time of the Battle of Britain in 1940, a chain of radar stations along England's eastern and southern coasts was providing enough warning of incoming Luftwaffe bombers to allow civilians to find shelter underground and Royal Air Force pilots to scramble their fighters into the air. King George VI recognized Watson-Watt's accomplishments with a knighthood in 1942. Some historians even credit the engineer with Britain's survival during those terrifying times.

Some 15 years later, when Watson-Watt was in his 60s and I was in my teens, he spoke at my Canadian high school. The best part of the talk for us was his story about having been pulled over in a radar speed trap. He read us a poem he had composed while waiting for his case to be called:

Pity Sir Robert Watson-Watt,
strange target of this radar plot
And thus, with others I can mention,
the victim of his own invention.
His magical all-seeing eye
enabled cloud-bound planes to fly
but now by some ironic twist
it spots the speeding motorist
and bites, no doubt with legal wit,
the hand that once created it.

Police with radar speed guns are indeed what leaps to most people's minds if you ask them what radar is good for, other than detecting aircraft. In fact, though, radar has proved to be an extraordinarily versatile technology, with established uses now



DISHING OUT WAVES:
A technician works on a Doppler weather radar's parabolic antenna, which is situated within a large tiled dome.

BROWNIE HARRIS/CORBIS

RADAR'S MILITARY ROOTS: Radar guided the naval airmen working on the aircraft carrier USS *Essex* in 1945 [top left]. The compact APS13 radar [top right] was used in some fighter aircraft of that era and also for altitude sensing in the first atomic bombs. Radar was further refined during the Cold War, when it scanned the skies for an impending nuclear strike. Initially, men, like those working at Fort George G. Meade in Maryland in 1957 [middle right], monitored the screens visually. Later, radar-based detection of nuclear threats, such as that supplied by stations of the Distant Early Warning Line [bottom left], was automated. All this was an outgrowth of radar's invention by Sir Robert Watson-Watt [bottom right].

in vehicles, weather monitoring, aerial reconnaissance, even for seeing through walls. But as applications for it proliferate at an accelerating rate, government regulators, including those in the United States, are having a hard time keeping up.

It's vital that they do, because foot dragging on their part threatens to slow the pace of innovation. If you have any doubts, read on and discover just how deeply radar has integrated itself into the fabric of modern industrial society, despite what I regard as a problematic regulatory environment. It's a cautionary tale, and though I'm concerned with radar here, the warning is relevant to many technologies—including drones, app-based ride sharing, and cryptocurrencies, to mention just a few.

Much of the development of radar during World War II, building on Watson-Watt's work, took place at MIT's Radiation Laboratory—the direct predecessor of the still-active Research Laboratory of Electronics. U.S. contributions helped to make radar equipment more effective and reliable, and also a lot smaller. One compact model, with electronics the size of a shoebox, warned fighter pilots of enemy aircraft approaching from behind. This device found another wartime application as well: The nuclear bombs dropped over Hiroshima and Nagasaki each carried four of these units to monitor the dwindling distance to the ground as the bombs descended, so that detonation could be triggered at a preset altitude.

Vigorous development of radar continued after the war, and along with improvements to military systems, two civilian applications quickly emerged:

CLOCKWISE FROM TOP LEFT: BETTMANN/CORBIS; ANTONIO FUCCI/RADIOMILITARI.COM; BETTMANN/CORBIS; HULTON-DEUTSCH COLLECTION/CORBIS; AP PHOTO

air-traffic control and maritime collision avoidance. The decades since have seen dozens of additional uses.

Current radar technology falls into two broad categories. One is the direct descendant of wartime radar and is capable of ranges of up to hundreds of kilometers, using high-power transmission concentrated in a relatively narrow slice of radio bandwidth. Regulatory authorities call this form of radar radiolocation. The other category covers systems that operate at much lower power levels, over much smaller distances.

For now, consider radiolocation. It's quite simple: Bounce a radio wave off a target and measure how long it takes for the radio echo to come back. That gives you its distance. The aiming of the antenna that produces the echo indicates the direction to the target.

The accuracy of your measurements depends, of course, on the electronics you use. The radar designers of the Second World War had to contend with the limitations of vacuum tubes. Postwar improvements, prompted by the advent of the transistor, included operation at ever-higher frequencies, which made possible tighter beams from smaller antennas, which in turn enabled longer range and better directional precision. More sensitive receivers further increased the working distance.

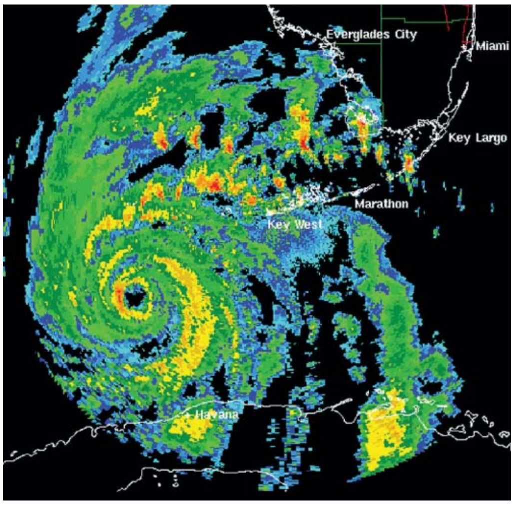
Advances in display technology were also important. Watson-Watt and his team had cleverly contrived displays out of existing laboratory oscilloscopes. A horizontal trace would start moving across the screen when the signal left the transmitter and deflect vertically—creating a "blip"—when the signal returned. The horizontal distance from the starting point to the blip indicated the range to the target. This worked, but the task of constantly watching for blips in the "grass" (noise) quickly fatigued radar operators, which increased the risk of error.

During the Cold War, the U.S. and Canadian governments installed the Distant Early Warning Line: a chain of 63 radar stations across the Arctic regions of both countries. The goal was to detect incoming Soviet bombers in time to launch a retaliatory strike. Foreseeing that either missed signals or false positives could be catastrophic, the designers developed an automatic blip-detecting system to back up the operators. Later applications, such as collision-avoidance radars in aircraft and self-braking systems in cars, increasingly came to depend on automatic responses.

Radiolocation's realm expanded dramatically with the application of the Doppler effect, relevant here because an electromagnetic wave reflected from an oncoming target comes back at a frequency higher than the transmitted frequency. Likewise, a receding target results in a lower return frequency. The difference between transmitted and received frequencies provides a measure of the target speed relative to the radar antenna. That difference is always small. A target approaching at 100 kilometers per hour raises the received frequency by less than one part in 5 million, for example. Fortunately, engineers have long known how to create circuits that can precisely compare nearly identical frequencies.

The earliest applications of Doppler radar simply measured raw speed, like the police radar that caught Watson-Watt in the 1950s. It would be another 20 years before the emergence of digital microprocessors made possible some truly amazing improvements. For example, the Doppler effect can be used to step up the angular resolution in synthetic-aperture radar, which takes multiple radar scans from a moving platform, such as an airplane or spacecraft, and combines them into what looks like an infrared photo. Ideal for military reconnaissance, the technology can reveal enemy facilities in total darkness and through cloud cover and foliage. Peaceful uses include the monitoring of lake and river ice, glaciers, crops, deforestation, and coastal erosion, as well as the tracking of forest fires, floods, volcanic eruptions, and oil spills.

Doppler weather radar, familiar to TV viewers and Internet weather junkies, measures the distance and lateral speed of falling particles of rain or snow, allowing forecasters to plot the evolving locations of storms and the winds swirling inside them. Such a system can even see through one storm to probe another one beyond it. Some versions compare the reflections from vertically and horizontally polarized signals to distinguish among rain, hail, snow, and ice pellets. These radars can also detect tornadoes from the presence of debris in the air and plot a twister's location and velocity in real time—information that lets officials warn people in its projected path. A variation used at some airports tracks the activity of small airborne particles to pinpoint wind shear, which if undetected can cause aircraft to stall and drop during takeoff or landing, with possibly fatal results.



STORM'S A-BREWIN': Doppler radar has proved invaluable for monitoring severe weather, such as Hurricane Charley, which devastated parts of Florida in 2004.

NATIONAL WEATHER SERVICE/AP PHOTO

Police and other first responders have access to another type of Doppler radar device, one that sees through building walls to locate hostages or captors and can even detect the breathing of an unconscious victim. A different configuration helps to find people trapped under the rubble of a collapsed building. Still another type, used at mining sites, both identifies underground rock strata and monitors instabilities in the terrain that can forewarn of an impending cave-in.

And these are just the things that are already being done. Forthcoming applications will detect birds near wind farms so as to cut down on avian mortality by halting the turbine blades when birds approach. Installed near airports, similar radars could prevent mishaps like the forced landing of an airliner in the Hudson River in 2009 after it ran into a flock of Canada geese on takeoff from New York City. Soon to come is a rearview radar for bicyclists.

The electromagnetic spectrum is a little like the space on a submarine: There's never enough to go around. So users of radio spectrum generally have to share it. The problem is that radiolocation does not share well. Long-range operation requires powerful transmitters and sensitive receivers because of the way the transmitted energy spreads out on its journey to the target and then scatters on reflection. Only a small fraction of the energy heads back toward the receiver, and that, too, spreads out as it travels. Overall, the received signal drops off in proportion to the fourth power of the target distance.

From a sharing standpoint, radiolocation presents the thorniest of all possible cases: a strong transmitted signal that is highly interfering to other users and a return signal so weak that it's extremely susceptible to incoming interference–although digital processing at the receiver can suppress some of the interfering signal. To make matters worse, many applications of radar, including defense, air-traffic control, maritime safety, and weather prediction, are critical to human lives and safety, so radio interference can have catastrophic consequences.

Given those concerns, you might expect to find a robust regulatory regime for radiolocation, one that sets out clear operating limits and requires new installations to protect those already using these airwaves. Yet no such regime exists in some countries, including the United States. The Federal Communications Commission prescribes what frequency bands such radars can use, as all countries' regulators do, but little else. The FCC approves (or disapproves) radiolocation power and bandwidth on a case-by-case basis, and it can similarly authorize any type of modulation "upon a satisfactory showing of need," with no guidance on what that entails. "No rules in advance," says the FCC, in effect. "Apply for something, and we'll let you know whether it passes muster with us."

Canada and Taiwan follow a similar strategy in regulating radiolocation equipment. Perhaps the intent is to reduce regulatory barriers to new technologies. That would be laudable. But vague rules are more likely to be a hin-

CAR'S A-COMIN': An upcoming radar product called Backtracker will help bicyclists detect vehicles approaching from behind.

BACKTRACKER

drance. That's because a company with an idea for a new radiolocation product, unable to know in advance whether it would qualify for approval, may be reluctant to invest in its development.

This loose approach is not universal, though. European regulators, for example, require compliance with certain well-described technical standards while grandfathering in older types of equipment and offering procedures to obtain approval of new types. In other places, including parts of Africa, regulators follow European standards and procedures. Japan has its own system. Some other non-Western countries avoid the problem entirely by keeping high-powered radiolocation equipment out of private hands, limiting its use exclusively to the government and the military.

The United States doesn't do that. Instead, it allocates 14 frequency bands, ranging from 70 kilohertz to 81 gigahertz, for nonfederal radiolocation services. All but one of these bands are shared with other applications. The most useful frequencies, from 2,900 megahertz on up, are also shared with federal radiolocation users.

But how do U.S. radar users outside of government share spectrum with one another? Some radio services that accommodate multiple users impose a procedure called frequency coordination. Details vary, but the aim is to assign each newcomer a frequency that minimizes the risk of interference both to and from incumbents. In the United States, the categories subject to frequency coordination include two-way radio, some satellite Earth stations, and also most fixed-microwave radio links, which are often used to connect cellular base stations, among other things. But radiolocation is specifically exempt. A company that wants to install some new radiolocation gizmo is free to choose its own frequency of operation within one of the radiolocation bands. Federal spectrum authorities study each filed application for the risk of interference to federal systems, but no one does the same to protect nonfederal users on these frequencies.

In the United States and other countries where the private use of radiolocation equipment is permitted, a licensing requirement of some sort seems to be universal, although it may not be widely respected. The FCC's database shows fewer than 2,000 active radiolocation licenses for the entire United States, not counting those for units used on vessels operating in U.S. waters—which are deemed to have licenses without anybody actually having to obtain them.

RADIOLOCATION ISN'T THE ONLY USE for radar, though. Another family of applications, which evolved later, transmits much less power—usually well under a milliwatt—over a much shorter range, usually just a few meters or less. It also uses a much wider radio bandwidth, typically in the tens to hundreds of megahertz.

These devices emit a train of short, sharp-edged pulses, which enable the equipment to measure return times more precisely. Another benefit is that such a waveform spreads energy over a lot of the radio spectrum—sometimes a gigahertz or more.

This kind of signal causes little radio interference to most other receivers, which are sensitive only to a narrow range of frequencies and so are affected by just a tiny fraction of the radar transmitter's total power output, which is small to begin with. Conversely, because the signals from most other kinds of radios are contained within a very narrow slice of spectrum, they have little effect on a wideband radar's performance.

The broad frequency range also confers a regulatory advantage. Because governments typically set power limits on a per-megahertz basis, a radar using a wide bandwidth can emit a relatively high level of total power and still remain in compliance with the rules.

Early examples of this technology appeared in the 1970s in the form of ground-penetrating radar (GPR). This equipment helps excavation crews find underground pipes and cables, detects invisible defects under the surfaces of highways and airport runways, and once even located a woolly mammoth below the Siberian permafrost. For decades, though, the United States had no regulations under which to authorize GPRs, so their sale and use were illegal. But the devices filled important needs, promoted public safety, and did not cause interference problems, so—for nearly three decades—regulators generally looked the other way.

The FCC finally authorized GPRs, along with several other kinds of radar-imaging systems, in 2002, as part of its ultrawideband proceeding. One reason it took so long was that the notion of allowing such wideband transmissions drew vehement opposition from virtually every organized group of spectrum users, including key U.S. government agencies, all of which warned of crippling interference to their systems. The FCC responded by setting very low power limits for all ultrawideband devices and mandated that this energy be spread thinly over the spectrum. It did this by stipulating that the power not exceed 75 nanowatts per megahertz. The FCC also imposed a minimum bandwidth equal to at least 20 percent of the center frequency or 500 MHz, whichever is less.

As time went on, and as the opponents' predictions of doom failed to materialize, other nations adopted similar rules. Some countries, including the United States and those of Europe, began allowing radar systems that use less bandwidth and, in some cases, higher power than initially permitted. Called wideband radars, these use either ultrawideband-type pulse trains or frequency-modulated continuous-wave signals. They gave rise to a host of vehicular, mining, industrial, public safety, and novel airport applications.

In contrast to the situation with high-power radiolocation, all countries that allow low-power, wideband radars have imposed detailed technical regulations. Some did so by adopting versions of one another's standards, although most of the world's ultrawideband rules generally track the U.S. model. Going in the other direction, a recent FCC approval of industrial level-probing radars (used to gauge the levels of liquids and of piles of dry material in buildings and outdoors) largely followed European technical rules. Manufacturers welcome this kind of global uniformity because it enables them to make products that they can sell in multiple countries.

Policies on the licensing of wideband radars are less uniform around the world. The United States permits all such units to operate without a license, although some are restricted to particular user groups, such as emergency personnel. Radar equipment for which Canada has technical standards are similarly license exempt. Some countries, though, including ones in Europe, require licensing for some categories of equipment, such as GPRs and certain industrial radars.

By far the most widespread application of low-power radar is in vehicles. A fast-growing number of cars and trucks now feature radar-enabled adaptive cruise control, collision warning, automatic braking, blind-spot detection, lane-change assist, and back-up alert systems [see "Making Bertha See," *IEEE Spectrum*, August 2014]. Nowhere, as far as I know, do these vehicular radars require a license. But vehicles go anywhere roads do, and their electromagnetic emissions go with them–a fact that worries some spectrum users, particularly radio astronomers, whose extremely sensitive receivers make observations on the same frequencies that many countries use for vehicle radars. Regulators have largely downplayed the astronomers' concerns, responding instead to the automakers' promises of better safety for motorists.

Perhaps favoring vehicle radars over radio astronomy was an easy call. But when the level-probing radar industry offered to protect radio astronomers from interference by accepting a prohibition on installation close to their sites, the FCC declined to impose such a requirement. The regulators may have reasoned that too many rules would slow the growth of this industry. Certainly, there are many instances where this has been true. But excessive flexibility in regulatory requirements breeds uncertainty, which can both deter innovation and unnecessarily threaten other services.

Watson-Watt jokingly told the police officer who pulled him over that had he known radar would be used for speed traps, he would never have invented it. He might have changed his mind–and it would have pleased him enormously–had he also known that his invention would not only protect civilians in their homes in wartime Great Britain but also make all of us more secure at industrial sites, in air travel, and on the highway. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/radar0215

THE BIRTH OF *INNOVATION*

CONTINUED FROM PAGE 45

ing in Chile during the 1973 U.S.-backed military coup, he was kidnapped and murdered by Chilean soldiers.)

By 1972, Maass had synthesized the Innovation Group's findings into a "self-energized program" for training change managers in any organization. Such individuals would work to cultivate institutional "climates" that were "flexible, responsive, and innovative." The program started by guiding these managers through a clear-eyed contextual analysis of technological change within their organizations and industries, informed by management science. Local innovation groups of 12 to 20 change managers could then formulate and execute "action plans" in their given organizations. Technology Communication facilitated the process by providing "discussion packages" and a library of then-cutting-edge videotapes.

In marketing these materials for change managers, the Innovation Group helped shape the skill set as well as the broader cultural image of the innovator. Change managers, the group decreed, had no fixed profession or institution. They merged social and technical solutions. They were creative and artistic. They swam in countercultural currents. They achieved financial and technical goals by drawing on human empathy. They were entrepreneurial risk takers. Most important, they achieved external rewards and inner satisfaction from their faith in the new as a key human virtue.

Innovation constructed intimate portraits of exemplary innovators. Its profile of Engelbart compared the SRI researcher with the antiauthoritarian protagonist of the 1959 short story "The Loneliness of the Long Distance Runner." Engelbart was "broad-shouldered" and "athletic," "wistful and boyish" but "prematurely gray," "diffident yet warm," "gentle yet stubborn," someone who "wins respect." Personality and physique mattered, as did passion: Engelbart had a "love affair with augmentation systems." What counted above all, according to the profile, was the researcher's clear vision and tenacity to bring that vision to life. Because Engelbart knew that a "revolution like the development of writing and the printing press lumped together" was coming, he had to withdraw from the world in the single-minded pursuit of its transformation.

In *Innovation*'s view, the ideal innovator was also a *managerial* iconoclast who wasn't focused solely on creating new ventures but could also turn around existing institutions, including corporations, universities, and government agencies. Writing in the November 1970 issue, psychologist Frieda B. Libaw described how the change manager was an archetype for "the creative corporation": a collection of individuals who could look change in the eye and embrace its risks and opportunities.

IF NOT FOR A SERIES OF UNFORTUNATE EVENTS, WE might still look to *Innovation* as we now do to *IEEE Spectrum* or *Wired* for wide-ranging analysis of technological change.

But just nine months after the Long Island workshop, Colborn died of cancer at the age of 58. A year later, Morton arrived at a New Jersey bar after closing, where he encountered two would-be muggers. A fistfight ensued. Morton was beaten, put in his car, and set ablaze in a gruesome murder.

Compounding these tragedies, a post-Vietnam recession in the defense industry thwarted the company's expansion. The stagnation prompted a May 1972 theme issue of *Innovation* on "myopic research management," which hectored readers to take advantage of its multimedia tools. A month later, the magazine unceremoniously published its final issue.

The core themes of the Innovation Group, however, exploded in importance during the 1970s and 1980s, as the tectonic shifts of the post-Vietnam period became clear. What once felt like an edgy glimpse into the future now appeared as a self-evident reality, with all manner of experts seeking to prepare a technical workforce for "innovation ecosystems."

Former *Innovation* contributors had a hand in this proliferation. Its staff dispersed to technology publications and corporate public relations, and its advisory members remained prominent thought leaders. It also had numerous imitators, including corporate magazines like DuPont's *Innovation*, which highlighted the company's R&D projects, and books like Gene Bylinsky's *The Innovation Millionaires: How They Succeed* (1976), which offered colorful profiles of entrepreneurs, scientists, and venture capitalists.

To read a selection of articles from *Innovation* or to post comments, go to http://spectrum.ieee.org/innovation0215

IEEE Spectrum itself bears an imprint of the Innovation Group. The IEEE had created the magazine in 1963 to link its 150,000 diverse members. Six years later, *Innovation* poached *Spectrum* senior editor Nilo Lindgren. In addition to writing the previously mentioned profile of Engelbart, Lindgren wrote for the December 1969 issue "The Splintering of the Solid-State Electronics Industry," arguably one of the most influential articles ever published about Silicon Valley. After the start-up's demise, Lindgren returned to *Spectrum*, and *Innovation* editor Michael F. Wolff, who'd taken the helm after Colborn's death, joined as a contributing editor. The two helped shape the magazine's tone into the 1980s, among other things creating an "Innovation" article series that profiled entrepreneurs.

Though largely forgotten, Technology Communication created a remarkably robust vision of technoscientific life. *Innovation* chronicled with gusto how a select few could achieve astonishing levels of creative and financial success. These accounts were not just for aspiring innovators but also for readers in cubicles at IBM, research parks in Palo Alto, Manhattan consulting firms, and academic departments. The change manager's creed, which *Innovation* helped define and which is now accepted as an article of faith throughout our digital culture, is that risk and uncertainty are the necessary price of technology-aided growth. Such is the joy and the burden of the technology insider. ■

The Department of Electrical Engineering at the Petroleum Institute (PI) invites applications/nominations for the position of Department Chair, starting Fall semester 2015 or Spring semester 2016. The Chair of Electrical Engineering serves as the academic and administrative leader of the Department. Consideration will be given to only those who merit appointment at the rank of Full Professor and have a record of distinguished research and educational achievements.

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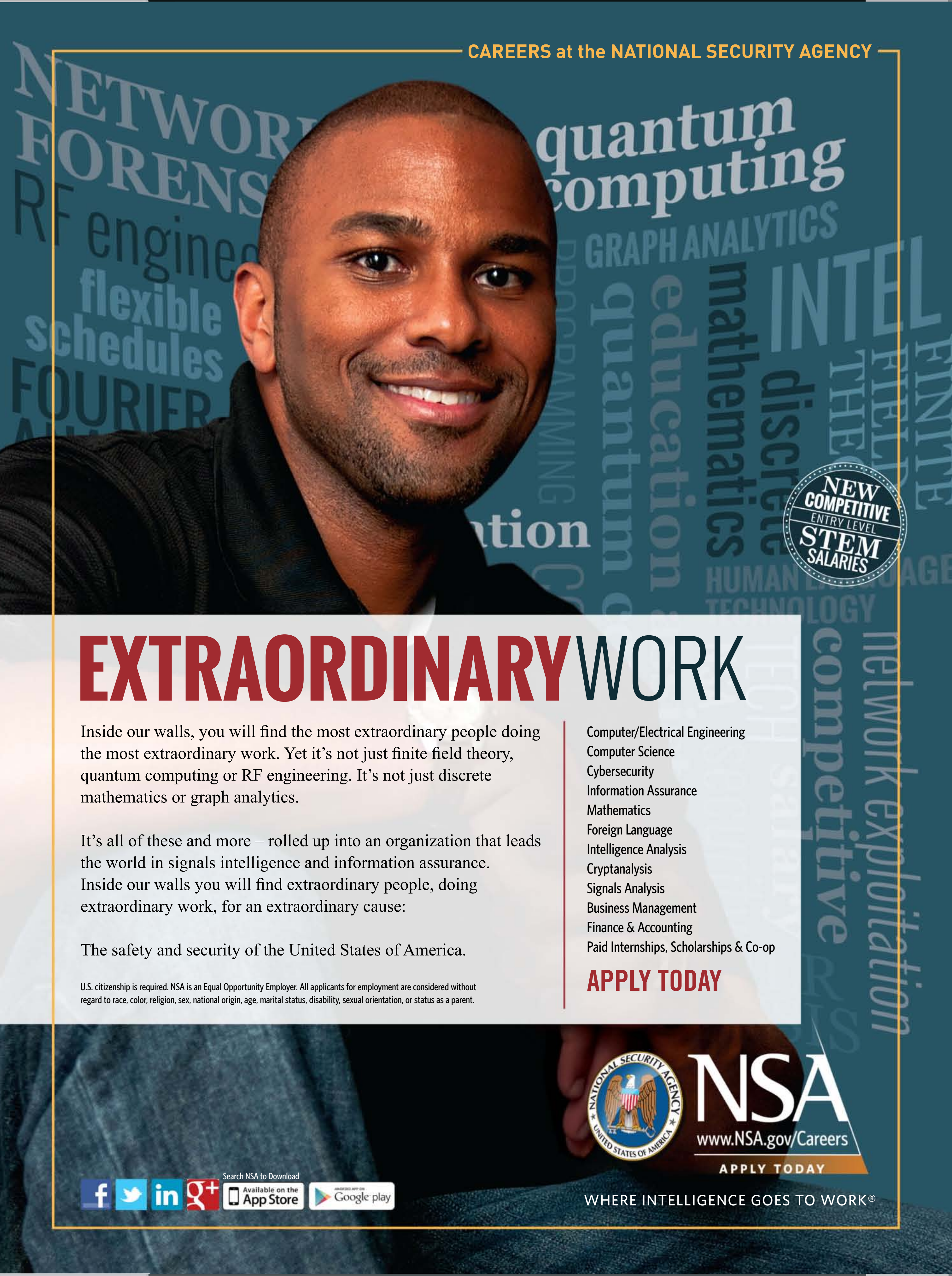
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Carnegie Mellon University
College of Engineering

Mechanical Design Engineer (Charlotte, NC): Lead the dvlpt and execution of subsystem design tools such as DVP&R, FMEA, & system specification. Execute projects & work with cross-functional teams while working with suppliers, procurement, electronics design group, laboratories, manufacturing divisions, & other engineering functions. Assist in the dvlpt of test & data acquisition plans to verify designs. Requirement: Master's degree or equiv in Mechanical Engineering or a rel field. 1 yr of exp in job offered or in rel occupation of Senior Engineer, Industrial Engineer, Graduate Engineer or a rel field. Exp in sheet metal part design required. Demonstrated capability to work across functional & technical boundaries to solve problems. Exp must include understanding of basic statistics & process capability & ability to understand interactions between systems & subsystems. Exp must include 3D CAD Design & drafting. Please email resumes to meghan.bottomley@electrolux.com.

LASSONDE SCHOOL OF ENGINEERING | YORK U UNIVERSITÉ UNIVERSITY

The Department of Electrical Engineering and Computer Science (EECS)

York University is seeking an outstanding candidate for an alternate-stream tenure-track position at the Assistant or Associate Lecturer level to teach relevant core areas of engineering and play a leading role in developing and assessing curriculum as a Graduate Attributes Coordinator. While outstanding candidates in all areas of EECS will be considered, we are especially interested in those with strong abilities to develop and teach courses in systems areas to complement the Department's existing strengths. Systems areas include, but are not limited to: computer architecture, operating systems, embedded systems and allied areas. Priority will be given to candidates licensed as Professional Engineers in Canada. Complete applications must be received by 15 March 2015. Full job description and application details are available at: **http://lassonde.yorku.ca/new-faculty/**. York University is an Affirmative Action (AA) employer and strongly values diversity, including gender and sexual diversity, within its community. The AA Program, which applies to Aboriginal people, visible minorities, people with disabilities, and women, can be found at **www.yorku.ca/acadjobs** or by calling the AA office at 416-736-5713. All qualified candidates are encouraged to apply; however, Canadian citizens and Permanent Residents will be given priority.

SDSU

South Dakota State University Department of Electrical Engineering and Computer Science Brookings, SD 57007 Assistant Professor of Electrical Engineering

Seeking applications for two 9-month renewable tenure track positions; open August 22, 2015. An earned Ph.D. in Electrical Engineering or a closely related field is required at start date. Successful candidates must have a strong commitment to academic and research excellence. Candidates should possess excellent and effective written, oral communication, and interpersonal skills. Primary responsibilities will be to teach in the various areas of electrical engineering and participate widely in the EE curriculum, and to conduct research in one or more of the following areas: image and signal processing, materials and devices, energy and power systems, or related areas. In addition to teaching in the identified research areas, preference will be given to those able to teach in one or more of the following areas: biomedical, computer, controls or communications engineering. To apply, visit **https://YourFuture.sdbor.edu**, search for posting number 0006848 and follow the electronic application process, which will require attachment of a cover letter, curriculum vitae, teaching statement, research statement, and reference page. For questions on the electronic employment process, contact SDSU Human Resources at (605) 688-4128. For questions on the position, contact Dr. Wei Sun, Search Chair, at (605) 688-4565 or **wei.sun@sdstate.edu**. SDSU is an AA/EEO employer. Women, minorities, veterans, and people with disabilities are encouraged to apply.

THE UNIVERSITY OF UTAH

Faculty Position in Experimental/ Theoretical Materials Research

The Colleges of Engineering and Science at the University of Utah invite applications for an open-rank tenure-track faculty position in the general areas of Plasmonics, Energy harvesting and/or Organic optics/electronics/spintronics. Candidates who have an exceptional track record in synthesis/fabrication, experimental studies, and/or modeling of functional materials are especially invited to apply. The tenure-track appointment is likely to be made at the junior level; however, candidates at higher rank will be considered. A doctoral degree in a relevant field is required. Details regarding the position and online application requirements can be found at **https://utah.peopleadmin.com/postings/38156**. Applications will be accepted until the position is filled.

The University of Utah is an Equal Opportunity/Affirmative Action employer and educator. Minorities, women, veterans, and persons with disabilities are strongly encouraged to apply. Veterans' preference is extended to qualified veterans. Reasonable disability accommodations will be provided with reasonable notice. For additional information about the University's commitment to equal opportunity and access, see: **http://www.utah.edu/nondiscrimination/**.

The University of Utah values candidates who have experience working in settings with students from diverse backgrounds, and possess a strong commitment to improving access to higher education for historically underrepresented students.

KU
DEPARTMENT OF ELECTRICAL ENGINEERING & COMPUTER SCIENCE
The University of Kansas
School of Engineering

The Department of Electrical Engineering & Computer Science (EECS) at the **University of Kansas (KU)** is seeking applicants for a non-tenure-track assistant professor, associate professor, or professor of practice in the areas of circuits, electronics, digital design and electrical energy conversion.

The successful candidate will be expected to prepare and present lectures for undergraduate courses as described in the approved course syllabi; hold office hours; design and supervise laboratories; projects; and exams as appropriate to the course and support student organizations; grade student laboratories, projects, and exams and/or supervise graders and teaching assistants; and assign or participate with other faculty members in assigning final grades. A full position description is available at **http://employment.ku.edu/academic/2371BR**.

The University of Kansas is focused on four key campus-wide strategic initiatives: (1) Sustaining the Planet, Powering the World; (2) Promoting Well-Being, Finding Cures; (3) Building Communities, Expanding Opportunities; and (4) Harnessing Information, Multiplying Knowledge. For more information, see **http://www.provost.ku.edu/planning/themes/**. Successful candidates should describe in their application materials how their work addresses one or more of KU's strategic initiatives.

Applications should be submitted at **http://employment.ku.edu/academic/2371BR** and include a letter of application, curriculum vitae, a two page statement on teaching philosophy, and contact information for three references.

Applications will be reviewed beginning **March 1, 2015** and will continue until the position is filled. Questions can be sent to: EECS_Search@eecs.ku.edu. KU is an EO/AAE. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex (including pregnancy), age, national origin, disability, genetic information or protected Veteran status.

Micron Technology, Inc. is seeking the following positions for its semiconductor R&D facility in Boise, ID; its manufacturing facility in Manassas, VA; its sales and design facilities in Folsom and Milpitas, CA; and design facility in Longmont, CO.

The following Micron subsidiaries are also seeking positions: Micron Semiconductor Products, Inc., at its headquarters in Boise, ID, and sales facilities in Meridian, ID; Folsom and Milpitas, CA; and its design facility Micron Technology Texas, LLC in Allen, TX:

> Electrical, Electronics, Communications, Chemical, Industrial, Mechanical, Materials, Computer System Analysts and Software Engineering; Physics, Materials Science, Engineering Manager and other related Engineering occupations. Marketing, Sales, Logisticians, Accounting and other related business positions.

Please submit your resume on the Web:
http://www.micron.com/jobs/search/

Resume and/or cover letter must reflect each requirement or it will be rejected. Upon hire, all applicants will be subject to drug testing/screening and background checks.

Note: some of these positions may require domestic and international travel for brief business purposes. Please read the full job description when applying online for such requirements.

EOE

1889 CLEMSON® UNIVERSITY

College of Engineering and Science Faculty Search

The Holcombe Department of Electrical and Computer Engineering at Clemson University is seeking applicants for multiple faculty positions at all ranks. The Department seeks applicants in technical areas associated with electronics (e.g., optoelectronics, lasers, semiconductor optical devices, integrated optics, fiber optics, microwave circuits, terahertz devices, lab-on-chip, microsystems, nanoscale devices, flexible electronics), intelligent systems (e.g., control systems, artificial intelligence, soft computing, robotics), and other areas of computer engineering (high-performance computing, computer vision, networking, cyber security, and software/data-enabled science). Outstanding candidates will also be considered for the Samuel Rhodes Professorship and the Warren Owens Assistant Professorship.

The Holcombe Department of Electrical and Computer Engineering is one of the largest and most active at Clemson, with 30 tenured/tenure-track faculty members, 570 undergraduates and 190 graduate students. Many members of the faculty are known internationally; they include seven IEEE Fellows, three endowed chairs, and eight named professors. Externally funded research expenditures exceeded $5.7 million in 2014. Clemson University is a land-grant institution committed to academic excellence, world-class research and a high quality of life. Six interdisciplinary colleges and schools house strong programs in architecture, engineering, science, agriculture, natural resources, business, social sciences, arts and humanities, health care, and education. A faculty of 1,500 and staff of 3,000 support over 80 undergraduate degree offerings, and more than 70 master's and 40 Ph.D. programs. An annual operating budget of approximately $1 billion and an endowment of more than $500 million fund programs and operations. Major new research, graduate education, and economic development activities are enhanced by public-private partnerships at three innovation campuses and six research and education centers located throughout South Carolina. Today, Clemson University is ranked 20th among national public universities by U.S. News & World Report, and remains true to its roots as a science- and engineering-oriented research university with a strong commitment to teaching and student success. Clemson University is described by students and faculty as an inclusive, student-centered community characterized by high academic standards, a culture of collaboration, school spirit, and a competitive drive to excel.

Applicants must have an earned doctorate in electrical engineering, computer engineering, or a closely related field. Applicants should submit a current curriculum vitae and a minimum of five references with full contact information. Electronic submissions (PDF files) to ecefacsearch@clemson.edu are preferred, but applications and nominations can also be mailed to ECE Faculty Search, 105 Riggs Hall, Clemson University, Clemson, SC 29634, USA. Application material must be received by **March 1, 2015** to receive guaranteed consideration, though the search will remain open until the position is filled.

Clemson University is an AA/EEO employer and does not discriminate against any person or group on the basis of age, color, disability, gender, pregnancy, national origin, race, religion, sexual orientation, veteran status or genetic information. Clemson University is building a culturally diverse faculty committed to working in a multicultural environment and encourages applications from minorities and women.

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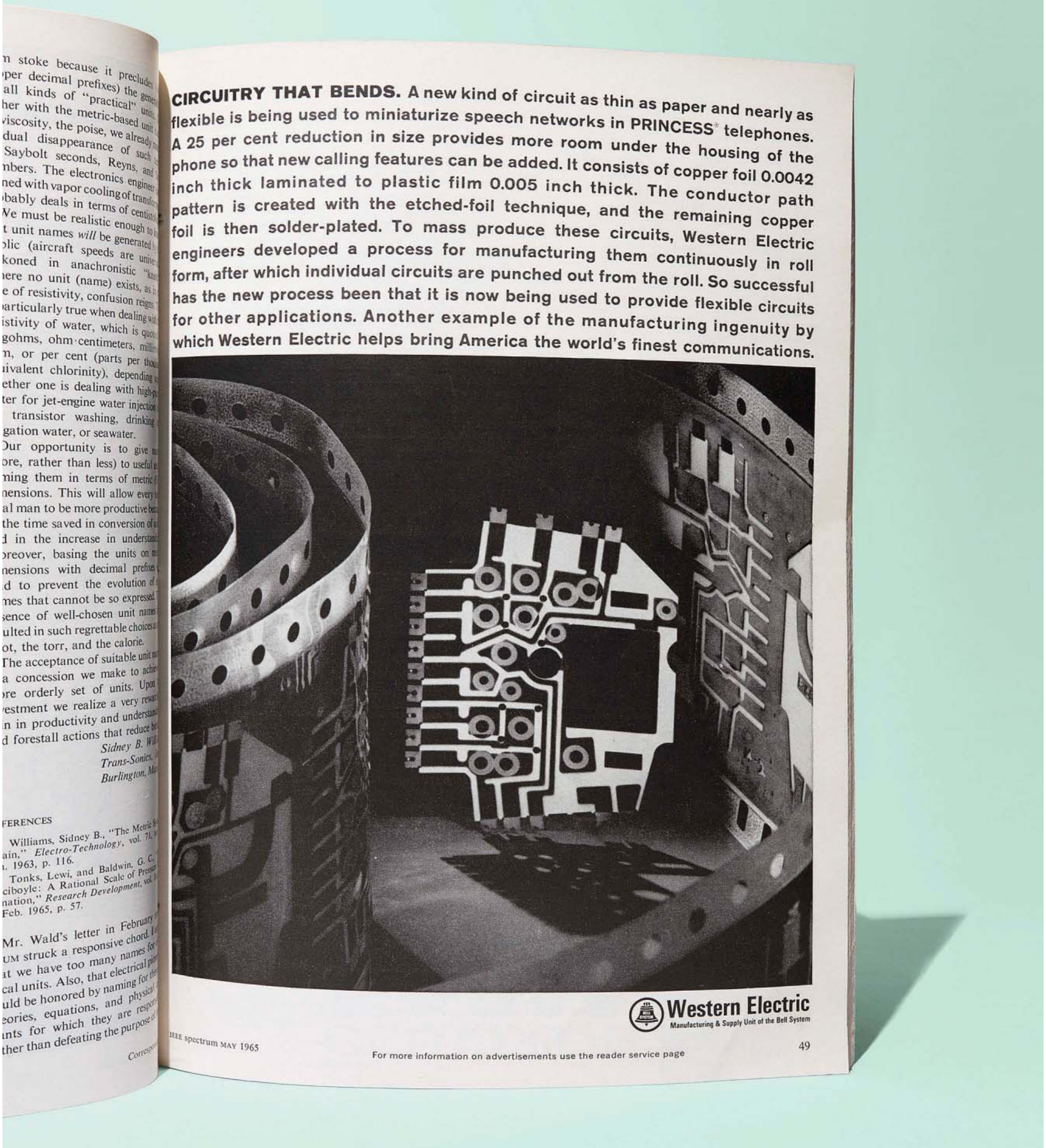
AND NOW THIS...

A FLEXIBLE APPROACH

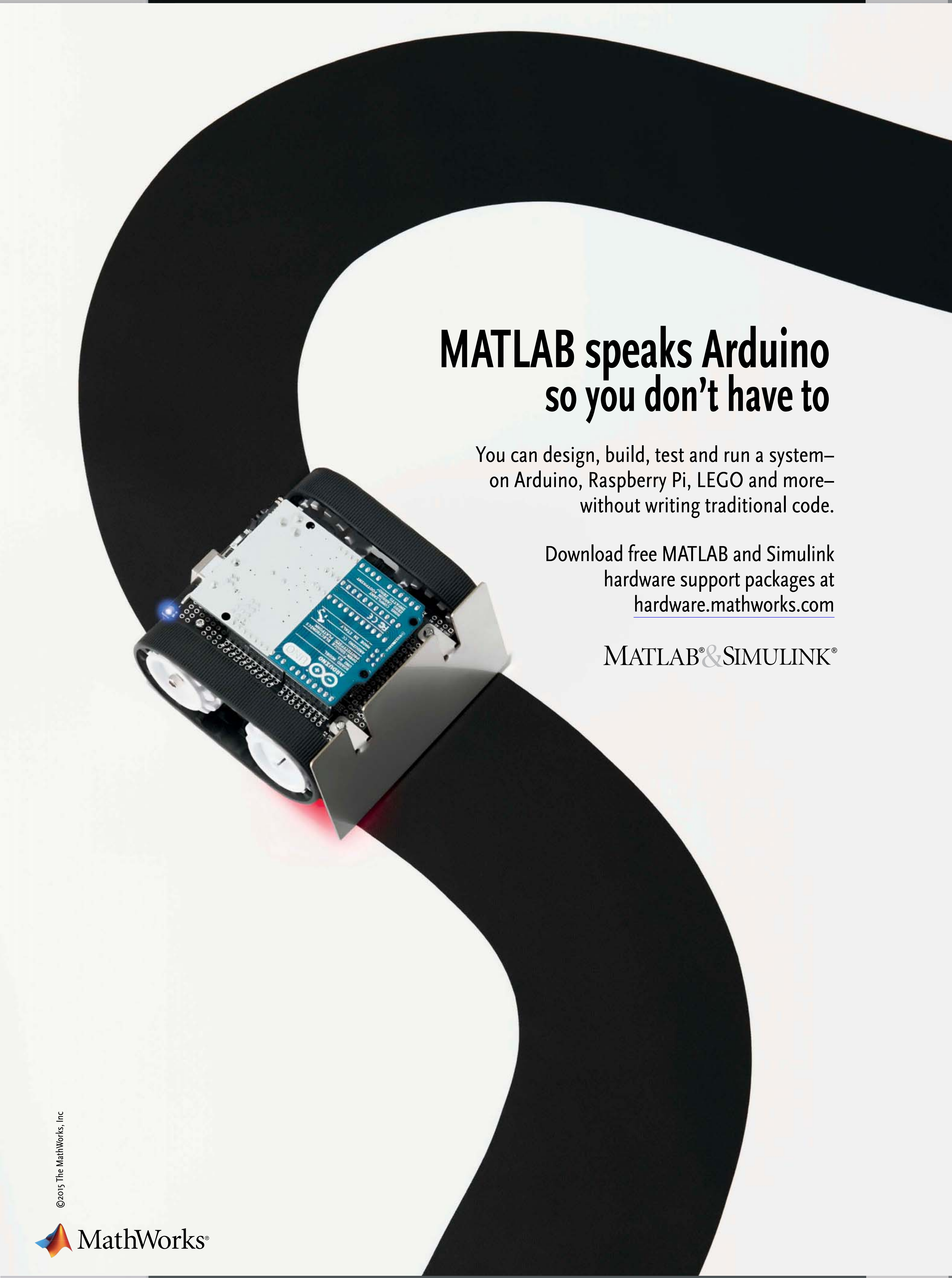
BENDABLE CIRCUITRY HAS A SURPRISINGLY LONG HISTORY

Electronic circuits that can bend and flex seem to bring out the science fiction writer in many a reporter (and indeed they've been used in numerous sci-fi movies and TV shows as a convenient way to underline the futuristic nature of a setting). Current excitement about the technology is centered on materials such as OLEDs and carbon nanotubes. But as this ad from May 1965 shows, the exciting future of flexible circuits is actually an old story. (Also worth noting is the reference to Princess telephones, which were first introduced in 1959 and sold until 1994. They are now considered a collectible design classic.) **—STEPHEN CASS**



PHOTOGRAPH BY Ben Alsop


Some things
don't make sense.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