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FOR THE TECHNOLOGY INSIDER | 03.15

ENGINEERING HEROES
SPECIAL REPORT

Pi in the Sky

EBEN UPTON'S CHEAP, TINY COMPUTER STARTED A REVOLUTION—AND IT JUST GOT A POWER SURGE **P. 38**

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On the Cover **Photograph for *IEEE Spectrum* by Dan Burn-Forti**

PHOTOGRAPH BY **Gabriela Hasbun**

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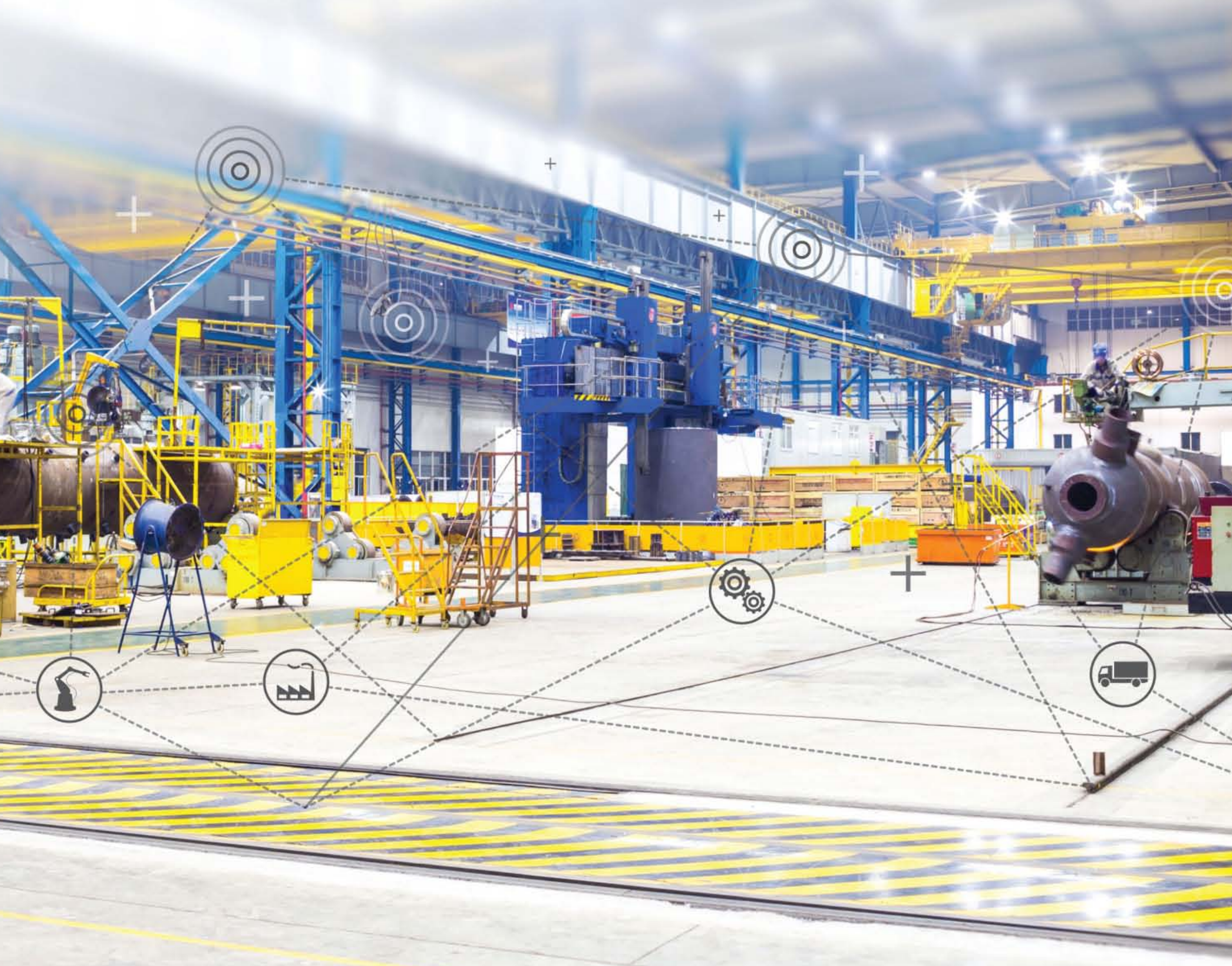

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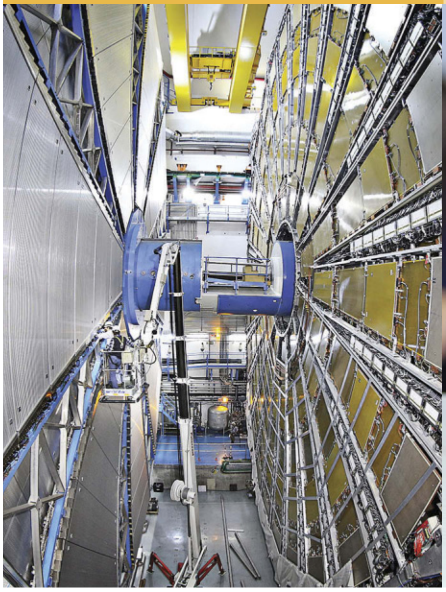

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THWARTING CYBERATTACKS The IEEE Cybersecurity Initiative is working on developing tools to help software engineers protect their systems from hackers. This issue also explores the development of secure mobile devices and apps and better training for those entering the cybersecurity field.

A HISTORY OF HACKING Incidents of hacking date back more than a century. They include hackers who disrupted a public demonstration of Marconi's wireless telegraphy machine and another who tampered with a Nazi computer to save the lives of Holocaust victims.

INTRODUCING THE 2015 FELLOWS *The Institute* congratulates 300 new IEEE Fellows this year. They join an elite group who have contributed to the advancement or application of engineering, science, and technology.

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FROM LEFT: CLAUDIA MARCELLONI DE OLIVEIRA; UNIFIED COMPUTER INTELLIGENCE CORP.; SANSTREAK CORP.

BACK STORY_

For Want of a Nail

FOR EVEN THE SIMPLEST STORY there are many things that can threaten a deadline. For *IEEE Spectrum*'s DIY and home-brew Hands On column, to that list must be added all the problems that can crop up in making electrons flow *just so*. Usually, these problems add zest to an article. But sometimes, it's just a cascade of failure.

In building the Membership Card–a kit that replicates the classic Cosmac Elf microcomputer–for this issue, it all began with a momentary lapse of concentration by Senior Editor Stephen Cass. He wired one component in backward. "It was classic Murphy's Law," says Cass. Then he damaged the traces on the printed circuit board while trying to extract the component.

But surely Lee Hart, the kit maker, could send replacement parts? Unfortunately, Hart was visiting family during the holiday season. But maybe his friend could FedEx parts from his unbuilt kit.... "The package arrived at my building on the Friday morning of the New Year's Day long weekend," Cass says. "In running down to the courier, I locked myself out of my apartment without my wallet. My wife was out of town. After 4 hours I got back in, only to discover I needed a part not in the package." Ultimately, he was able to salvage the last component from the damaged board and complete the kit–just hours before hopping on a plane to cover the 2015 Consumer Electronics Show. ■

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Elise Ackerman

In this issue, Ackerman, a freelance writer based in the San Francisco Bay Area, writes about Topher White, inventor of a cellphone-based system to thwart illegal logging [p. 44]. Her reporting included helping White and some volunteers disassemble donated Android phones. "My job was ripping out the speaker and vibrator with a pair of pliers," she says. The volunteers really believed in the cause, she notes. "They just wanted to do something hands-on to move the project forward."

Alan Grau

As a college student, Grau found and fixed a security flaw in his college's mainframe computer that was allowing unfettered access to the campus e-mail system. He's been focused on electronic security solutions, like those described in "Can You Trust Your Fridge?" [p. 48], ever since. The work has taken him from Motorola to AT&T Bell Laboratories to Digital Storage Technologies to his current position as president of Icon Labs, an embedded systems security company he cofounded in 1992.

Mark Harris

Contributing Editor Harris has written for *IEEE Spectrum* on a wide range of subjects: defibrillators, patents, computer gaming, Google's self-driving car. With his feature on the Harvard Forest project [p. 28], the British-born Seattleite adds environmental science, an interest he cultivated last year as a Knight Science Journalism Fellow at MIT. "Technology is giving a voice to organisms that have traditionally been mute," he says. "It creates a digital dialogue between us and the living world that feels very natural in the Internet age."

Neel V. Patel

Patel is an editorial fellow at *Wired* and a former *IEEE Spectrum* intern. In this issue, he profiles the electronic music maven known as Jerobeam Fenderson [p. 22] and the anticounterfeiting expert Brian Monks [p. 45]. The two men are very different, Patel says, "but both Fenderson and Monks share a technical mastery of their craft that keeps them innovating. It was fascinating to see such similar work ethics produce such diverse work in the end."

Mark Peplow

Peplow is a freelance science journalist based in Cambridge, England. In this issue, he profiles Eben Upton, creator of the low-cost, credit-card-size Raspberry Pi computer [p. 38]. Peplow's own coding skills peaked around 1987, when he wrote a program for the BBC Micro that tested the user's knowledge of the world's capitals. "Yet despite my dismal record with computers," he says, "Upton's infectious enthusiasm inspired me to buy a Raspberry Pi." Peplow's daughter is now patiently teaching him how to use it.

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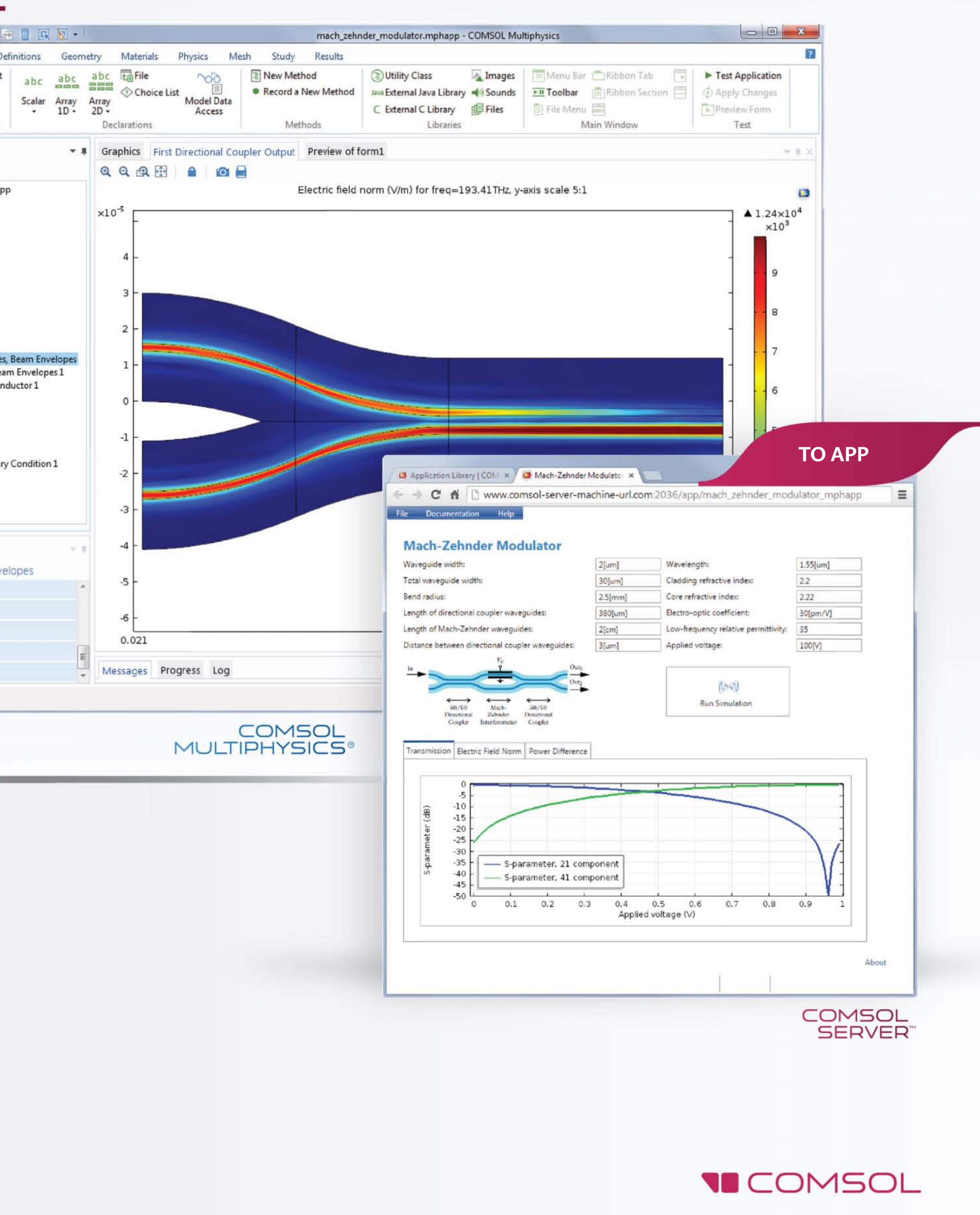
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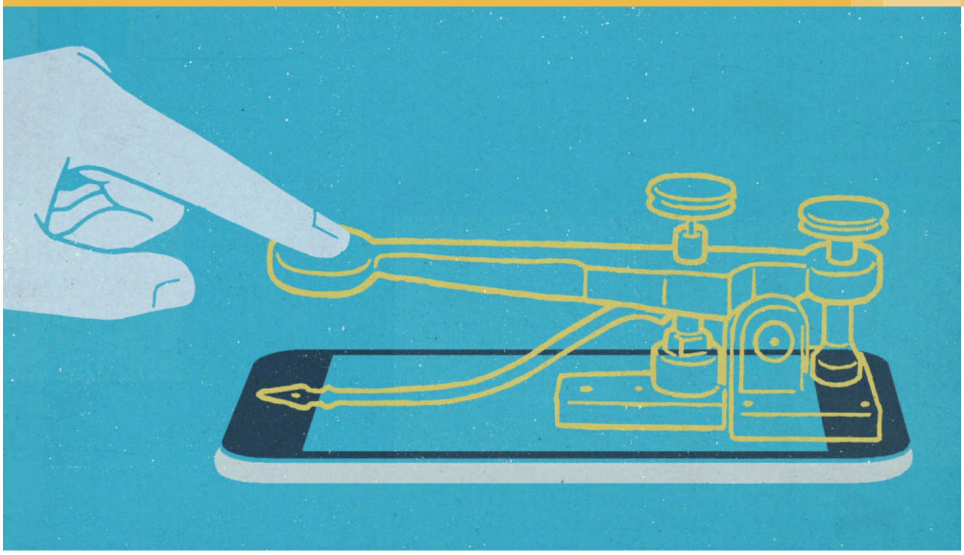


When the Past Is Not a Preview

Engineering historians teach the past to help make a better future

What is the history of engineering about?

A. The "eureka" moments of unusual men and women
B. Groups, tribes, and gangs of creative geeks
C. Robust, durable, and adaptive institutions
D. All of the above

Much time is spent on debating how best to approach the history of engineers and engineering. The stakes are high: Those who define the story of the past inevitably influence the present and the future. Yet telling the story of bygone engineers is difficult because the answer to the above question often says more about who gives the quiz than who takes it.

My choice of D, or all of the above, affirms the complexity of engineering as an activity and a historical force. Edison, Tesla, Turing, and Jobs understandably dominate chronicles of engineering movements, but seminal figures thrive as part of technical networks or teams. These teams, in turn, depend on government, universities, corporations, financiers–organizations and institutions embedded in particular societies at specific times. By following these various threads, the fuller tapestry (D) emerges.

Or nearly so. Engineering has also incubated new social history, arising from how people adopt, shape, and hack the stuff made by engineers. Histories as varied as those about the telephone and the pencil, the automobile and the computer, electricity and fertilizer, also reveal much about how and why we use the fruits of an engineer's toil.

The emphasis on process over person helps explain why today's engineering heroes, like those profiled in this issue, tend to go unsung. Deciding whom to elevate among the many socially committed engineers is trickier than identifying the historical significance of, say, the "open source" or "miniaturization" movement in engineering. Without question, Manuela Veloso's robots and Eben Upton's $35 Raspberry Pi computers have transformed their respective fields. Are they making history? It's too soon to say.

New engineering histories such as Andrew Russell's *Open Standards in the Digital Age* illustrate how collective battles over standards can trump individual achievements. Says Russell, a professor at the Stevens Institute of Technology, in Hoboken, N.J., "The kinds of stories we tell about standards matter more," because standards set the rules of the game for individual engineers and provide valuable context for both engineers and consumers.

The prosaic quality of standards wars creates another challenge for historians. To engineers and their financial backers, the most important battles are over the future, not the past. Reputations and fortunes largely rise and fall based on who defines future artifacts and standards. The engineer as "tomorrow maker" remains the ultimate metric of achievement. Historical amnesia would hardly seem to imperil an engineer's career.

Yet the siren song of the future need not blind engineers to lessons of history that are vital to making sound decisions today. Patent disputes often turn on historical readings. Studies of past mistakes such as the space shuttle *Challenger* explosion, for instance, teach us much about how to prevent inevitable human errors from causing catastrophes.

Accounts of movements can also capture the imagination. In Henry Petroski's magisterial account of the design of pencils, the names of individuals can be forgotten, but the "world pencil war" of the 1890s, ignited by German dominance and American fears of dependence on foreign pencils, cannot be.

Studying the past in order to improve the future is reasonable. But to do so risks reducing the past to mere rehearsal. It is not. Historians revel in understanding the past for its own sake. Engineers need not apologize for doing the same.

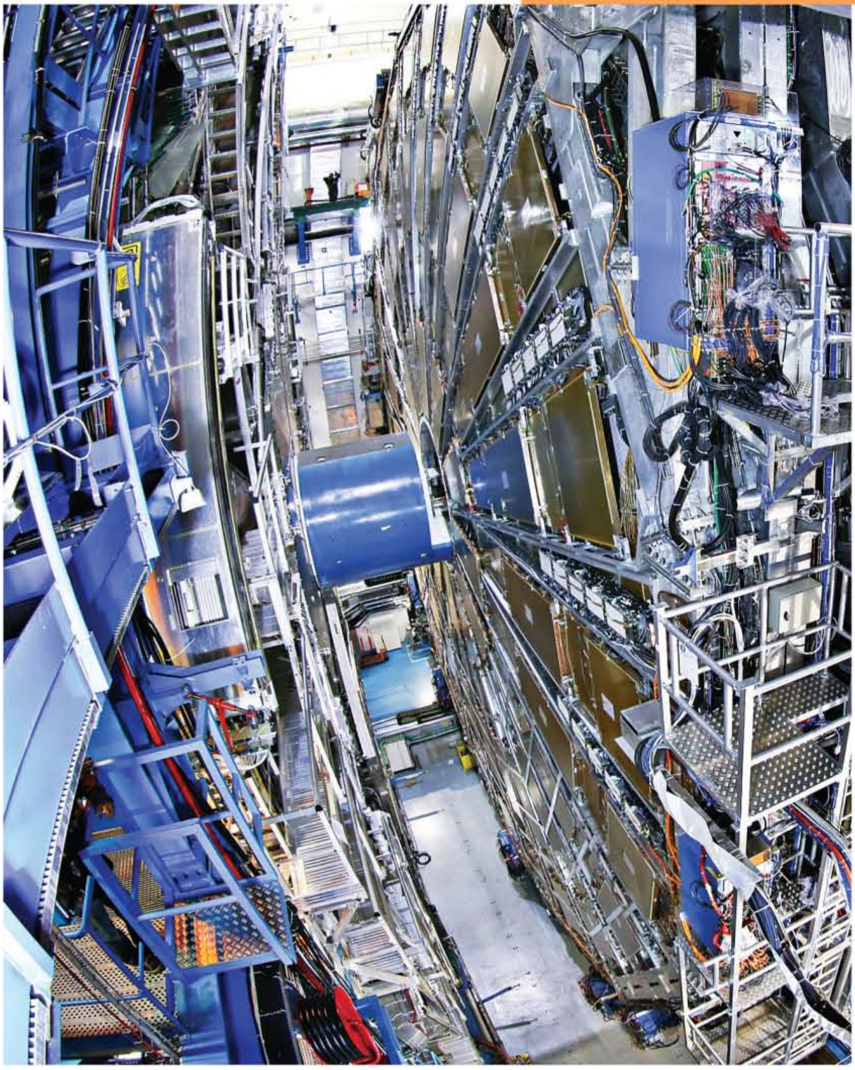
—G. PASCAL ZACHARY

G. Pascal Zachary is the author of *Endless Frontier: Vannevar Bush, Engineer of the American Century* (MIT Press, 1999).

CORRECTION: In a photo caption for "The Birth of Innovation" [February], we incorrectly identified the magazine's founding editor as Richard Colborn. His name was Robert Colborn.

ILLUSTRATION BY Dan Page

NEWS



CLAUDIA MARCELLONI DE OLIVEIRA

TAKING THE LARGE HADRON COLLIDER TO THE MAX

Four fixes that will double the power of the world's greatest physics machine

Later this spring, scientists at CERN, the European Organization for Nuclear Research, will restart the world's biggest particle physics experiment, after a hiatus of two years. Beams of protons are scheduled to start circulating through the Large Hadron Collider (LHC) in mid-March. Physicists hope to start smashing the protons together and recording data before midyear.

When it restarts, the LHC will be able to smash protons with nearly twice the energy it had before. Even at its previous power level researchers were able to use the LHC to find the Higgs boson. This particle–whose existence was predicted decades ago–explains why some particles have mass. But scientists hope that the higher-energy collisions will reveal some new (if more difficult to explain) discoveries, such as the elusive supersymmetric particles or even possible candidates for dark matter, the mysterious material that binds the universe together.

The LHC got off to an inauspicious start, and that bad begin-

SLEEP NO MORE: The Atlas experiment, dormant for two years, will rumble back to life following several upgrades.

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BACK WHERE IT BELONGS: A muon chamber is slotted into place in preparation for the restart of the Large Hadron Collider.

CLAUDIA MARCELLONI DE OLIVEIRA

ning explains some upgrades. In September 2008 during a final commissioning phase—and before the accelerator reached its planned maximum energy of 14 teraelectron volts—one of the more than 10,000 interconnections for wires supplying power to the superconducting magnets of the LHC failed, causing an arc that melted through a helium line and damaged a several-hundred-meter stretch of the system. After a year of repairs, the LHC started up and eventually reached a reduced collision energy of 7 TeV.

The upgrade being finished now is to reach 13 TeV. And it was clear from the beginning that it would require a complete overhaul of the interconnections. So CERN management decided to shut down the accelerator for a two-year period, starting in early 2013. This allowed the LHC engineering teams to update and upgrade several other systems, including the data gathering and storage technology and the cryogenics, which keep the system's superconducting magnets at a crisp 1.9 kelvins. Also, the Atlas detector—one of four enormous machines in which the actual particle collisions take place—was equipped with an extra layer of particle detectors, increasing its precision substantially.

—ALEXANDER HELLEMANS

TOUGHER INTERCONNECTIONS

A team of about 280 technicians undertook the checking and reinforcing of more than 10,000 interconnections that connect the Large Hadron Collider's superconducting wires. These cables, which have a trapezoidal cross section, are overlapped for several centimeters, pressed tightly together, and held in place with a silver-based solder. At full operation, the splices can carry a current of 13 kiloamperes, and the slightest fault would cause the junction to heat and fail.

The revision of the connections has now been completed, reports Jean-Philippe Tock, who leads the project. All junctions have been tested at room temperature. Those displaying anomalies were resoldered. All junctions have also been equipped with copper shunts, which can take over in case of failure, he says. The system that keeps watch on the new junctions has also been upgraded to provide better accuracy and resolution. "We have many more measuring points," says Tock. For example, voltage surges that occur over groups of connections, which normally have a resistance of less than 3 nano-ohms, will automatically shut down the accelerator. "We have not invented new technology; we have applied existing technology to a very high level of quality and quality assurance to an unprecedented level," he says.

SAFER COOLING

When an electrical interconnection between two helium-cooled magnets failed in 2008—knocking askew accelerator magnets and damaging about half a kilometer of the 27-kilometer machine in a flood of coolant—the system lost a much larger quantity of helium than was expected.

"In response to this incident, we increased the number of safety valves on our vacuum systems, so that we do not get this avalanche of helium pressure that caused the displacement of magnets," says Laurent Jean Tavian, leader of the cryogenic group at CERN's technology department.

BIGGER DATA

"The data acquisition and storage system has been overdesigned from the beginning. We would have needed much more data than anticipated to run into problems," says Niko Neufeld, who is responsible for the upgrade of high-speed data acquisition for LHCb. (LHCb is short for the LHC Beauty Experiment, which seeks to detect b [beauty] quarks and anti-b quarks; a difference in their decay rates would explain the matter-antimatter asymmetry in the universe.) Nevertheless, he and his colleagues have been upgrading data systems by replacing obsolete hardware with more efficient and compact modern systems. In the past CERN has developed and pioneered new hardware itself–the CAMAC (computer automated measurement and control) industrial data-acquisition standard and capacitive touch screens are examples. Although CERN now makes fewer custom systems, Neufeld says there is a need for specialized high-speed, radiation-hardened electronics that can operate in strong magnetic fields. And a bigger upgrade is in the works. For experiments scheduled to start in 2019, the data flow is expected to increase by two orders of magnitude. "This will require a significant change, and new technologies will have to be put in," says Neufeld.

SUPERIOR SENSORS

The Atlas detector is one of four placed around the few points where the counterrotating protons collide head-on. Benjamino Di Girolamo, the technical coordinator of the Atlas experiment, says that workers had to replace a layer of detectors, or "pixels," that were close to the beam pipe because of radiation damage. However, such a replacement proved impossible because of structural constraints in the detector, so they decided to build an insert, called the IBL (insertable B layer) that would fit between the beam pipe and the innermost layer of the detector assembly. The IBL was then able to take advantage of better radiation-hardened detector pixels, which were developed by a research program at CERN. But the most important aspect of the IBL is that it improves the precision of Atlas. "Having a layer at the beginning of a [particle] track is very important to us. If you have high precision very near the start of the track, then you can even relax the precision you need in the outer layers [of the detector assembly]," says Di Girolamo.

He reports that the insertion of the IBL, which was a very delicate operation, was successful. "The IBL, for its operation, has been cooled down and is now fully working," he says.

AIs vs. Poker

Making computers unbeatable at Texas Hold 'em could lead to big breakthroughs in artificial intelligence

Life is not a game. But there are similarities. That's why it's worthwhile to invent artificial-intelligence algorithms that can win games. One such AI has now finally solved one of the simplest versions of poker. It's a crucial first step on a potentially long road toward beating human poker champions in more complex versions of the games. This isn't just about bragging rights: Poker playing can train computer algorithms to tackle the complexities of real-world challenges in security and medicine, where the available information is rarely perfect or complete.

The many possibilities for deception in poker means there are a huge number of possible plays, even in a limited version with just two players. Computers have solved simpler games such as Connect Four and checkers by figuring out the perfect, unbeatable strategy for each move starting from the beginning of each game. But analyzing all the possible plays in even the simplest poker game is a far greater challenge because each player has hidden cards–information hidden from the opponent. In that sense, poker is an "imperfect-information game," similar to real-world scenarios with various degrees of uncertainty.

"The solutions for imperfect-information games require computers to handle the additional complication of not knowing exactly what the game's state is, such as not knowing an opponent's hand," says Neil Burch, a computer scientist at the University of Alberta, in Edmonton, Canada. "Such techniques require more computer memory and computing power."

Burch and his colleagues laid out their algorithm's solution to "heads-up limit" Texas Hold 'em in the journal *Science* in January. In AI parlance, it's only a "weak" solution to a specific version of poker. The game has just two players, fixed bet amounts, and a fixed »

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number of bet raises. But the software is still good enough to make it virtually impossible—from a statistical significance standpoint—to distinguish the algorithm's solution from perfect play during a lifetime of poker games.

The algorithm, named CFR+ by its creators, uses an improved version of a technique called counterfactual regret minimization (CFR). Regret-minimization algorithms are easiest to understand for a single-step game, such as rock-paper-scissors. They compare the outcome of a game, say, how much money you lost, with the outcome of the best possible choice. The difference is the regret value. The algorithm then comes up with a strategy—expressed as the probability that you'll make a certain move—for the next time you play that minimizes the total regret for all the times you've ever played. Counterfactual regret minimization extends the process to work for games like poker where there are many steps between the start and finish of the game. And CFR+ boosts the efficiency of the process by taking fewer and bigger steps toward the best solution.

Past CFR algorithms never tried solving the full game of heads-up limit Texas Hold 'em because of the huge amount of memory required—roughly 262 terabytes. But CFR+, helped along by some memory compression techniques, was efficient enough to solve the full game.

The next big challenge is trying to solve heads-up no-limit Texas Hold 'em, a more complex version that allows unrestricted bet sizes. Algorithms must consider many more information sets that each represent the possible moves made by opponents at each stage of the game. The difference in the number of information sets is huge—about 147 orders of magnitude. For that reason, researchers cannot hope for an algorithm that can sort through every single possible play. Instead, they fall back on using "abstractions"—simplified representations of the full game.

A Carnegie Mellon University group led by Tuomas Sandholm has developed a computer program capable of handling an abstract version of no-limit Texas Hold 'em that is six times as large as any previous abstraction of the poker game. In fact, it may be the largest imperfect-information game ever attempted by a computer.

Carnegie Mellon's abstraction algorithm works by breaking the abstract game into smaller pieces and spreading them across different blade servers in the Blacklight supercomputer at the Pittsburgh Supercomputing Center—a 37-teraflops machine. One "parent" part of the abstraction exchanges information with the smaller pieces on other servers. That allows the team to create a much larger abstraction than if it was all located on one server. It's also about three times as fast as spreading the abstraction across many servers that must all communicate with one another.

Once the CFR algorithm analyzes the abstract game and develops a poker-playing strategy, a reverse-mapping algorithm is needed to apply that strategy back to the full version of no-limit Texas Hold 'em. Sandholm's group developed such an algorithm—called pseudo-harmonic mapping—which can reduce the possibility of exploits by opponents who take an action that is not covered by the abstraction.

The Sandholm group's AI showed its worth in 2014 by beating the best rival poker-playing programs. It's not a solution for no-limit Texas Hold 'em, but it's still useful. "The algorithms we developed are not for solving poker; they're for solving imperfect-information games in general," Sandholm says. "Poker is a benchmark where we can test progress from year to year." —JEREMY HSU

> The Sandholm group's AI showed its worth by beating the best rival poker-playing programs, at a competition in 2014.

MICROGRIDS FOR A POST-FUKUSHIMA JAPAN

Three projects use diverse energy sources to supply power during disasters

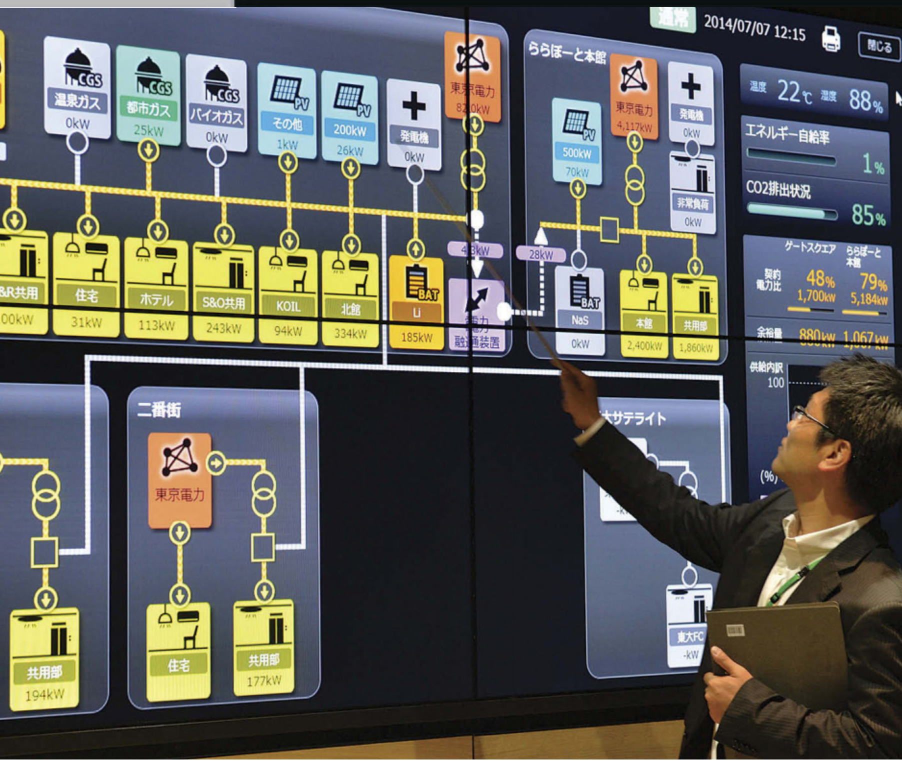
Before the Fukushima earthquake and tsunami four years ago this month, Toyota's automotive plant in Miyagi Prefecture, north of Fukushima, had relied entirely on the Tohoku Electric Power Co. for energy. But when the disaster shut down power to its plant for two weeks, managers realized that the company needed a more secure source. The factory couldn't be independent of the electric grid, but it could manage that energy better—and supplement it.

"The earthquake was a big turning point," says Atsuji Morita, a project manager for Toyota. "We had this big blackout and realized we needed a new system to increase our energy security."

That's a common theme in Japan these days. After the disaster knocked out power to much of eastern Japan, smart microgrid projects from industrial to residential changed their approach. Initially focused primarily on energy efficiency, projects have shifted the emphasis to generating energy where it is consumed and to having a diversity of power sources.

In February 2013, Toyota formed a limited liability partnership called the Factory Grid, or F-Grid, to create a smart grid that manages and provides supplemental power to seven factories (most of them owned by Toyota) within the industrial park.

F-Grid has built its own natural-gas-fired cogeneration plant, which produces 7,800 kilowatts. That plant is supplemented by 740 kW from solar panels. And, in a creative twist, the factory uses an array of old Prius batteries capable of adding 90 kW of power from energy stored during slow periods at the industrial park. In an outage, even if all other



MULTIPLE INPUT, MULTIPLE OUTPUT: The Kashiwanoha smart-city project uses energy from electric-vehicle batteries, biogas, storage batteries, solar panels, and the grid.

YOSHIKAZU TSUNO/AFP/GETTY IMAGES

power sources fail, the Prius batteries can supply enough power to keep satellite phones and computers running for three to four days.

The microgrid is operated by a community energy management system, which polls each facility about power needs and manages distribution of energy among them. In the event of an outage, F-Grid plans to also supply power to the local disaster response center, located in a village about a kilometer away.

The need for power diversity is reflected in small, residential projects as well. Honda, for example, is developing a smart-home system in cooperation with Toshiba and the biggest home builder in Japan, Sekisui House. Honda has so far built two demonstration homes in Saitama, a part of the metropolitan Tokyo area. Although plans for the project had already been in the making, after the earthquake the project developers' focus shifted to providing energy security during emergencies. "That is the new meaning of 'smart' in Japan," says Naohiro Maeda, a manager in Honda's Smart Community Planning Office. "Our goal is to produce the energy on-site that we need to consume on-site."

Each home's energy system consists of rooftop solar panels, a gas cogeneration unit, a home battery unit, a hot water tank, an electric car (a Honda Fit), and an energy management system called Smart-e Mix Manager. The home battery stores energy for times when solar power is not available. Ninety percent of Japanese households use both gas and electricity, and after the 2011 disaster, natural gas came back on in many areas sooner than the electricity, according to Maeda. The cogeneration system produces electricity to power homes and heat water. That's important, because 60 percent of household energy use in Japan is for heating, and half of that is specifically for heating water for baths and cooking, says Maeda. Daily bathing is so important in Japanese culture that the Japanese army made it a priority to set up a communal bath for evacuees after the 2011 disaster, he says.

The shift to emergency energy also happened in a smart-city project, called Kashiwanoha, on the outskirts of Tokyo. The project is backed by the real estate developer Mitsui Fudosan, Hitachi, and Sharp, in cooperation with local government, the University of Tokyo, and Chiba University. This smart city has been in development for several years as a retail and business area. Last summer, the project started offering apartments and condos.

Kashiwanoha uses a wide variety of power sources, although it still draws most of its power–some 90 percent–from the electricity grid. The high-rise apartment buildings take advantage of natural hot springs beneath them to create a communal bathing area on the third floor. Water for the residences is heated using biogas generated from food waste. The town uses a bank of Hitachi lithium-ion batteries that can store up to 3,800 kilowatt-hours' worth of energy, collected from the solar panels that are distributed on rooftops throughout the city and purchased from the grid at night, when rates are cheaper. There are a few small-scale wind turbines scattered throughout the development as well.

The facility has a gas cogeneration engine to provide power and heat in emergencies, and it keeps a supply of oil on hand in case the gas supply is interrupted, says Kiyoko Hama, a representative from Mitsui Fudosan and a member of the Kashiwanoha urban planning and development department. Communal electric vehicles can also be used to store electricity. All told, in an emergency there would be enough auxiliary energy to meet 60 percent of normal residential power requirements for three days.

The city optimizes energy use through an energy management system. Residents can monitor energy use through an app on their tablets or phones. The development even encourages residents, like 56-year-old Ryoji Iwasawa, to reduce usage by rewarding them with points they can use to shop at the mall across the street. It's not like they need that much of a push to cut down on their usage, however. "We've all become more cognizant of our energy use since Fukushima," says Iwasawa. –TAM HARBERT

GOOGLE GLASS IS DEAD, BUT AUGMENTED REALITY LIVES ON

Industrial and enterprise apps are the near-term future of AR

It seemed like the nascent augmented-reality industry was on a roller coaster at the start of the year. Things looked bad when Google announced that it was terminating sales of its Glass headset in favor of developing some new version to be announced at some time in the future. (Possibly in a galaxy far, far away.) But then the future looked bright again when Microsoft unveiled its HoloLens AR headset at a razzle-dazzle press event in late January.

But the truth is that well before the debut of HoloLens, the AR ecosystem had been moving away from Google's model of always-available wearable computing and toward the idea that AR headsets should be—at least for now—something you use only for specific tasks. At the Consumer Electronics Show (CES) in Las Vegas just after New Year's, most of the capabilities advertised a few weeks later by Microsoft for its HoloLens prototypes were already on display on the show floor (albeit spread among several exhibitors), and they were mostly doing industrial and enterprise work.

One example was a US $5,000 industrial headset from San Francisco-based Osterhaut Design Group. Unlike Glass, whose single display is tucked away at the far side of the frame, occupying a small corner of the wearer's field of view, ODG's binocular system delivers graphics front and center. Flipping down a sunglasses-like visor blocks the wearer's view of the outside world and converts the headset from augmented reality to virtual reality. (A $1,000 consumer version is planned for release later this year.)

Similarly, Epson was showing its Moverio BT-200 smart glasses. Most important, Epson didn't bring just the glasses; it also brought third-party developers with examples of AR applications. While some developers were showing

game and entertainment software, the most impressive demos were aimed firmly at enterprise and government users.

A Moverio demo by Herndon, Va.-based APX Labs featured Skylight, a system for field workers. When I tried it, arrows popped up on my view of the conference to indicate the direction of distant wind turbines. When I looked in that direction, I could call up data on the turbine's performance and even see video of it.

Augmenta, headquartered in Oulu, Finland, eliminated the need for voice commands—always tricky in noisy work environments—with a system that can recognize hand gestures. I used it to play rock-paper-scissors, but ultimately the technology should allow a wearer to see a keyboard or industrial controls overlaid on the palm of one hand and "press" them using a finger from the other hand.

At the Moverio demo by Ngrain, of Vancouver, Canada, a scale model of an electric generator sat on the table. Once I put on the glasses, I could look at the model and highlight a particular part, causing a 3-D representation of that piece, overlaid on the generator, to pop up. The 3-D models tracked the changing perspective as I turned and moved my head, albeit with some jitter in the image.

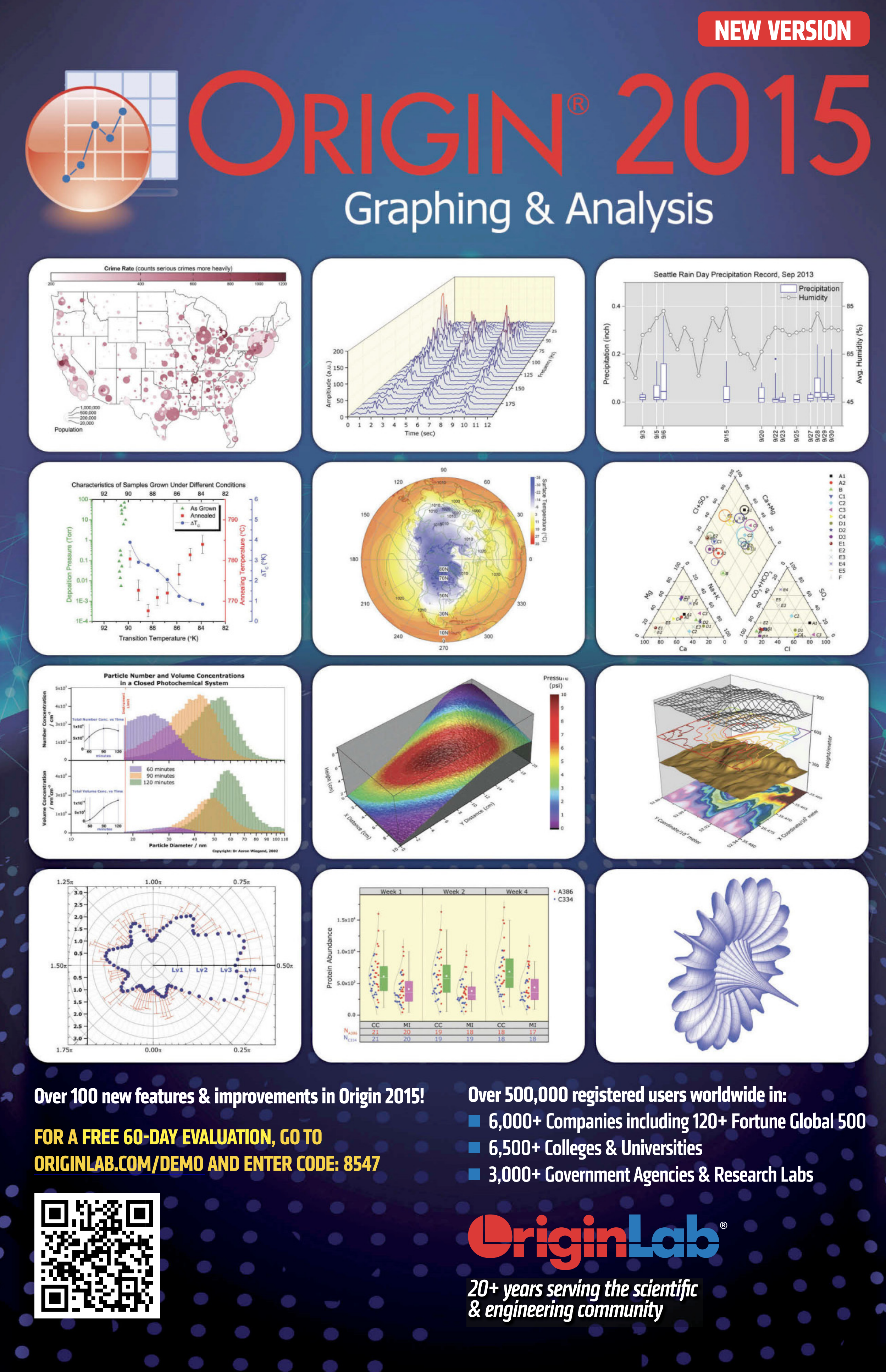
Finally, I used the Moverio glasses to look at a pump mechanism using an app made by Scope AR, based in Edmonton, Alberta. Looking at the pump through the Moverio glasses allowed me to watch a series of instructions for performing maintenance, with virtual tools such as a wrench overlaid on the areas where they would be used on the real pump, plus an animation of the required motion.

And even though HoloLens is targeted firmly at the consumer, Microsoft's presentation emphasized its usefulness for physical tasks. Like the AR instruments at CES, the HoloLens makes no attempt to emulate Google Glass's minimal intrusion into the wearer's field of view: The headset looks like a pair of ski goggles. The system can track eye movements, listen to voice commands, and follow hand gestures much as a Microsoft Kinect does. (Alex Kipman at Microsoft developed both the Kinect and the HoloLens.)

At its press event, Microsoft put users into an immersive version of the popular *Minecraft* world-building game, but it also showed several equipment maintenance and installation demos similar to those seen at CES. Even the use of hand-gesture interfaces wasn't new. OVSR also demoed it at CES, combining its Razer headset with a gesture-detection sensor from Leap Motion.

We may yet see headsets displace the smartphone as the universal portable networked computer du jour, but it looks like we'll first be taking a detour through living-room entertainment and factory-floor maintenance. —STEPHEN CASS *with* CHARLES Q. CHOI

PHOTO-ILLUSTRATION: RANDI KLETT; PHOTOS: GETTY IMAGES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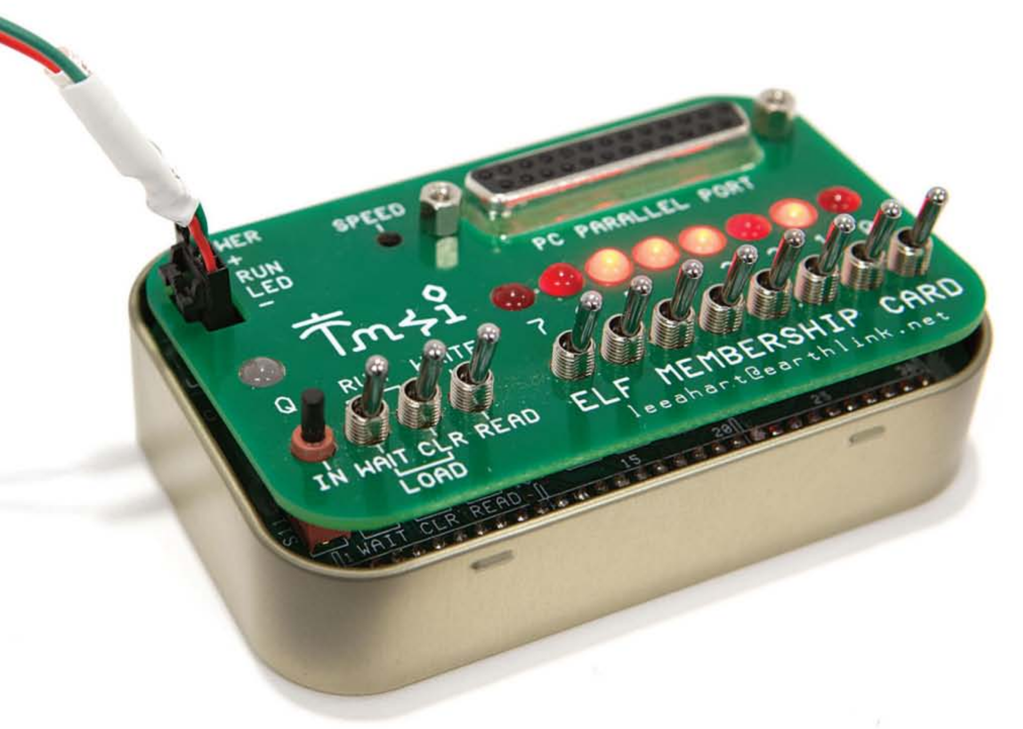
SOLAR SCOOTER

WHEN YOU THINK OF the centers of futuristic automotive design, Afghanistan probably doesn't come to mind. But motorcycle mechanic Mustafa Muhammadi designed and built this enclosed two-seater motorbike in about six weeks, using car tires and motorcycle parts. He showed off his handiwork—which he says cost 90,000 afghanis (roughly US $1,600) to get on the road—in Kabul in December. What sets the three-wheeler apart is that it's all electric. A solar panel on its roof supplements the energy in the plug-in vehicle's batteries, extending its range to 40 kilometers on a single charge. And just in case the trike does run out of juice, Muhammadi included pedals so that it can run on human power until it reaches a charging station.

RESOURCES

THE GALILEO SPACE PROBE TO JUPITER, LAUNCHED IN 1989, WAS CONTROLLED BY CDP1802 PROCESSORS.



YOU CAN'T KEEP A GOOD ELF DOWN

A MODERN VERSION OF A 1976 MICROCOMPUTER HAS SURPRISING POTENTIAL

RESOURCES_HANDS ON

Regular readers of this column may have noticed that I have a fondness for new takes on old technologies. So you won't be surprised that when I came across Lee Hart's Membership Card kit, I leapt at the chance to build it. The Membership Card is a modern version of the 1976 Cosmac Elf. The Elf was an influential early microcomputer built around RCA's CDP1802 processor. What may be more surprising is that the Membership Card might be just the ticket for modern makers looking to build microcontroller-based devices that can run for a year on a few AA batteries. ● The original Elf dates from the heroic age of personal micros, a time before QWERTY keyboards and bitmapped displays became standard and made us all soft. Input was via a set of toggle switches, hand-setting each bit in a byte. You wrote programs in pure machine code. You read the output via a two-digit LED display capable of showing one hexadecimal digit apiece, plus one additional so-called Q LED. The Membership Card is even more severe on the output front than the original: "Numeric" output is via a row of eight LEDs that display a byte in binary. You can't get closer to raw computation without an erasable marker and a really long piece of tape. ● The Q LED is tied to one of the unusual features of the 1802 processor, and these features help explain how the Elf and its descendants maintained their popularity well into the 1980s and still find some uses today, particularly in aerospace. The Q LED is directly connected to a processor pin that can be turned on or off with a single instruction. The ease of hooking up external circuitry to this Q pin, and the relative ease of writing software to control it, meant that the pin was used to communicate with all kinds ▸

PHOTOGRAPH BY Randi Klett

of external devices, such as serial interfaces or loudspeakers. Connecting the Q output to a speaker and turning it on and off at the right frequencies generates musical tones. So the Elf was popular among synthesized music pioneers, as demonstrated by the Elf's prominence at the First Philadelphia Computer Music Festival, in 1979.

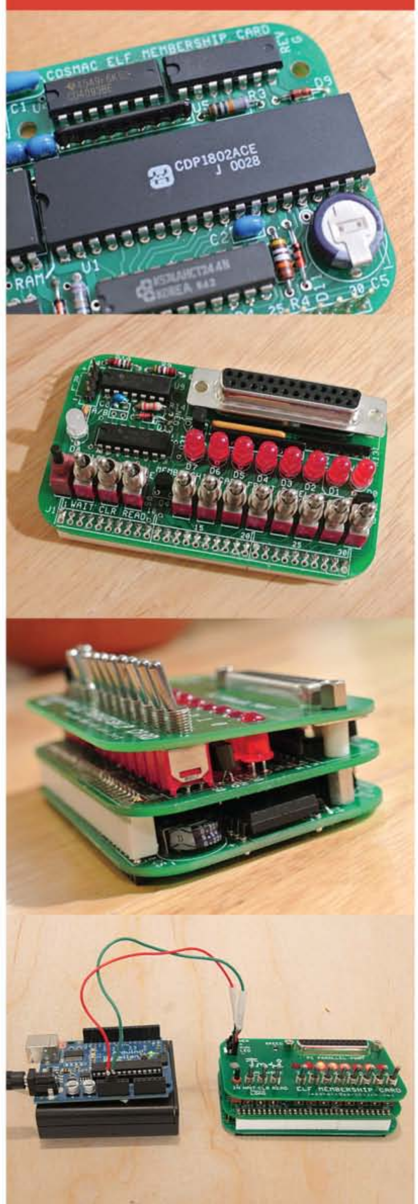
The 1802 also features four special input pins. The state of these pins can be read and branched upon using a single instruction apiece, greatly simplifying the physical circuitry and software required to accept input from peripherals. Another handy quirk of the 1802 is that its clock speed can be dynamically adjusted, from about 1.8 megahertz (in the case of the Membership Card) right down to zero. Stopping the clock doesn't cause the processor to reset, and the clock can be restarted without the 1802 missing a beat. At low speeds the 1802 needs little voltage and draws only a tiny amount of power. These features should make the 1802 of interest to anyone who needs a reliable embedded controller that could potentially be run on a small solar cell.

The standard Membership Card Kit, from Hart, costs US $79—I paid an extra $10 for a version that includes a cover for the kit's front panel. Hart also sells a bare-bones printed circuit board without any components, but buying the components with the kit means getting an 1802 processor without the hassle of dealing with resellers on eBay. (Intersil, the current manufacturer of 1802 processors, sells only a few thousand military-spec versions a year, at $124 apiece, bulk orders only.)

The kit takes the form of two interconnected boards sandwiched together. The bottom board is actually a complete computer that holds the 1802, system memory, and some supporting circuitry. The top board is the "front panel" and holds the toggle switches and LEDs used for input and output, as well as a power socket and a 25-pin socket. The latter can be used to connect the kit to a PC parallel port.

The bottom board can function without the front panel. It comes equipped with a 32-kilobyte static RAM chip, but if you buy some additional third-party components, you can install a second RAM chip or EEPROM. These chips would make boot loaders and other code permanently available to you. Hart has also included a hefty capacitor that can maintain the contents of the RAM chip for several hours.

ELF IN A TIN



A COSMAC SQUEEZE: This remake of the 1976 Cosmac Elf uses the same CDP1802 processor [top] and a stripped-down version of the front panel found on early micros [second photo from top]. The processor and panel board are sandwiched together [third photo]. The computer is externally powered: I used an Arduino as a 5-volt regulated power supply [bottom].

Squeezing the Elf into a form factor that can fit inside an Altoids tin means that assembly is a pretty fiddly operation (although most of the difficulties I had were due to insanely bad luck rather than Hart's design). And programming software more than a few dozen bytes long is tedious and error prone.

Fortunately, as of a hardware revision from last February, the Membership Card now includes improved support for serial communications, which allows you to load programs from, and communicate with, a host computer much as you would with an Arduino.

There are two wrinkles: First, you must decide in advance if you want to use "TTL" voltage levels for the serial interface (which works with many serial-to-USB adapters) or "RS-232" levels (for interfacing with the serial ports found on older PCs). The circuitry is slightly different for each. Second, you'll have to provide your own software to handle the serial interface (this is where the ability to install an EEPROM comes in handy). Fortunately, you can get lots of help and advice on this—and many other matters related to the Membership Card and the 1802—on Hart's website as well as on the pages of Retrotechnology.com.

As I don't have an EEPROM burner, I'm currently working on an Arduino-based interface that will connect via the parallel port provided by the front panel. The goal is to duplicate the functions of the original hexadecimal keypad and display while also allowing longer programs to be uploaded from a PC, but this will have to be the subject of a follow-up article. For now I've contented myself with toggling in some of the sample programs available for the Elf, including a few from the original series of articles in *Popular Electronics* that introduced the computer to the world. One of these is ETOPS-256, a 32-byte-long operating system. It's not exactly a sophisticated OS, but it is the only one I can say I have the pleasure of fully understanding. —STEPHEN CASS

FROM TOP: STEPHEN CASS (3); RANDI KLETT

RESOURCES_TOOLS

GIVE YOUR HOME A "STAR TREK" VIBE

PROGRAM VOICE COMMANDS INTO THE UBI WALL COMPUTER

BY YOUR COMMAND: You can program Ubi to respond to custom voice commands, which it can listen to from up to several meters away.

UNIFIED COMPUTER INTELLIGENCE CORP.

Ambient computing has been the stuff of science fiction for decades. On "Star Trek," for example, the crew of the *Enterprise* could say "Computer" into the air, followed by a command. An intelligent system would reply and attempt to obey, whether it was turning on the lights or executing the self-destruct sequence. Now—at least when it comes to the lights—fiction has become fact.

Interest in using voice to control smart homes has taken off in recent months. In June of last year, Apple announced HomeKit, software that will eventually enable users to command connected devices using the Siri voice interface. Amazon has begun limited sales of its cylindrical US $200 Amazon Echo, which can do things like provide weather reports or play specified music on voice command. While the Echo doesn't yet integrate with smart-home devices, I'll eat my hat if that functionality isn't added sometime in the next 12 to 18 months.

But you don't have to wait: You can try the $300 Ubi today. Like the Echo, the 10- by 10- by 3-centimeter Ubi can obey voice commands to do things like play music or send text messages on your behalf. But I already have pretty painless tools for those kinds of things. What I was really interested in were the smart-home capabilities: When you come through the door carrying grocery bags, that's when you *really* want an alternative to fiddling with a smartphone.

Installing the Ubi was easy: I plugged it into the wall and set up an online account with its maker, the Unified Computer Intelligence Corp. (UCIC), in Toronto. This account allows you to configure the computer and connect it to your home's Wi-Fi router.

The Ubi has built-in support for Smart Things home-automation devices and Nest thermostats, but to link my Ubi to the Philips Hue lightbulbs I have in my home, I had to use the IFTTT (If This Then That) website. This acts as a sort of glue between an extensive range of smart devices and online services. Support for both Ubi voice commands and my Hue lightbulbs has already been integrated into IFTTT, so creating a new command was simple: I used the Ubi "trigger" template to specify that my Ubi should pay attention to the words "Turn on lights." Then I used the Hue "action" template to set this command to turn on all my apartment's lightbulbs. Setting up a command to turn off the lights was a similar process.

To actually use a command, I first have to get the Ubi's attention, which I do by saying "Okay, Ubi!" Then I can say, "Turn on lights," and a couple of seconds later a voice confirms my command and the lights turn on. Usually.

Ubi uses Google's voice recognition system, which is not as good as Apple's. I sometimes have to repeat a command two or three times, and sometimes my Ubi gets confused about the difference between "turn lights *on*" and "turn lights *off*."

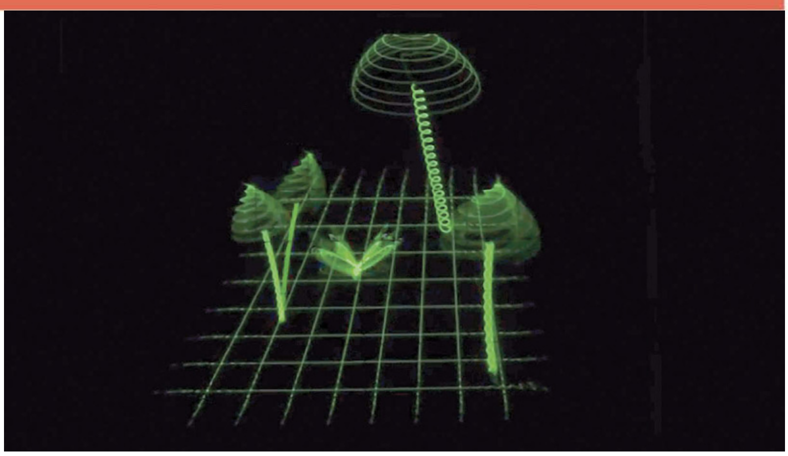
There are other rough edges—such as a clunky online portal—as UCIC rolls out tweaks and upgrades with some frequency, suggesting that Ubi is still somewhat in beta mode. So why get an Ubi now, instead of waiting for Apple or Amazon to release what are sure to be polished products in the next year or two?

Because, in order to ensure a no-fuss consumer experience, those big-name products are likely to be pretty tightly nailed down. In contrast, UCIC is willing to let you get your hands dirty—for example, you can have an Ubi respond to incoming HTTP requests or send out its own. This means you have access to a vast range of online APIs (application program interfaces). The ability to quickly create your own voice commands is powerful and eliminates much of the guesswork that can sometimes come with Siri. You can also program triggers based on built-in sensors that monitor and log the levels of light, sound, air pressure, humidity, and temperature. You could have lights turn a warning red if the bottom drops out of the barometer, for example. After all, what's the point in living in a science fiction world if it isn't any *fun*? —STEPHEN CASS

RESOURCES_GEEKLIFE

SYMPHONY FOR OSCILLOSCOPE

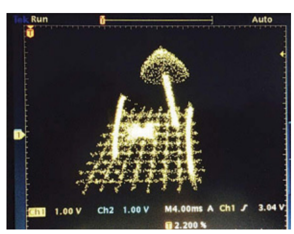
JEROBEAM FENDERSON'S MUSIC ENCODES ITS OWN TRIPPY VISUALS



On YouTube, there's a video of animated green mushrooms spinning around in a three-dimensional field, with a sound track of strange electronic tones. That premise itself is nothing extraordinary—the Internet is full of stranger things than dancing mushrooms. But what makes this video special is that the sounds are creating the images onscreen. Since the video first appeared last year, a lot of people have been skeptical about the 3-D graphics effect produced—including the editors here at *IEEE Spectrum*, until we dug out an oscilloscope and played the sound file into it for ourselves.

It's all possible thanks to an old-school cathode-ray oscilloscope and a concept that many engineers and physicists will remember from their undergraduate days: Lissajous figures.

The mastermind behind the video is Christian Ludwig, an Austria-based electronic-music artist who performs as Jerobeam Fenderson and runs a small music label called Ordia Muszc. Through his oscilloscope musical projects, Ludwig creates audiovisual experiences, both online and for live audiences around the world. Ludwig says he used to make "a lot of rock music and other kinds, based on my favorite bands." But more recently he's been more interested in "experimental music and noise music, so I've tried to find some approaches to create something new that isn't just sound," he says.



TRUST BUT VERIFY: Christian Ludwig used a high-end oscilloscope and sound card to create his YouTube video [top]. However, even a standard PC audio output and oscilloscope [bottom] can be used to re-create much of the effect from his sound files.

As a teenager about 10 years ago, Ludwig took time off from school and did a vocational apprenticeship at Heidenhain, an electronics company. "It was not exactly the most creative job, but I did gain some useful practical skills there," he says. "That's how I got to know about oscilloscopes and electronics. I always thought I should do something with it because it somehow looks very cool. I like the laboratory aesthetics [that are involved]." After four years, Ludwig finished his schooling and started studying for a bachelor's degree in sound engineering. Although he never finished his degree, he has taken that knowledge with him toward his endeavors in electronic music, in particular the oscilloscope projects that began two years ago.

Ludwig uses an analog CRT oscilloscope—specifically a Tektronix D11 5103N. When connected to a computer's audio interface (in the case of the mushroom video, he used a USB-based RME Fireface UC operating with a 192-kilohertz sampling rate), the left audio channel triggers a horizontal deflection onscreen, and the right audio channel triggers the vertical deflection. "It's like vector graphics," he says. "Together, they can create certain shapes."

In other oscilloscope works, Ludwig has created patterns and shapes of all kinds, including a magenta outline of a girl's face in a piece titled "Khrang." Typically though, the visuals are something much simpler and act to complement his music, whether it's posted online or played during his live shows. Ludwig has just come back from a tour he did in the United Kingdom, where he thinks his performances were well received. With suitable hardware and the right kind of software for making waveforms (Ludwig suggests the Pure Data open-source visual programming language or the commercial visual language Max), anyone can emulate his work and design their own sound-based visualizations.

Still, Ludwig sees this as a temporary interest. "I really want to do an album with this and more shows. But I think after a year or so I will go on with something else." In the meantime, the interest his work has generated is likely inspiring other sound geeks to experiment with oscilloscopes in their own way. We may see more than just dancing mushrooms in the near future. —**NEEL V. PATEL**

TOP: JEROBEAM FENDERSON; BOTTOM: STEPHEN CASS

SANSTREAK LOWERS THE COST OF HIGH-SPEED PHOTOGRAPHY

WILL A LOW-COST HIGH-SPEED CAMERA CREATE NEW APPLICATIONS?

High-speed photography is a lot of fun. Ever since Eadweard Muybridge photographed galloping horses in the late 1800s, people have been using high-speed photography to see what happens when a water balloon bursts or when a lightbulb smashes. And, of course, high-speed cameras are ubiquitous in sports.

But high-speed photography has more serious applications too. Manufacturers, for example, can use it to monitor fast-moving assembly equipment. Adoption, however, is limited by the expense of the equipment: Today's high-speed cameras typically cost around US $30,000 to $150,000 or rent for up to $5,000 a day.

Enter Sanstreak Corp., cofounded by Mike Matter in 2012. Sanstreak is a small company in San Jose, Calif., funding itself with angel investment, a 2013 Kickstarter campaign, and sales. Sanstreak's strategy is to prioritize price over performance: It sells its Edgertronic camera for just $5,500. Says Matter, "It's equivalent to buying a $2,000 oscilloscope—it's not the fanciest one out there, but it's a good, solid product that gets the job done."

At age 12, Matter souped up a strobe flash to take stop-action photos of a golf club hitting a ball; as an electrical engineering student, he studied under high-speed photography pioneer Harold "Doc" Edgerton. So after spending a career designing computers, MPEG decoders, and electron microscopes, he decided to make something he really wanted—an affordable high-speed camera.

First, he eliminated frills, such as the camera's display screen. High-speed cameras are typically set up on a stationary platform or tripod, not hand carried, and most users have a tablet or laptop handy, so the Edgertronic piggybacks on that external display. And if you're connecting to an external computer, you don't need controls on the camera either.

Matter's current design shoots 1280 by 1024 pixels at about 500 frames per second and up to 18,000 frames per second at reduced resolutions. It comes in a small, square blue metal case and was named in homage to Doc Edgerton. The company says it has sold about 400 cameras to date and earned back its development costs by the end of 2013.

Matter has already heard of a few new applications for the Edgertronic, which could help expand the market for high-speed photography: One customer, he says, is using one to research better ways to literally separate the wheat from the chaff.

Sanstreak's timing is right, says Christopher Chute, a vice president at the analyst firm IDC. The video-camera market is moving away from the rental model, with even 4K-resolution cameras, another previously expensive technology, selling for under $10,000. Whether or not Sanstreak will ultimately be successful, Chute says, depends on how much momentum it can gain. "And that could be tricky," he says, "because the cinema space is still a cottage industry," while the nonprofessional, camera enthusiast market is bigger but harder to define. Eventually, he says, the real value will likely be in industrial and medical applications, so Matter will need to tap these markets.

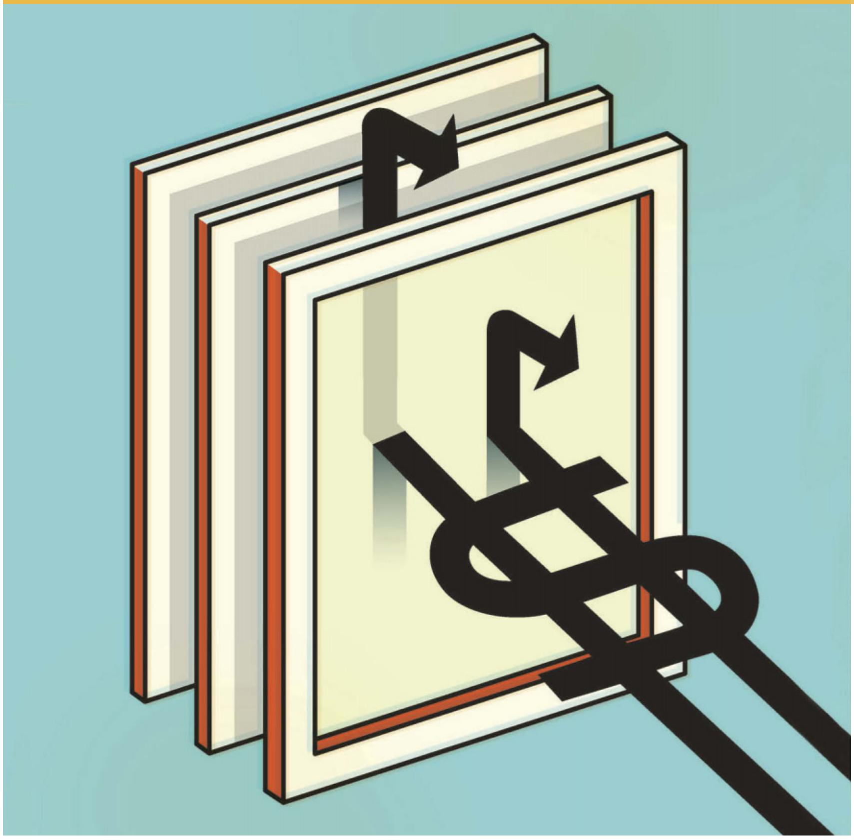
And, says Chute, while Matter has no immediate rivals at his current price, he will likely face competition soon: "There are probably other similar projects germinating in a lab or in someone's brain right now."

—TEKLA S. PERRY

Company: Sanstreak Corp.
Founded: October 2012 **Headquarters:** San Jose, Calif. **Founders:** Mike Matter, Juan Pineda **Funding:** Not disclosed **Employees:** 1 full-time, 5 part-time **Website:** http://edgertronic.com

IT'S HAMMER TIME: The Edgertronic can capture the details of brief events, such as the demise of this lightbulb, without dropping a single frame.

SANSTREAK CORP. (4)



THE VISIONARY ENERGY SOLUTION: TRIPLE WINDOWS

THE LUST FOR UNTESTED TECHNOLOGICAL FIXES IS THE curse of energy policy. Take your pick: self-driving solar-powered cars, inherently safe nuclear minireactors, or genetically enhanced photosynthesis. • Why not start with what is proven? Why not simply reduce the demand for energy, beginning with residential and commercial buildings? • In the United States that sector accounts for about 40 percent of total primary energy consumption (transportation is a distant second at 28 percent). Even now heating and air-conditioning account for half of residential consumption, which is why the single best thing we could do for the energy budget is to keep the heat in (or out) with better insulation. • The most rewarding place to do that is in windows, where the energy loss is the highest. That is to say, it has the highest thermal transmittance, measured in watts passing through a square meter of material, divided by the difference in temperature in kelvins on either side. A single pane has a heat transfer coefficient of 5.7 to 6 watts per square meter per kelvin; a double pane separated by 6 millimeters has a coefficient of 3.3. Applying coatings to minimize the passage of ultraviolet and infrared radiation lowers it to between 1.8 and 2.2, and filling the space between the panes with argon chops it to 1.1. Do that with triple-glazed windows and you drop to between 0.6 and 0.7. Substitute krypton for argon and you can get it down to 0.5. • That's a reduction of up to 90 percent. In the world of energy savings there are no other opportunities of that magnitude applicable on a scale of billions of units. Bonus point: It would actually work.

And there is also a comfort factor: With the outdoor temperature at -18 °C and the indoor temperature at 21 °C, the internal surface temperature of a single-pane window is just around 1 °C, an older double-pane window will register 11 °C, and the best triple-glazed window 18 °C. At that temperature, you can sit right next to it.

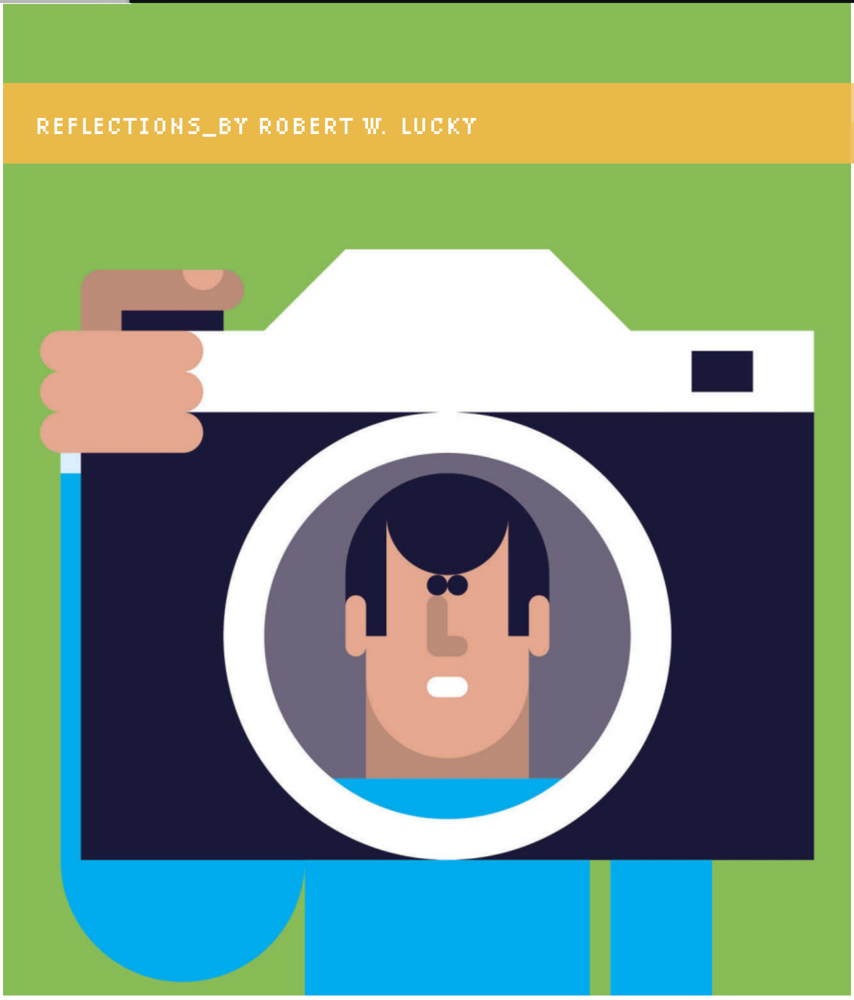
And triple windows have the added advantage of keeping out noise and reducing condensation. They are common in Sweden and Norway, but even in Canada windows must meet the standard that is equivalent to just a double-glazed window with one low-emissivity coating.

Cold-weather countries have had a long time to learn about insulation. Not so in the warmer places, which need it now that air-conditioning is becoming widespread. Most notably, in rural China and rural India, single panes are still the norm. Of course, the temperature differential for hot-weather cooling is not as large as in higher latitudes for heating. For instance, at my home, in Manitoba, Canada, the average lows in January are -25 °C, enough to make a difference of 40 °C even when the thermostat is turned down for the night. On the other hand, air-conditioning in many hot and humid regions runs for much longer periods than does heating in Canada or Sweden.

Physics is indisputable, but economics rules. Although triple-glazed windows may cost just 15 percent more than double panes, their payback times are obviously longer, and it is commonly claimed that the step from double to triple design is not justified. That may be so if you ignore comfort, condensation, noise, and above all, the fact that triple panes will keep reducing energy use for decades to come.

Why, then, do visionaries want to pour money into arcane conversion technologies that may not even work and, even if they did, would likely have bad side effects on the environment? What's wrong with simple insulation? ■

ILLUSTRATION BY Harry Campbell



THE UBIQUITOUS CAMERA

Technology has transformed photos from treasured keepsakes to personal propaganda

FOR MUCH OF THE LAST CENTURY, CAMERAS REMAINED fundamentally the same. A good camera was a lifetime investment. Who would have guessed that in the space of a few years Kodak would go into bankruptcy and that the most frequently used camera in the world would be manufactured by a company that makes phones? • Now camera technology is in the midst of dramatic change. There is continuous improvement in sensors and in the capabilities of software algorithms for computational photography. We even have the first light-field cameras, which allow post-capture changes in focus and in point of view. However, it is still the little smartphone camera, when combined with the sharing power of the Internet, that's driving the big changes in how we use and regard photography today. • This is all exciting stuff, and as I walk about, I'm constantly looking for things to photograph. But I'm not sure why I'm doing this. I already have about 25,000 photos on my computer, and I almost never look at any of them. There are just too many. Moreover, every city and vacation spot on Earth has been photographed to death: You can even virtually walk down the streets and look around using Google Street View. And if the current camera ubiquity isn't enough, wait until everyone decides that they want their own camera-carrying drones. I hold my camera at the ready and feel an irresistible urge to click, but I wonder: What am I adding to this sea of images?

In the past, the rarity of pictures gave them value. For centuries we were constrained to view the world through the eyes of painters and sketchers. The purpose of image creation was mostly artistic expression, though this was often influenced through the patrimony of religious institutions or wealthy nobility. I see the pompous portraits that line the halls of castles and manor houses, and now I think of them as the selfies of another day. I am amused, for example, by Hans Holbein's iconic 1536 portrait of King Henry VIII, which was apparently "photoshopped" to make him look more kingly–taller, younger, fitter. I suppose it wasn't enough to be ruler of all the land–Henry felt he had to look the part. Today we have our own carefully curated self-images, peeping out from social media profiles or Web pages.

When cameras were first put in the hands of ordinary people, perhaps the main purpose became the creation of what I think of as "mantel photos." These are the pictures I so often see in people's homes lining the mantelpiece or piano, telling the family history in a handful of images. I know when I took photos in the past I was looking either for particularly artistic shots or ones that might become fossilized memories adorning a mantel. Film was limited and expensive, and I chose carefully.

Now that rarity is long gone, lost in an ocean of mostly forgettable images. With all this great image technology, I'm wondering: What new purposes for photography are being created? Beyond the selfie, for some people there are opportunities for lifelogging. There is also a new habit in taking snaps, say of documents or possessions, as an aid to memory. But the big new purpose is using photos as an enabler and conduit for attracting social interaction online.

So now when I walk about with my ever-ready camera, I'm not looking so much for pretty sunsets or tourist attractions. I'm thinking, how will this look on Facebook? ■

ILLUSTRATION BY Greg Mably

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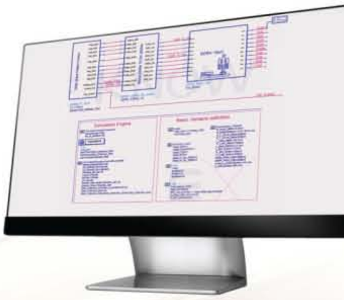



256 * 6Gbps =
throughput
limited
future
memory
DDR4/LPDDR4
256 I/O
I/O
Gbps/pin
6 Gbps

Scientists are using a web of sensors in Harvard's forest to infer the effects of climate change on-site and throughout the world

The INTERNET *of* TREES

By MARK HARRIS

▲▲▲

Photography by BOB O'CONNOR

"EVERYTHING IS CONNECTED TO EVERYTHING else," says the First Law of Ecology, laid down in 1971 by the U.S. biologist and activist Barry Commoner. He was addressing scientists who had been trained to manipulate a few key variables, after isolating them from all outside influences, to see their effects on a few outcomes. But in ecology, everything varies together; an interwoven web links microbes to mountains. ▲ Even a single forest has enough entwined connections to boggle the mind. Tree growth depends on fleeting changes in the atmosphere, soil, and water. The arrival of new plant and animal species, or the disappearance of old ones, might spell disaster now or a bloom some years hence. Even the tiniest microorganisms can shape the fate of towering oaks. ▲ Until now, forest ecologists have been forced to largely ignore this complexity, focusing instead on the most obvious linkages or easily compartmentalized processes. But what if they could carve out an ecosystem small enough to let them measure pretty much everything happening within it, and to keep doing so for years on end? If the natural, underlying processes in this small volume could be understood and its connections unraveled, then it should be possible to predict what will happen in this corner of the world as the planet warms.

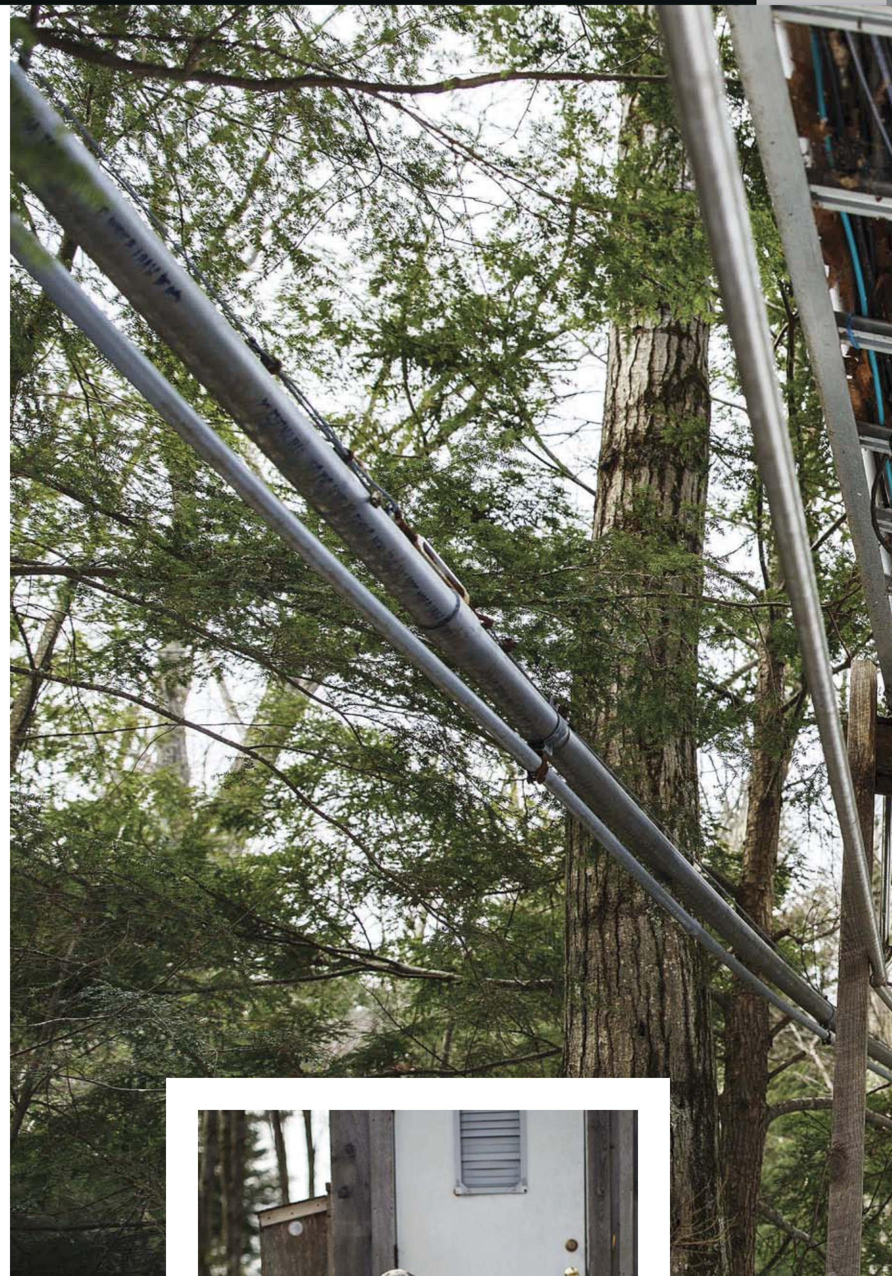
Such a living network exists in a woodland in central Massachusetts. But you could walk right through this preserve without noticing that its trees have eyes and its meadows, ears. Nevertheless, knowledge gathered here is already leading to fundamental discoveries about the wilderness, its biological processes, and how they have changed over the past 25 years. And it seems set to allow scientists to formulate strategies to mitigate the worst effects of climate change for forests, woods, lakes, grasslands, and farms around the globe. As any economist will tell you, that could be worth trillions of dollars in a world already experiencing shifts in agriculture, precipitation, extreme weather, and wildfires.

APRIL AT THE HARVARD FOREST finds snow still blanketing the ground, bare trees sagging under a wintry chill, and stone walls skirting the memories of long-abandoned farms. At first glance it looks as it might have back in 1907, when Harvard University acquired 1,520 hectares of land in Petersham, Mass., as a living laboratory for botanists.

But here, bright orange cables are snaking halfway up a tree. There, cryptic dials on a slim gray box are crusted with frost. And overhead, visible through the branches, metal towers bristle with antennas and cameras. For this forest is pervaded by a digitized network of sensors that scrutinize growing plants, scurrying animals, waterways, and the air itself. Primary electric power is supplied to many research plots in the forest, while more remote devices use batteries. Thousands of sensors make millions of observations every day, monitoring the soil, the streams, and every breath of wind. If a tree falls in the Harvard Forest, rest assured that a gadget is positioned to hear it.

From the very beginning, Harvard has gathered data here. At first, scientists tracked the health of trees and vegetation for forestry. But since 1988, the Harvard Forest has also been a Long-Term Ecological Research (LTER) site, funded by the National Science Foundation. This designation broadened its mandate to observe other aspects of forest dynamics, focusing on its rivers and streams as well as changes in the air that sweeps by.

Such studies posed problems. Deluges of data from atmospheric monitors would fill the largest hard drives in days, forcing scientists to trek around the forest swapping them out. And though the trickle of data from watercourses could be



ANDREW RICHARDSON [above] regularly climbs towers [near right] that are topped by a clutch of "phenocams" [middle right], which feed data to logging devices on the forest floor [far right].

THE FOREST BACKBONE [far left] extends the network to a tower, which samples trace gases. Trees with yellow marks [left] have been studied individually for decades. The National Ecological Observatory Network tower [below left] measures atmospheric changes.

A SAP SENSOR [above] contains two needles, one of which is heated. The temperature gap reflects sap flow, a measure of the tree's health.

AARON ELLISON [below] puts ants in chambers [right] heated by hot air [bottom] to model the effects of global warming.

logged for much longer, that longevity came with risks. "Murphy's Law says that when you only get out to these once a month, if you have a problem it's going to be the day after your last visit, and you'll lose a month's data," says Emery Boose, who manages the forest's internet of trees.

In 2010, Harvard Forest researchers decided to move to a wireless network. But tall trees and steep hills created dead zones that a traditional Wi-Fi network could handle only with scores of access points. A high-powered cellular system, on the other hand, would cost a lot of money and need regulatory approval.

In the end, the project's engineers concocted an ingenious hybrid of three kinds of wireless technology. Five towers poking above the treetops provide the main backbone for the network, communicating via 5.8-gigahertz radio links capable of very high data rates. Because these high-frequency signals are attenuated by foliage, a dozen 900-megahertz radios are used to punch through leaves and branches. The third leg of the hybrid consists of a handful of 2.4-GHz Wi-Fi access points at ground level to provide Internet access for the laptops and smartphones of researchers working nearby.

ASIDE FROM SIGNAL-SAPPING FOLIAGE, nature has other devilry. Animals chew on cables, ice builds up on metal equipment, and storms knock down trees and cables. But the main enemy is lightning. Every summer, dozens of bolts surge into the towers. The towers are well grounded, of course, so many strikes are not even noticed. However, says Boose, "last summer we had three or four episodes of significant damage. Our insurance company realized that this was no longer a good business model for them, so we aren't able to insure any longer." To keep replacement costs down, the forest now uses hand-me-down switches and access points from the main university campus.

Each experimental site in the forest has many devices and sensors associated with it. Some are gathering information for a particular project; others are collecting background data that could help scientists years from now. A weather station, for example, collects a full set of meteorological data every second, including air and soil temperatures, humidity, precipitation, and solar radiation. Meanwhile, the level and flow of every stream is monitored by ingenious pressure meters whose trick is to force water through a carefully shaped trough

where the height of water is proportional to the rate of flow.

Nestled in the undergrowth are three Raspberry Pi-powered acoustic sensors. They are part of a pilot project to survey birds and insects by detecting their distinctive songs. Each unit, built for US $100, records every sound within a radius of 10 to 15 meters, compressing and wirelessly transmitting audio over the Internet to researcher Erik Sobel's office on the outskirts of Boston. "Nobody is going to sit and listen to terabytes of sound data," says Sobel, whose background is in target and pattern recognition for defense applications. He is now working on algorithms to identify different forest species. "The concept is to develop low-cost technology that can automatically detect when the first cardinals arrive in the spring and when the earliest crickets chirp, then correlate that with temperature and so on."

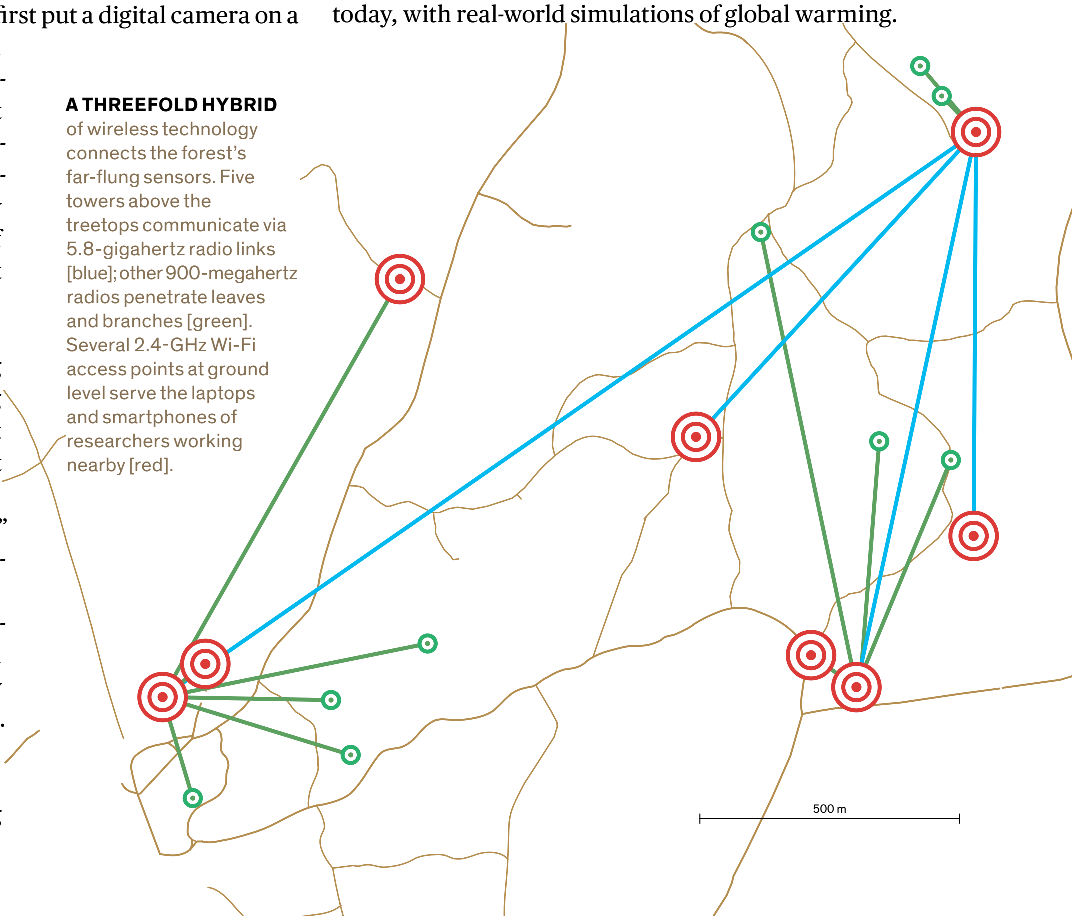
This process of studying natural cycles is called phenology, and it is the core of the Harvard Forest mission. Every year since 1990, Harvard investigator John O'Keefe has been noting when the leaves of dozens of tree species first bud in the spring and when they change color and die in autumn. Now his role is in danger of being usurped by cameras mounted high above. Harvard biology associate professor Andrew Richardson first put a digital camera on a tower at the Harvard Forest in 2005, to "get some pretty pictures to illustrate lectures." But he soon realized that by comparing colors in time-lapse photos, he could track and identify seasonal changes. The dozens of "phenocams" he has installed at 12 locations around the United States have captured more than 5 million images. "We're doing what satellite remote sensing does," says Richardson. "But we're doing it with cameras that cost a couple of hundred dollars rather than a hundred million." To be fair, many satellites capture far more than just visible light. But by comparing phenocam data with images shot from orbit, Richardson can quantify uncertainties in the satellite data.

"We're improving satellite data for the whole world," says Richardson. He is now using thermal cameras to follow trees' responses to heat stress, and he has even installed an aerial tram that scoots over the canopy on wires. The tram carries sensors that measure the canopy's height, color, and ability to absorb different wavelengths of light–a key indicator of photosynthesis and plant health. The tram can be controlled from a Web interface via its 2.4-GHz ZigBee radio; it returns its data the same way.

ALONGSIDE THE CAMERAS–and the main reason for Harvard Forest having towers at all–is a host of atmospheric sensors. Eddy flux devices measure tiny swirls in the wind and, with the help of infrared analyzers, track the movement of gases in the air several times a second. There are six of these systems mounted at different heights on each tower, from the forest floor to clear air above the canopy. Researchers can thus follow the absorption of carbon dioxide and the emission of water vapor, as well as the changes in man-made pollutants like ozone and oxides of nitrogen.

Harvard Forest's eddy flux towers have been collecting data since 1991–"the longest time series like that in the world," says Richardson. It allowed Richardson and colleagues to prove last year a long-held suspicion that forests are now doing more photosynthesis with less water than in the past. As carbon dioxide levels in the atmosphere rose from the combustion of fossil fuels, trees actually removed and stored more of it.

This extra carbon sequestration might seem like good news. But ecologists are trying to understand what the secondary effects could be. And a few are not prepared to wait decades to see how climate change might develop: They want to see it today, with real-world simulations of global warming.



A THREEFOLD HYBRID of wireless technology connects the forest's far-flung sensors. Five towers above the treetops communicate via 5.8-gigahertz radio links [blue]; other 900-megahertz radios penetrate leaves and branches [green]. Several 2.4-GHz Wi-Fi access points at ground level serve the laptops and smartphones of researchers working nearby [red].

HARVARD FOREST PROJECT

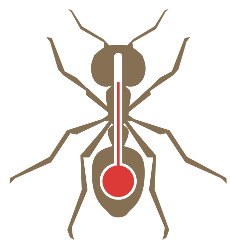
A WORLD *of Woven* TREES

Harvard Forest hosts scores of research projects, some of which go on for decades

PHENOCAMS
Six cameras shoot images at 30-minute intervals during daylight hours. The hundreds of thousands of photos captured are used to create a “greenness index” of the forest. The cameras can determine the precise biological beginning of spring and autumn to within a day.

EDDY FLUX TOWER
Installed in 1989, the tower is 30 meters high and located 1.7 kilometers from forest headquarters. It provides the world’s longest continuous record of net ecosystem carbon dioxide exchange, evaporation, and energy flux between the atmosphere and the forest. Individual sensors measure the air multiple times a second, and the gas exchanges are recorded at hourly intervals.

WEATHER STATION
The station measures air temperature, relative humidity, precipitation, incoming and net radiation, barometric pressure, wind speed and direction, and soil temperature every 15 minutes. Hydrological stations record stream discharge and water temperature at four stream sites, and water level and water temperature at two wetland sites. A pressure-sensitive “snow pillow” measures the rate of snowfall and the water content of the snow pack over the winter.



ANT WARMING
An open-top chamber simulates warming from a change in climate of between 0.5 °C and 5.5 °C. The annual heating and electricity costs are $50,000. Ants are sampled every month to see which species thrive and which leave or die off.

ACOUSTIC MAPPING SYSTEM
Three $100 devices monitor audio in the forest: bird, animal, and insect life, as well as tree falls and human activity. Devices use Raspberry Pi hardware running Linux and include Wi-Fi and a microphone that samples audio at 24 kilohertz. Data is streamed continuously to remote hard drives. Future plans include algorithmic identification of individual bird and insect species.

HURRICANE-MANIPULATION EXPERIMENT
In 1990, the experiment simulated a large hurricane in a 0.8-hectare (2-acre) forested area by pulling down trees with a large winch. Researchers have studied the regrowth of tree species since then, as well as the response of the forest ecosystem to a catastrophic storm. Such hurricanes have traditionally occurred only every 50 to 200 years, but that could happen more frequently with climate change.

One of the very first LTER experiments used underground cables to heat a few hundred square meters of the forest floor to five degrees centigrade above ambient (a temperature gain that we may face late this century). The goal was to study how the heat affected the amount of carbon dioxide released by the microbes. Understanding this process matters hugely because soil microbes already release nearly 10 times as much carbon dioxide each year as human activity does. The researchers discovered that the microbes in the soil at first released more carbon dioxide than before. But as the years passed, emissions fell again as the microbes adjusted to the warmth.

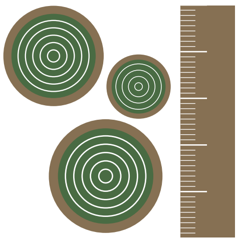
Tall trees are harder to heat up. Pamela Templer, an associate professor at Boston University, decided to start at the roots, in a project that’s testing the counterintuitive notion that a warming environment might mean colder soils. The U.S. Northeast’s famous winter storms deposit a blanket of snow early in the winter that insulates the ground from frigid air later on. As temperatures rise in years to come, climate models predict less snow but still freezing temperatures.

To simulate this, Templer’s team shoveled away the first snows from beneath 12 red oak and 12 red maple trees at the Harvard Forest. They then fitted each tree with three sap-flux sensors, each consisting of two needles, one of which is heated. The temperature difference between the needles reflects how well water is flowing up the trunk, a measure of the tree’s overall health. As the seasons progressed, the sap of the red maples slowed down, while that of the red oaks did not. Templer believes that the red oaks were less affected by freezing soil because their roots generally run deeper into the earth.

The most ambitious simulation, however, involves some of the forest’s shortest-lived residents: ants. These insects create an inch of topsoil in North America every two centuries, replenishing soil lost to farming. To observe how warming might affect their behavior, ecologist Aaron Ellison set up dozens of chambers on the forest floor and heated them to successively higher temperatures, ranging from 0.5 °C to 5.5 °C above those of the ambient air. (The heating bill for his hot air blowers alone is $50,000 a year.) The ants are free to come and go from the chambers, and their numbers are sampled each month. Most of the ants at the Harvard Forest adapted to the higher temperatures, continuing to generate topsoil as before. However, some species at an identical setup in subtropical North Carolina either left the chambers or perished.

Microbes, ants, and oaks: With continuing investigations starting to come together, Ellison refers to an “ecosystem of experiments” at the Harvard Forest, whose interconnections mirror those of the forest itself. For example, he has also sampled ants from an experiment originally designed to study

ILLUSTRATIONS BY MCKIBILLO



MEGAPLOT
This 35-hectare plot of the forest precisely maps woody stems over 1 centimeter in diameter—more than 116,000 stems in total. It is part of the Forest Global Earth Observatories, a project of the Smithsonian that tracks the function and diversity of over 6 million trees in 24 countries around the world. Harvard Forest is one of the first temperate forests in the project. It will remeasure the trees every five years.

HEMLOCK REMOVAL
Researchers simulated the arrival of the invasive Asian woolly adelgid bug by deliberately killing hemlock trees in 6.5 hectares of the forest. Within the next 10 years, wild hemlock trees are predicted to die off completely in the United States. The study monitors the impact on native wildlife by regularly assessing each woody stem that's at least 30 cm long, for browsing by moose, porcupine, and deer.

PREDICTING RAGWEED-ALLERGY HOT SPOTS
A three-year field survey gathered data on pollen from 1,250 specimens of common ragweed, a species that causes hay fever. Expected outcomes include better predictive tools and maps for forecasting allergy hot spots, as well as models of how climate change affects human exposure to pollen.

DETRITUS INPUT AND REMOVAL TREATMENTS (DIRT)
Researchers study forest soil by measuring respiration, nutrient leaching, and various chemical properties. Results last year suggest that sequestering carbon in forest litter (to offset burning fossil fuel) is probably not practical.

the effects of warming on plants, while other researchers are making use of an experiment that is manipulating the canopy (ostensibly to track the decline of hemlock trees) to see how climatic changes might affect plants and animals beneath. "We do these parallel experiments all the time," he says.

"We would love to have a crystal ball that says, 'In 100 years the temperatures are going to increase by *x* and the forest is going to respond with *y*,' " says Templer. Accurate forecasting could allow governments to plant appropriately adapted species, manage development, reduce the spread of invasive species, and ultimately make climate change less disastrous for all of us.

Accelerating data collection is one of the most important techniques that researchers are using to get to that goal. Take "water budgets"–the balance of precipitation, runoff from streams, and evapotranspiration, the water returned directly to the atmosphere through evaporation and the respiration of plants. Many ecologists have been tracking it at various sites for decades. But this monitoring is typically conducted on an annual timetable. Now, the Harvard Forest can provide accurate numbers on a daily or even hourly basis.

Senior investigator Boose hopes this trend will lead to a new kind of prediction. "We've gotten pretty good at forecasting the weather, but no one's ever really been able to do ecological forecasting," he says. "To do any sort of prediction, you need access to data quickly. New wireless techniques give us the potential to pull this all together and calculate water budgets that are right up-to-date."

EVEN IF HARVARD SUCCEEDS in predicting the behavior of its own forest, questions remain about how that success might apply elsewhere. So far, ecological experimentation has been of just two kinds: hyperlocal but richly detailed, such as John O'Keefe's painstaking observations of the first spring buds in the Harvard Forest, or global in scope but thinly observed, such as satellite data of the same phenomenon. To fill the gap between these extremes, another tower was put into service in Petersham last summer. Although it carries many of the same meteorological and atmospheric instruments as Harvard's other structures, it is just one of 60 identical towers that will rise in every ecoclimatic domain of the United States, from Alaska's tundra to Hawaii's beaches. Every site in the National Ecological Observatory Network (NEON) will measure the same things, in the same way, at the same time, for the next 30 years.

"When you integrate studies from different investigators, using different techniques, you get a large error band," says Elizabeth Blood, NEON's program director at the National Science Foundation. "With NEON, we'll reduce the error bands so we can begin to see patterns and interconnections that weren't visible before." The data from NEON's continent-spanning towers, as well as its three airborne observatories, 46 aquatic sites, and thousands of citizen scientists, will quickly be made available online.

"We want to develop a forecasting capability just like the weather service," says Blood. "NEON will help us reduce the noise in the data and give us the ability to make predictions in both the near and longer terms." Richardson's group is working with NEON to start the first citizen-science program. The effort will make use of the Zooniverse website, which recruits volunteers to work as scientists' helpers. Users will check the network of minicams for features that often elude conventional computer-vision systems, such as signs of flowering or snow on the ground. The $450 million NEON project should be fully operational by 2017, just in time to share data and insights with networked forests in Australia, Brazil, Canada, Costa Rica, Singapore, and the United Kingdom.

Climate change, of course, is a global issue. At the moment, these big-budget efforts are largely confined to the richer countries. "There are still large parts of the world we don't know that much about," admits Richardson.

But mighty forests from little acorns grow. One day, the tools being pioneered in this small New England forest might help realize a global ecological prediction network, one in which everything is connected to everything else. ▲▲▲

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TODAY'S ENGINEERING HEROES

Turns out there are plenty of extraordinary engineers. You just need to look for them

LAST JULY, *IEEE SPECTRUM* CHALLENGED readers to identify today's unsung engineering heroes—those worthy engineers who are making a difference in the world and yet have not received the recognition they deserve. As author G. Pascal Zachary noted, engineering suffers from an unusual lack of heroes. "The hero deficit is…bad for engineering," he added, "because it diminishes the enterprise in the eyes of the public, and it constricts the flow of talent into the field." • We were therefore delighted with the outpouring of reader suggestions, and here we profile six of them. Each of these exceptional people saw a glaring need, whether in public health or education or the environment, and then applied his or her considerable skills and expertise to engineer a solution.

PHOTOGRAPH BY Dan Burn-Forti

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Eben Upton	36	Founder, Raspberry Pi Foundation	Cambridge, England	Dismayed at students' poor coding skills, he created a capable yet ultracheap computer to get them hooked on programming.
IEEE MEMBER	AGE	OCCUPATION	LOCATION	HERO MOMENT

The Raspberry Pi-oneer

Eben Upton just wanted to help some kids learn to code. Four million units later, his $35 computer has sparked a revolution

In 1988, 10-year-old Eben Upton bought his first computer: a beat-up, secondhand BBC Micro. This little machine was ubiquitous in British schools at the time, not least because it ran a simple programming language called BASIC, which Upton quickly mastered and used to create various games.

Fast-forward almost two decades. Upton had just been appointed director of studies in computer science at the University of Cambridge's St John's College. And he noticed a big problem: Applications to study computer science at the university were declining, and few incoming students had any programming skills at all.

Like many of his contemporaries, Upton, who holds a Ph.D. in computer science from Cambridge and had already founded two software companies, owed his career to a childhood spent twiddling bits. "Kids today don't have that experience," he says. Instead of diving in deep with programmable computers like the BBC Micro, most of today's youth only scratch the surface of computing, despite all the hours they log with their phones, game consoles, and Web browsers.

Upton's solution was to create a miniature computer, barely bigger than a credit card, which cost just US $35. It was essentially a circuit board fitted with a smartphone processor chip, 256 megabytes of RAM (since boosted to 1 gigabyte), and some attractive options for connectivity: USB ports, a slot for a memory card, general-purpose input-output pins to link it with other devices, an Ethernet port, and HDMI and analog ports to connect it to a television or computer monitor. "It's trying to be cheap, it's trying to be robust, and it's trying to be fun," says Upton.

When the Raspberry Pi launched on 29 February 2012, Upton figured that getting a thousand units into the hands of the right kids would help to end the drought of qualified candidates applying to study computer science at Cambridge. Instead, demand exploded: To date, more than 4.5 million units have sold, including the stripped-down Model A+, which boasts a $20 price tag, and the more powerful Pi2, which debuted last month. The Pi's low cost means that pretty much everyone can own one.

"Overly sleek things can be bad for education," says Alan Mycroft, a professor of computing at the University of Cambridge's Computer Laboratory and a trustee of the Raspberry Pi Foundation. This charity, which Upton set up, takes the profit from Pi sales and plows it into education initiatives and other outreach activities.

Mycroft credits Upton for helping inspire a new generation of student coders, hackers, and hobbyists. "He's brought inspiration, leadership, and persistence to it–Eben just won't let go."

Growing up in the small town of Ilkley in northern England, Upton didn't have a techy household–his father was a professor of English, his mother an English teacher. In part because of his own background, he's thrilled that the Raspberry Pi is providing those without IT-savvy parents an opportunity to learn about computing.

That egalitarian spirit pervades the Raspberry Pi headquarters as well. Right after Upton politely asked the office manager to make me a cup of tea, he bounded after her to apologize. "I'll do it," he said. "You've got better things to do, and I was being an ass."

Raspberry Pi's success can be tied to its vibrant user community. In June 2012, Pi enthusiast Ben Nuttall organized the first "Raspberry Jam"—part fan-club meet, part hackathon—and since then there have been hundreds more of these community-led events. "They're full of kids learning to solder," Upton says happily.

Although the Pi sells globally, penetration in the developing world remains patchy. The foundation has set up showcase projects that include using the computer as a local server for remote villages that lack high-bandwidth mobile or landline connectivity. The computers come loaded with useful information—Wikipedia entries, books, videos—and are then stationed in the middle of town so that people can access the database wirelessly.

Back home, the Pi is also playing a growing role in schools. At St John's College School, just a 10-minute walk from Pi headquarters, a lunchtime programming club is buzzing with more than 25 pupils busily writing code and tinkering with the computers. "They learn by hacking and experimenting, which fixes it in their memories much better than if you give them a traditional course," says Graham Hastings, the school's head of information and communications technology.

The Pi computers can run Scratch, free education software that portrays commands as jigsaw pieces, which children can quickly click together into working programs. Then they typically graduate to Python, "one of the few languages that genuinely spans the range from trivial introductory level to professional software engineer," says Upton.

With millions of Pi computers now in circulation, Upton says the main barrier to getting more kids coding is a lack of skills among teachers. The Raspberry Pi Foundation aims to help with its Picademy, which since April 2014 has offered free computer training for teachers. The foundation plans to roll out more education initiatives to bring the Raspberry Pi into more schools. Meanwhile, the U.K. government recently launched a revamped curriculum for students studying information and communication technology that places greater emphasis on programming.

"The government has given us the curriculum of our dreams. So if we can't manage to get kids coding, then we should just give up and go home," says Upton. It's clear he has no intention of doing anything like that. "We've got to make it work." —MARK PEPLOW

RoboCup's Champion

Manuela Veloso transformed robot soccer into a global phenomenon

Stepping out of the elevator on the seventh floor of Carnegie Mellon University's Gates Center for Computer Science, I'm greeted by an ungainly yet courteous robot. It guides me to the office of Manuela Veloso, who beams at the bot like a proud parent. Veloso then punches a few buttons to send it off to her laboratory a few corridors away.

Veloso, a computer science professor at CMU, in Pittsburgh, has worked for over two decades to develop such autonomous mobile robots. She believes that humans and robots will one day coexist, and my robot escort, named CoBot (for Collaborative Robot), is one of her contributions to that future.

Her far greater contribution is as the force behind the global sensation of robot soccer. The RoboCup competition, which she has championed since its earliest days, has not only advanced the field of robotics but also drawn many

Manuela Veloso	57	Robotics researcher, Carnegie Mellon University	Pittsburgh	She promoted the international robotics competition as a vehicle for training young researchers and advancing autonomous robots.
IEEE FELLOW	**AGE**	**OCCUPATION**	**LOCATION**	**HERO MOMENT**

PHOTOGRAPH BY Ross Mantle

into the discipline, shaping bright minds into skilled researchers and designers. The 2013 championship in the Netherlands attracted 410 teams from 45 countries and 40,000 spectators. It's safe to say that the phenomenon would not have gone as far if not for Veloso's pioneering research, energetic promotion, and keen foresight.

Veloso's introduction of artificial-intelligence techniques to RoboCup was a game changer, says Minoru Asada, a robotics professor at Osaka University, in Japan, and a founder of RoboCup. As a leader in RoboCup and in related research and education, Veloso has mightily advanced robotics, he says, calling her work "an invaluable bridge" between AI and robotics.

Veloso walks fast and talks in bursts, her spry body barely containing the energy inside. Back in the early 1990s, Veloso was a freshly appointed professor at CMU, where she'd received her Ph.D., and she had an interest in artificial intelligence. In 1994, at an AI conference, she saw a demo of some soccer-playing robots. Despite growing up in soccer-crazed Portugal, she cared little for the sport. But as a challenge for autonomous systems, it was perfect, she says. And so she became one of the first researchers to jump at it.

She started by developing soccer simulations with her student Peter Stone, now a professor of computer science at the University of Texas at Austin. Soon after, Veloso and other students began designing small robots that could observe, reason, act, cooperate, and learn while moving about on a field. It took her team two years to get the motors, controllers, and sensors right. Even trickier was figuring out how to make five of them play together.

In 1997 she cofounded the RoboCup Federation and helped launch the first games. She later held various leadership roles and continues to advise the CMU team. The change over the years has been remarkable. Early on, researchers were lucky if their soccer-playing automatons moved as programmed. These days, teams of humanoid robots play real games, complete with defensive and offensive tactics and penalty shoot-outs.

That sophistication is due in no small part to Veloso's own contributions to AI. The roughly coffee-can-size cylindrical robots that her team competes with in the Small Size Robot League–in which they hold the most finals titles–plan their moves with stunning accuracy, shooting balls with such force that they've left dents in her lab's walls. The team's early bots were made with Erector sets, but even then their intelligence surpassed that

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of other machines. Veloso's secret weapon was a vision algorithm that used lines, patterns, and color to help each robot track the ball and other bots.

In 2009, Veloso shared her team's vision software with other competitors, establishing an open-source approach that both leveled the field and raised the bar at RoboCup.

RoboCup's official goal is for a robot team to defeat the human World Cup champions by 2050. Indeed, a highlight of the games is always the final match, between the top team of robots and some talented amateurs.

But beating humans at the sport is a means, not an end, Veloso says matter-of-factly. The real goal, she says, is to hone both robots and roboticists. After all, robots that serve an accurate pass could also serve lunch. "The idea is to push robots well beyond the playing field and into daily life," she says. She has been instrumental in establishing the new RoboCup@Home, RoboCupRescue, and RoboCup@Work competitions, which test robots in realistic domestic, disaster, and industrial settings.

Just as she envisioned robot soccer as a powerful vehicle for inspiring a new generation of roboticists, Veloso also sees the great potential for CoBot and other thinking machines to one day help humans at the office, on the shop floor, and in the home. It's a work in progress, says Veloso. "The beautiful thing about AI and robotics is that you're never done."

—PRACHI PATEL

The Humanitarian Inventor

Ashok Gadgil's work on water purification, cookstoves, and arsenic removal has bettered the lives of tens of millions of people worldwide

No! No! No! In Ashok Gadgil's cluttered office at the Lawrence Berkeley National Laboratory, hidden among the stacks of books and awards and whiteboards and ID badges from humanitarian organizations, you'll spot tiny pictures of former U.S. first lady Nancy Reagan. "Just Say No!" each picture implores.

Gadgil has appropriated Reagan's antidrug slogan for his own ends. "I tend to say yes too often," he laughs. "Saying no is valuable, because I'm interested in lots of stuff, but my time is full."

Gadgil's career is a testament to being interested in many things. Starting with a Ph.D. in physics in 1979 from the University of California, Berkeley, he moved from working on the general theory of relativity, to applied math, to computational fluid dynamics, to mechanical engineering. "Kind of a convoluted way to get there," he admits. "But I wanted to do something that was closer to having a societal impact."

For more than two decades, Gadgil has focused his energy and expertise on devising technologies that help the poorest and the most vulnerable. Early on, he realized that to provide the biggest benefit to the most people, he'd have to be both disciplined and pragmatic in selecting which projects to undertake.

His first foray into socially beneficial technology was sparked by a 1993 cholera epidemic in south and southeast Asia, which left thousands dead. Preventing outbreaks of such waterborne diseases could save millions of lives each year. So Gadgil began investigating ways to use ultraviolet light to disinfect water. By 1996 he had devised a 60-watt water treatment unit (later reduced to 40 W) that's the size of a microwave oven and runs on a car battery or solar cell, sterilizing 15 liters of water per minute with minimal oversight or maintenance. The lab patented the system, called UV Waterworks, and then licensed it to WaterHealth Inter-

Ashok Gadgil	65	Environmental engineer, Lawrence Berkeley National Laboratory and UC Berkeley	Berkeley, Calif.	He's devoted his career to identifying technologies to benefit the most vulnerable–and then inventing them.
IEEE MEMBER	AGE	OCCUPATION	LOCATION	HERO MOMENT

national, a company that specializes in providing drinking water to rural areas. To date, about 5 million people have benefited from Gadgil's system, which has saved 1,000 or more lives per year.

"It's good," Gadgil says. "It needs to go to 500 million."

The water purifier was just a start. In 2004, the U.S. Agency for International Development (USAID) asked Gadgil to help design a more efficient stove for the millions of refugees living in camps in the western Sudan region of Darfur. Traditional wood-burning stone fireplaces are inefficient, and women must risk their safety to hunt for firewood or else trade their food rations for fuel.

"I didn't want to design a stove for Darfur," Gadgil admits. "People had been designing fuel-efficient stoves for 30 years. So I said, 'Here are some stoves. Why don't you get some and test them?' " Instead, his USAID contact asked Gadgil to test the stoves himself. It soon became apparent that none of them was enough of an improvement, so Gadgil led the development of an entirely new design: the Berkeley-Darfur stove.

Now on its 14th iteration, the Berkeley-Darfur stove burns less than half the wood or charcoal of a traditional stone fireplace, boils water almost twice as fast, reduces CO_2 emissions by over 1.5 metric tons per year, and saves the average family in Darfur the equivalent of US $300 per year in fuel. Getting from version 1 to version 14 involved focusing on what the refugees needed and wanted. The stoves were modified to make them cheaper and simpler to manufacture locally; refugees receive them for free, while local villagers can buy the stoves for US $20. About 40,000 of them are now in use in Africa.

Located in the hills above the UC Berkeley campus, Lawrence Berkeley National Laboratory commands a gorgeous view of San Francisco and the Golden Gate Bridge. The land here would likely be packed with multimillion-dollar homes if it weren't instead devoted to "bringing science solutions to the world," as the lab's slogan puts it. Gadgil's stove lab is housed in a small shed that used to store radioactive materials. It sits behind a thick concrete wall intended to protect nearby buildings from stray radiation.

When we stop by, three grad students are measuring smoke-particle distribution with lasers. The stove is now being adapted for use in Ethiopia, Haiti, India, and Mongolia. More generally, Gadgil and his team are trying to find ways to reduce particulates, carbon monoxide, and other toxic emissions by a factor of 10. These emis- | CONTINUED ON PAGE 56

PHOTOGRAPH BY Gabriela Hasbun

Topher White IEEE MEMBER	33 AGE	Founder and CEO, Rainforest Connection OCCUPATION	San Francisco LOCATION	He tackles the twin scourges of e-waste and deforestation with an alert system built from discarded cellphones. HERO MOMENT

The Rain Forest's Defender

Topher White's solar-powered, repurposed cellphones can detect the sounds of illegal logging

Like many people, Topher White knew that the Earth's forests were rapidly disappearing. But there didn't seem to be much that the young physicist could do to stop it.

Then, in July 2011, White and his girlfriend (who's now his wife) were volunteering at an ape sanctuary in Indonesian Borneo when they stumbled upon loggers illegally cutting a tree into two-by-fours. "We had been walking just 5 minutes from the rangers' station, and yet you couldn't hear the chain saw," White recalls.

An idea came to him: He could reprogram used cellphones to listen for the chain saws and then send out alerts to the rangers, taking advantage of the site's surprisingly good cell coverage.

Over the next four years, White overcame nearly all the many obstacles and complications to realize this seemingly simple solution. He's run trials of the system on the Indonesian island of Sumatra and, more recently, in Cameroon, and he is now moving forward with a number of other deployments. Equally important, he's won the support of environmentalists and forest law-enforcement groups. Randy Hayes, founder of the Rainforest Action Network,

PHOTOGRAPH BY Gabriela Hasbun

calls White's system "a powerful tool that could do a lot of good on the planet."

Getting to this point hasn't been easy. When White started the project, he was still working for ITER, the international consortium that is building a nuclear fusion reactor in southern France. In his spare time, he tinkered with used cellphones on a workbench in his bedroom.

The following spring, he left ITER and moved to California to join a startup. But he couldn't stop thinking about the system he had conceived in Borneo. And so after just a few months, he left to focus full time on finishing the prototype and launching a nonprofit called the Rainforest Connection.

He opted for Android phones over iPhones because the former were easier to configure, and he replaced the manufacturer's version of the operating system with CyanogenMod, a popular alternative. For the acoustical-analysis software, White wrote scripts that scrutinize recorded sounds using Fourier transforms. An ornithologist suggested looking at chain-saw harmonics, which White discovered easily stood out from the forest soundscape.

The biggest challenge was power consumption. To cut the current draw, he shifted the number crunching to cloud servers, underclocked the processor, and disabled or ripped out every system on the phone that wasn't necessary, including the speaker, the vibrator, and the screen.

White had counted on using commercial solar panels, but he hadn't considered the diminished light under the tree canopy. Diving into the scholarly literature, he learned about sunflecks—transient spots of direct sunlight that comprise most of the solar radiation in the rain forest. He designed petal-shaped panels to harvest the sunflecks. Each petal consists of three 0.5-volt cells, wired in series, and seven petals are then wired to each device in parallel. White's solar flowers reliably generate 1.5 V, which he boosts to 5 V using a simple circuit.

After a successful test in the Santa Cruz Mountains, White headed back to Indonesia to test | CONTINUED ON PAGE 55

Brian Monks | 57 | Anticounterfeiting expert, Underwriters Laboratories
IEEE MEMBER | AGE | OCCUPATION

The Counterfeiter's Nightmare

Brian Monks keeps bogus electronics out of consumers' hands

Brian Monks, vice president of anticounterfeiting operations for Underwriters Laboratories (UL), is an affable guy, poking fun at himself in a gruff voice that bears traces of a British accent. But he approaches his job with severity and focus, operating his division like a highly trained police unit.

He and his team spend their days improving security on UL's certification marks, conducting undercover surveillance, scouring intelligence reports, and coordinating with law enforcement on raids. His work and determination have made Monks an international leader in anticounterfeiting. But even after two decades, the mission is still the same: stopping the criminals.

"Counterfeiters are trying to cheat and deceive," Monks says. "They only care about money, not our well-being, and it jeopardizes the safety of all of us."

A simple extension cord can be rendered dangerous by a counterfeiter. "It will look and feel like a real extension cord, but inside it's actually more like a telephone wire," Monks explains. "A hazard waiting to happen," it could eventually result in electrical shock or fire.

UL's main line of business is certifying a vast range of products, including batteries, lighting, appliances, even missile launchers. Last year nearly 23 billion legitimate products carried the UL logo. But countless counterfeit products camouflaged with a phony UL designation also turned up on the market, and detecting and deterring the counterfeiters has become an increasingly important part of the company's operations.

When Monks—who holds a B.S. in electrical and computer technology from New York Institute of Technology—joined UL in 1983, the company wasn't focused on counterfeiters. That all changed in the early 1990s, when customs agents at John F. Kennedy International Airport seized a shipment of fake goods bearing false UL labels. Monks suggested that UL start

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Melville, N.Y.
LOCATION

He leads an internationally recognized team dedicated to protecting the public's safety by checking the spread of phony goods.
HERO MOMENT

working with law enforcement, and UL's anticounterfeiting division was born.

One of the chief ways that Monks and his team thwart the counterfeiters is by enhancing the security features on UL labels. "Anytime you add something new, it's harder and more expensive for the counterfeiter to duplicate," he explains. In recent years, the company has turned to holographic materials, sequential numbering, and covert security coding. More complex products get labels embedded with microchips.

He and his team also offer training on how to fight counterfeiting. Several years ago, Monks helped create the International IP Crime Investigators College, a joint initiative between Interpol, the international police organization, and UL that educates investigators on how to enforce intellectual-property laws and stem counterfeit manufacturing. "UL can't do this work all by itself," says Monks. "It's a global problem."

Still, he admits, there are many more counterfeiters than there are people like him. "It can be frustrating," he says. "But that's what drives me in this job and makes me want to come in every day and work harder to stop them."
—NEEL V. PATEL

Medical MacGyver

Robert Malkin is inspiring students to tackle urgent problems in the developing world

It's 1989. Five years after earning his bachelor's degree in electrical engineering, Robert Malkin is designing cardiac pacemakers in Switzerland. It's a good job, but he's unhappy. Very unhappy. "I decided I didn't want to be an engineer," he says. "Actually, I didn't want to work anymore, period. I had a party, burned my time card, and disappeared into the sunset."

Disappeared into the *sunrise* is more like it. Malkin headed southeast to Thailand, where he joined a YMCA-sponsored team that was trying to get poor Thai parents to stop selling their daughters into that country's booming sex trade. "It was more or less sexual slavery," says Malkin.

The team had a simple strategy: to give vulnerable girls some skills that would make them too valuable to sell off. His job was to teach the girls English so they could help customize and peddle the handicrafts the villagers were making for tourists.

PHOTOGRAPH BY David Yellen

Robert Malkin	52	Biomedical engineer, Duke University	Durham, N.C.	He left a tenured professorship to work on health-care challenges in the developing world.
IEEE SENIOR MEMBER	AGE	OCCUPATION	LOCATION	HERO MOMENT

In one village his team visited, the local product was blue Mao shirts. The dye process required soaking the shirts for four or five days. Another volunteer showed them that by regulating the temperature, they could shorten the dyeing to just 45 minutes, recalls Malkin.

"That guy knew a really small tidbit of information," he says, yet it was enough to change the economic calculus. "Overnight that village stopped selling their girls into prostitution." The episode taught him that a tad of clever engineering can sometimes make an enormous difference in people's lives.

Malkin then got a good offer to return to the United States and enroll in graduate school at Duke University, in Durham, N.C. His plan was to get a Ph.D. and return to the mountains of Thailand.

He soon earned master's and doctoral degrees in electrical engineering, specializing in a biomedical application aligned with his earlier work in Switzerland: cardiac electrophysiology. But he didn't go back to Thailand. Instead, he got married, started a family, and took up faculty appointments, eventually landing at the University of Memphis and the University of Tennessee. He was granted tenure and later became a full professor.

Malkin knew that his academic research might improve some people's lives, but not in the direct way he had witnessed in Thailand. He and a like-minded engineering colleague, Mohammad Kiani, often discussed their frustration. "We had both spent time in the developing world and realized that engineers had a unique opportunity to make a difference," says Malkin. But how exactly?

They approached William Novick, a surgeon with the Memphis-based International Children's Heart Foundation, and asked his advice. He suggested they join one of the teams of cardiac surgeons that the foundation sent to developing-world hospitals. The engineers could presumably help out if a piece of equipment malfunctioned.

"The very first day of the very first trip, the heart-lung machine broke," recalls Malkin. "The surge protector had blown out–it was a 5-minute fix." For an electrical engineer, that is. Most surgeons and nurses wouldn't know how.

In his free hours Malkin discovered a lot of defunct equipment. Kiani found the same to be true in the hospitals he visited. So they hatched a plan to provide such hospitals with surplus gear from Tennessee. "We collected university equipment and formed a club to fix it and prepare it for shipping," says Malkin. "Very soon we started getting calls from hospitals throughout the developing world." So they began sending these facilities both equipment and engineering students to help keep things working.

His university grew uneasy with the legal liabilities this activity created, though. So Malkin, Kiani, and a business partner set up a not-for-profit company called Engineering World Health. Even then, Malkin's department chairman wasn't pleased. He wanted to see Malkin remain focused on academic research and grant seeking.

"It created a huge tension," says Malkin. "So I left."

In 2004, he walked away from an endowed full professorship to take up a non-tenure-track faculty position in biomedical engineering at Duke, where Malkin is a lot happier. There, he's been able to get his | CONTINUED ON PAGE 55

PHOTOGRAPH BY D.L. Anderson

Can You Trust Your Fridge?

TODAY'S INTERNET OF THINGS IS FULL OF SECURITY FLAWS. WE MUST DO BETTER

By Alan Grau • Illustration by J.D. King

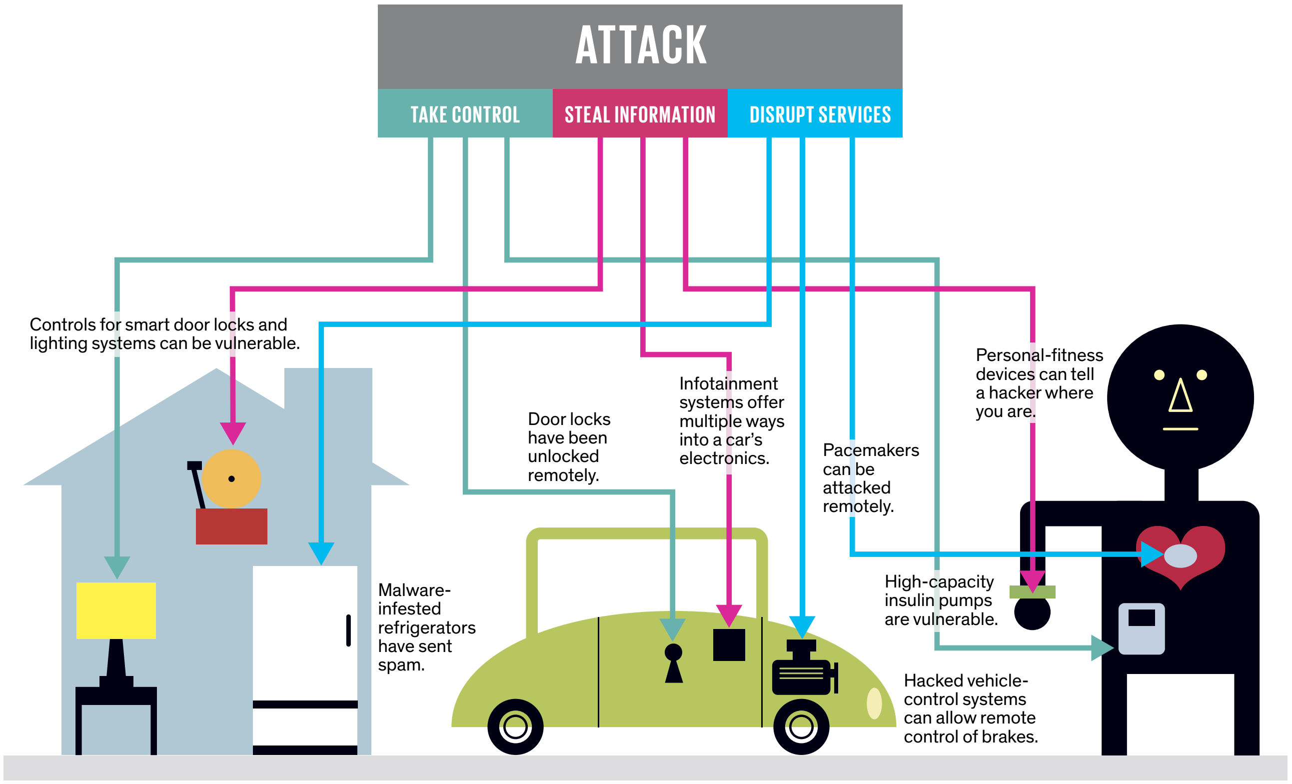
Imagine a criminal using your nanny cam to watch your house or to scream at your child—or even to post footage of your home on a crime boss's website. And suppose your refrigerator were spewing spam e-mail, enraging people you'd never even met.

The Internet of Things has been touted as many things. But what you haven't heard is that it could be your worst enemy. Yet all of these incidents have actually occurred, according to news reports. And it's likely that even more disturbing transgressions have been taking place unbeknownst to homeowners. For example, researchers have discovered that in some cases, they can hack the Internet of Things to intercept each document you print and divert it to a remote site, use your smart TV to bug your house, and even control the traffic light on the corner outside your home.

For although the Internet of Things offers great convenience by linking our gadgets—an estimated 50 billion of them worldwide by 2020—it can also let hackers take control of your house, your car, and even your body.

The vulnerabilities lie all around you. A recent HP Research study reported that the average Internet of Things gadget has an astounding 25 security flaws, and 70 percent have at least one such vulnerability. Many of these problems may yield to solutions like those adopted by the personal computer industry decades ago. As I'll explain later, there are also some that require new approaches that take into account the vast scale and narrow profit margin of the emerging world of Internet-augmented products.

LET'S START WITH YOUR HOME. Your smart meter—if you don't have one, you soon will—can turn off selected appliances, such as air conditioners, whenever the power network is close to being overwhelmed. That's fine. What's not so fine is if a hacker gets into your home's smart meter and makes it cut off elec-



NO PLACE TO HIDE: With the Internet of Things spreading throughout our homes, cars, and even bodies, new vulnerabilities seem to emerge almost daily. The smart locks and security systems in your home could be disabled by a would-be burglar. Your car could be forced to unlock its doors and start its engines; a thief would only have to get in and drive. Implanted pacemakers and insulin pumps are also vulnerable to hacking.

tricity to security systems. That would certainly simplify a burglary attempt. A Web-connected security system could also be hacked directly, with a hacker using a brute-force attack to guess your password. In fact, a Russian website may have already done the job. The site, which was recently shut down, provided links to 73,011 locations with unsecured security cameras in 256 countries. In an unrelated incident, a hacker in Cincinnati compromised a baby monitor and used it to scream at a sleeping infant.

Or perhaps you have the latest smart locks, the kind that let you use your smartphone at a distance to open the front door for a guest. Perhaps you also have Web-connected lighting systems. Wouldn't a would-be burglar love to unlock the doors, turn off the lights, and disable your home security?

Now consider your car. It has or soon will have the ability to record and report diagnostic information, remotely start and turn on the heat when signaled by your cellphone, and use integrated GPS, map, weather, and traffic data to select the best route. But these capabilities also mean that hackers can remotely flash your car's lights, enabling them to identify it on your street, unlock the door, start the engine, and drive it away. Hackers might even gain control of the car while you're driving it, thanks to malware that infected the car when it communicated with a computer back in the repair shop. In February 2014, the U.S. Department of Transportation began working on a regulatory proposal that would require all new vehicles to be equipped with car-to-car and car-to-infrastructure communication capability, providing yet another path for reaching into automobiles remotely.

Your body itself may not be safe from hackers. Already patients are being monitored and even treated with medical devices like pacemakers and insulin pumps, ventilator systems and blood chemistry monitors. These products are connecting to the Internet because it's so much better to monitor patients in their homes than in medical facilities. But if a personal health device connects to the Internet, it can be hacked.

In an episode of the TV show "Homeland," a murderer kills remotely by accelerating a heart pacemaker—a trick that hasn't been reported in real life but has been demonstrated in the lab. In fact, doctors disabled the wireless capabilities in the pacemaker of former U.S. vice president Dick Cheney to protect him from such malfeasance. If this kind of attack happened to an implanted pacemaker, we might never know; it might be impossible to distinguish between a product malfunction and a cyberattack. Researchers have also demonstrated that insulin pumps, used to help control diabetes, can be remotely instructed to pump out all their insulin at once, killing or severely injuring the user. The same applies to pain medication pumps.

More subtle hacks might be tried to avoid arousing suspicion. A criminal might tweak a monitoring system so it would report that a dangerously sick patient was just fine.

ICONS: J.D. KING

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INFILTRATING THE INTERNET OF THINGS (or IoT, for short) doesn't necessarily require a dedicated computer coder gone bad, willing to devote long hours to finding a vulnerability. These days, an amateur hacker can download existing tools and use them to conduct a basic attack. On the other end of sophistication, organized crime and nation states have entered the hacking game.

Unlike business computers, which for decades have been sheltered behind corporate firewalls and intrusion detection and prevention systems (IDPS), the products now being linked to the Internet are frequently on their own. A Columbia University study that ran a set of attacks against business systems and embedded systems in such consumer products as home entertainment systems, webcams, and Wi-Fi access points found problems in just 2.46 percent of the business products–and a whopping 41.62 percent of the consumer products. Even in those products that do have shields, the protections are often not enabled or are undermined by the use of default or weak passwords.

Too many manufacturers worry more about getting a product to market quickly than securing it. In some cases, a manufacturer has taken an apparatus designed for use in a private network and simply connected it to the Internet without building in any protection to speak of. It's also true that the devices themselves are often so small that it's hard to build in the right protection.

And most IoT products, even if secured, have no way to automatically update their security software when vulnerabilities are discovered. As things now stand, bad actors can exploit any vulnerability they find for as long as the 10 or even 20 years the devices remain in use.

The situation has got to change. Product makers–and the people who use these gadgets–have to protect against hacking. And it is possible to do it.

HACKERS WHO ATTACK ALL THESE SYSTEMS–home, car, and health–are typically trying to do one of three things: take control of the apparatus, steal information, or disrupt service.

Taking control of the apparatus means somehow logging in as an authorized user, perhaps by figuring out the password, finding a backdoor, or compromising the authentication mechanism. Strong authentication methods–such as randomly generated passwords; secure, token-based authentication; biometric authentication; and certificate-based authentication–can make this much more difficult.

Stealing information can mean eavesdropping or getting into the systems and collecting data, such as patient information from a medical device or credit card numbers from a TV used for home shopping. It can also mean using a product like a phone system, printer, or video camera to collect and transmit data. Disrupting service usually means flooding a system, such as a home-security or vehicle-control system, with messages in order to make it unable to function.

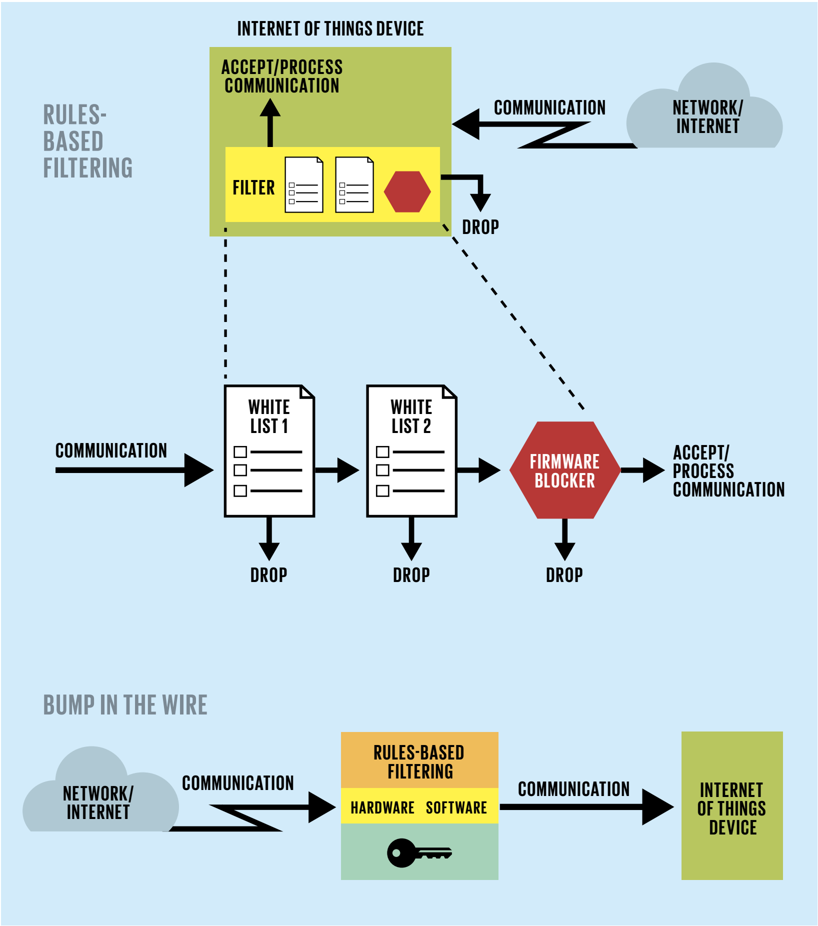
The simplest way to stop all these attacks is by preventing hackers from communicating with the gadgets they are trying to hack. And that means using a firewall and an IDPS.

A firewall acts as a gatekeeper, blocking traffic that should not be permitted to pass through. An IDPS monitors the computer

EMERGING STANDARDS FOR IoT SECURITY

Security standards for IoT products are evolving. Most of the current standards came out of a specific industry or application—for example, the North American Electric Reliability Corp. has set critical infrastructure protection (CIP) standards to secure the electric grid, the U.S. Food and Drug Administration has a set of guidelines to help product makers better protect patient health and information, and the National Institute of Standards and Technology has created the somewhat broader Cybersecurity Framework to help the financial, energy, and health-care industries. Some relate peripherally to the Internet of Things. But new standards specifically targeted at the IoT are beginning to emerge. These include:

- **The Industrial Internet Consortium:** The Industrial Internet describes a world in which physical manufacturing and other machinery connects with sensors and software that gather data, analyze it, and use it to adjust the machinery—essentially, the nonconsumer IoT. The IIC was created to make sure that products from different companies can easily share data; its members will be building security protections into its reference architectures.
- **The Open Interconnect Consortium:** This group of technology companies, such as Cisco, Intel, and Samsung, is developing interoperability standards for the IoT and will consider security as it does so.
- **The International Standards Organization's (ISO) Special Working Group on the Internet of Things:** This group is assessing existing standards that might apply to the IoT along with current efforts to develop standards; it plans to help guide their evolution to better account for security. For example, this may mean that the world's most widely adopted family of information technology security standards, ISO 27000, gets an update that will make it able to work better with the IoT.
- **IEC 62443/ISA99, Industrial Automation and Control System Security Committee:** This committee develops security standards and technical reports that define procedures for implementing secure industrial automation and control systems.
- **A number of IEEE standards address elements of security that can be applied to the Internet of Things,** including IEEE P1363, a standard for public-key cryptography; IEEE P1619, which addresses encryption of data on storage devices; IEEE P2600, a standard that addresses the security of printers and copiers; and IEEE 802.1AE and IEEE 802.1X, which address media access control security.



DEFENSIVE WEAPONS: Rules-based filtering [top] uses a small set of policies—such as no unauthorized remote updates of embedded firmware—to block dangerous commands from getting past a simplified firewall. Rules-based filtering systems can also consult white lists of trusted computers so that only "good guys" have access to certain functions. A "bump in the wire" approach relies on a small, dedicated piece of hardware and software that sits between an IoT device and the Internet; a bump in the wire can shield devices that don't have built-in protection.

system and the network to which it is attached to detect, block, and report suspicious activity. But the software for firewalls and antivirus programs takes up a lot of storage space and requires a lot of processing power to run. Most things in the Internet of Things can't handle the software.

WE HAVE TO TAKE A DIFFERENT APPROACH. For the most part, the gadgets that make up the Internet of Things are what we call embedded systems–that is, dedicated computers that perform specific functions within more complex systems. For instance, they might control the operation of a machine within a water-processing plant, manage the lighting of a smart home, or monitor an organ in the human body. Limiting the function means they can be small, fast, and efficient.

The security systems must be just as specialized, protecting only against the specific attacks to which the equipment is vulnerable. Yet we don't want to completely reinvent the wheel each time we create a new smart thermostat or television, so we also need a system that's flexible enough to shield devices as diverse as automobile communication gateways, home printers, and smart door locks.

To do this, you need to pay as much attention to what you omit from the embedded security system as to what you include. What we don't need are systems with powerful processing engines and large databases of virus signatures and other chunks of code that act as fingerprints to help detect known threats. Instead of databases, IoT security can use rules-based filtering.

To understand how this works, let's look at a home printer; it's similar to a lot of other IoT devices. A printer has only a few communication ports and a limited number of communication protocols. It supports both print commands, which may be sent from any other device, and administrative commands that are accepted only if received from a few predetermined computers. A small set of simple firewall policies known as a white list is all it takes to enforce these two distinct communication policies. One set of white-list rules allows communication from any device that knows the printing protocols. Another white list specifies that administrative commands will be processed only if they are from a machine on the white list. An additional rule blocks print commands that contain embedded firmware updates to make sure that malicious users cannot modify the behavior of the printer.

The complete firewall policy may consist of as few as 5 to 20 rules as opposed to the 200 to 2,000 rules of a typical business computer's firewall. This smaller, faster, simpler approach to an IoT security system does not compromise security; it allows anyone to print with the machine while preventing malicious users from changing settings, downloading firmware, or performing other harmful actions (like sending copies of anything you print to a third party). Other, specific sets of rules could protect door locks, cars, or pacemakers.

SOME OF THE MAJOR PLAYERS in the embedded-systems market–Green Hills, Intel, McAfee, Mentor Graphics, Renesas, Wind River, and Zilog–are already incorporating such embedded security technology into the hardware and software building blocks used for IoT devices. These companies typically don't make the connected products themselves but rather the processors and operating systems used to build IoT equipment. But given that some devices in the Internet of Things are rarely replaced, it will likely take a decade or two–or more–to bring all systems up to modern security standards. New systems

ILLUSTRATION BY Mark Montgomery

will likely have higher levels of security, but vulnerabilities are bound to exist for the foreseeable future.

There are two approaches for securing existing systems. For newer products that support software updates or those that are still being developed, the manufacturer can build a firewall and security capabilities into the product's software. The makers of gadgets like the Nest thermostat can take this approach. Many older systems have communication capability but don't support software updates–say, older hospital-monitoring systems and older factory-control systems. Here it may be possible for consumers or the product manufacturer to add a firewall through the "bump in the wire" approach. This refers to a box sitting between the target apparatus and the Internet that contains hardware and software to shield the device from attack. My company, Icon Labs, makes such a system, the Floodgate Defender. Tofino Security and Innominate Security Technologies offer similar products.

As equipment becomes more secure, this approach may no longer be needed, but it provides an immediate solution for vulnerable items.

A FIREWALL, HOWEVER, isn't enough to protect the Internet of Things against hackers. That's because manipulation isn't the only problem–there's also eavesdropping.

Data encryption is therefore needed also. Smart locks and heart pacemakers need strong passwords, the kind that include letters, numbers, and perhaps special characters as well. Even better, products should include certificate-based authentication–that is, an electronic document that identifies an individual, a piece of equipment, or some other entity addressing the gadget. This technology is used today in point-of-sale terminals, gas pumps, and ATMs, and it will likely be incorporated into future versions of home medical devices and home security solutions. It hasn't reached these products yet in part because manufacturers haven't invested in the up-front engineering effort necessary to make this kind of security work with their hardware.

One reason for the lag is the market itself. These are high-volume, low-margin products, so the cost of additional memory and a faster processor could make a product less competitive. Even worse than cost, though, is the problem of integrating a product with the other Internet-linked products in a home. For example, if a smart door lock uses certificate-based authentication, then the smartphone that communicates with the door lock must also handle such authentication. Working this all out in a way that is easy for the consumer to use will take time.

To make the Internet of Things even more secure, product manufacturers can integrate a device-management agent into their products. This piece of software would allow the product to communicate with a security management system, like the McAfee ePolicy Orchestrator. The agent would report things like failed access attempts and attempted denial-of-service attacks.

It could also be used to update security software as threats emerge. Again, the trick is going to be getting this to work without making the devices that use it a lot more expensive and unduly complicated. Industry is just starting to work on this approach.

In the meantime, there are a few things you can do to protect your connected gadgets. If you are on a personal computer or mobile device, make sure that any available firewall and antivirus software is activated and up-to-date. Make sure you scan your system regularly to identify and remove any malware or possible intrusions. A computer infected with malware or breached by a hacker can be a launching point for attacks against the IoT equipment in your home, or it may store passwords for IoT products that the hacker can use.

If your apparatus allows you to set user names and passwords, make sure to turn that capability on and also create passwords that are not easy to guess. Don't use your name, your kids' or spouse's names or birthdays; do use unique spellings, number combinations, characters, and symbols, such as ampersands, question marks, or asterisks. I know, you've heard this all before, but it bears repeating because too many people still are setting their passwords as "password."

Finally, watch out for phishing and social engineering. Hackers are very clever when it comes to sending e-mails and messages that ask for user names and passwords. Be very suspicious. If you get a phone call asking for this confidential info, don't give it. Make sure you hang up and then call the number of the business or organization that the caller had claimed to represent. Don't use any phone number the caller may provide.

The situation will get better. Manufacturers are becoming more aware of the need to protect their Internet-connected products. Research is under way to develop new biometric authentication methods for the mobile devices you use to control your Internet of Things, providing authentication based on retinal scans, hand geometry, facial recognition, and other hard-to-spoof human attributes. The fingerprint authentication introduced in Apple's iPhone 5s is a huge step in the right direction.

And consumers are slowly developing good judgment. By combining commonsense methods with state-of-the-art security technologies, we can prevent hackers from turning our devices against us.

In the not-too-distant future, self-driving cars, wearable gadgets, and smart homes will communicate without our constant monitoring, automating many of our everyday tasks. Robots–guided by GPS beacons and connected sensors–will assist in firefighting, law enforcement, and search-and-rescue operations. Wearable and implanted health-care systems will take care of us outside of doctors' offices. But we will be unlikely to use any of these amazing new technologies if we don't remove the fear of cyberattack and build what is truly an Internet of *Secure* Things. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/internetofthings0315

MEDICAL MacGYVER

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students directly engaged with the health-care problems of the developing world. And in 2009, he launched the Global Public Service Academies, which arranges for high school students to volunteer at clinics and hospitals in Central America. What's more, something happened that surpassed even his most optimistic expectations: The engineering students he was educating about health-care problems in the developing world actually started solving some of them.

The student-designed equipment includes battery-operated lights to treat newborns suffering hyperbilirubinemia, a common form of jaundice, and special packaging for antiretroviral drugs that can help pregnant women with HIV avoid passing the virus to their babies. Getting this equipment into the right hands is an economic and logistical challenge, but Malkin and his colleagues have come up with creative solutions, including setting up not-for-profit companies to sell the products cheaply to facilities in need.

"He's woven this into the fabric of his profession–and his life," says Kiani, now at Temple University, in Philadelphia. And by doing so, Malkin gets to revel every day in the realization that so moved him as a young man in Thailand: that a little engineering know-how, applied to the right problems, can do an enormous amount of good.
—DAVID SCHNEIDER

THE RAIN FOREST'S DEFENDER

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his system. On the second day, midway through the installation, the first alert came through. The group raced to the site to confront the loggers, there was an amicable discussion, and the loggers left–and stayed away even after the pilot program ended. The devices operated for about a year; they could detect sounds up to a kilometer away, so each phone can monitor about 300 hectares.

Word of the successful test spread quickly among the conservation community, helped in part by a Kickstarter campaign that raised US $167,000 last July. A few months later, Rainforest Connection, with the Zoological Society of London, announced a second trial, in Cameroon. And later this year, White's team will install devices in the Brazilian Amazon, to provide real-time information to the Tembé, an indigenous community that is fighting to protect 600,000 hectares in the northeastern Amazon.

To have a real impact on deforestation, White knows he will have to expand far beyond these pilot programs and also figure out how to operate in places that lack terrestrial wireless networks. First, though, there's a global network to be built and millions of hectares of forest to protect, one refurbished cellphone at a time.
—ELISE ACKERMAN

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THE HUMANITARIAN INVENTOR

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sions cause more than 4 million premature deaths annually, mostly among women and children.

After we leave the stove lab, we drive down Cyclotron Road onto the Berkeley campus to see Gadgil's water lab. Inside is a prototype of his next project: a low-cost, sustainable way to remove arsenic from drinking water. Over 60 million people in India and Bangladesh drink groundwater that's been naturally contaminated with arsenic at up to 100 times what the World Health Organization considers safe. And arsenic poisoning now kills one out of every five adults in Bangladesh.

Gadgil notes that many people have tried to do arsenic decontamination at the household level. "But in most of the developing world, the infrastructure doesn't exist," he explains. "People normally leave their homes to collect water." Insights like these helped Gadgil think about the scale of the technology that was needed. He concluded that centralized water sources are the easiest to integrate into communities and the most efficient to build and maintain.

To learn more about our engineering heroes and their work, or to post a comment, please visit http://spectrum.ieee.org/heroes0315

"Knowledge of how people live, and what their practical lives are like, has been useful in forming the design and vision of dissemination or implementation," Gadgil says. "And that gets folded into the design itself."

On the way back up the hill to Gadgil's office, I ask him how it feels to have been recently inducted into the National Inventors Hall of Fame for his work on safer drinking water. Gadgil's hexagonal tile at the hall, in Alexandria, Va., hangs between those of Steve Jobs and Arthur Fry, inventor of the Post-It Note. Indeed, most of the Hall of Famers "do phenomenal work, but it's been predominantly with first-world markets," Gadgil observes. His work, which the citation says has made a difference in the lives of about 100 million people, "is kind of a departure," he says.

The next steps for the stoves and the arsenic-removal system will be to move the innovations from his labs into the world at a scale where they can have a real impact.

And after that, even more problems are waiting, he says. "There is always this scanning the horizon for where I could make a difference. What are the serious problems where I could apply my knowledge and my skills? There are many of them. We're not short of problems–we're short of bandwidth."

Gadgil laughs, and from behind his computer monitor, a tiny Nancy Reagan offers him advice. –EVAN ACKERMAN

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AND NOW THIS...

THE APEX OF ANALOG

WHO NEEDS DIGITAL?

Many of the first practical nonhuman computers were analog machines, most famously the mechanical Differential Analyzer built by Vannevar Bush in 1931. Even after digital computers arrived, analog computers remained popular into the 1970s, especially for simulations (they were used to drive flight simulators for the X-15 rocket plane and early spacecraft). And innovation continued well beyond the Differential Analyzer's wheels and cogs. As advertised in March 1964, this PACE TR-48 analog computer was not only "fully transistorized" but also mobile—once you put it on its stand and pushed it to another electrical outlet.

—STEPHEN CASS

PHOTOGRAPH BY Ben Alsop


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