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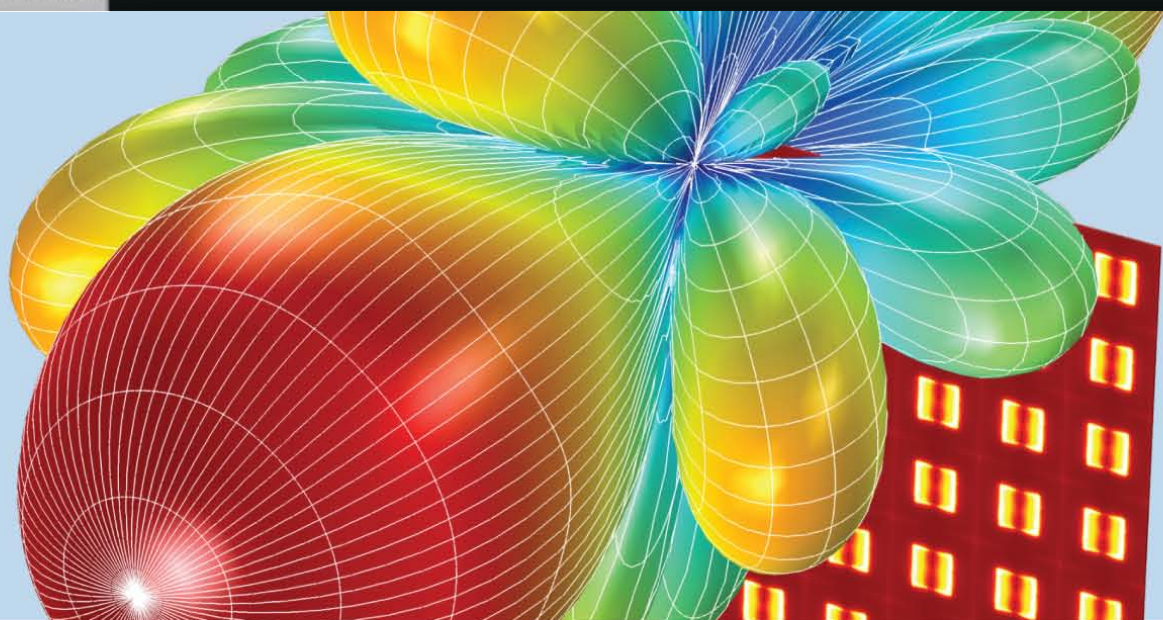
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MULTIPHYSICS FOR EVERYONE

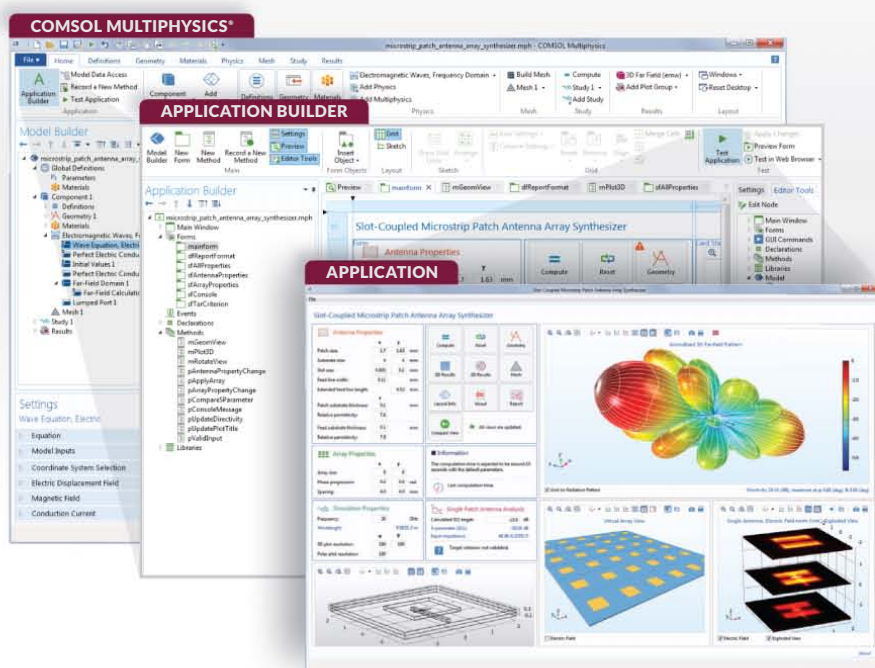
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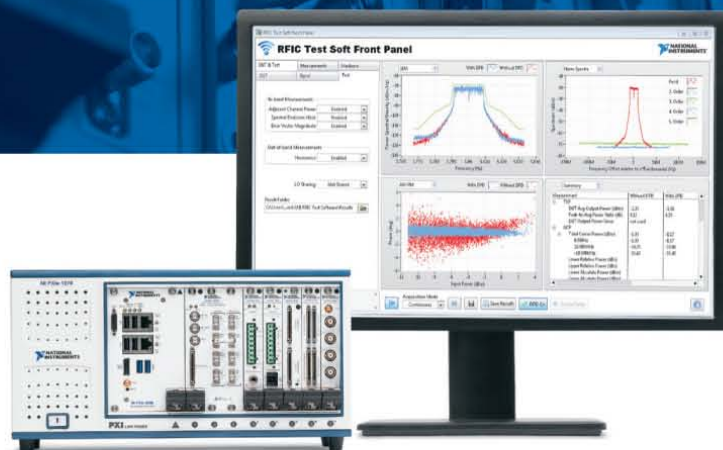
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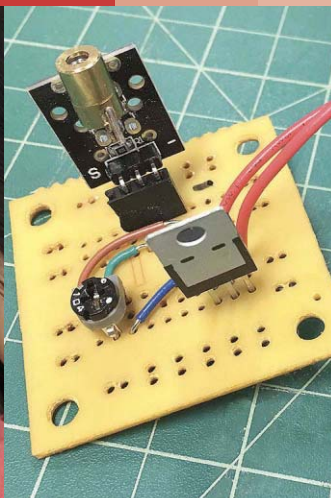
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BACK STORY_



Shaking Up Shipbuilding

IT'S FAIR TO SAY THAT FOR OSKAR LEVANDER, author of “Autonomous Ships on the High Seas,” in this issue, ships and shipbuilding are in his blood. His father, Kai, was a naval architect for Aker Yards, in Finland, where he helped bring innovation to what is generally a very staid industry. A cruise ship with a giant pedestrian promenade running down the center? Thank Kai Levander for that now-common configuration.

“As a young boy, I went to my dad’s office and played with a lot of models,” says Oskar, referring not to small display models but to things big enough to sit in. And today, from his perch as a vice president in Rolls-Royce’s marine division, he is spearheading his company’s efforts to bring advanced automation to ships.

For a pair of ferries now under construction for use in Norway, Rolls-Royce will supply what it calls an automatic crossing system, which will allow these ships to navigate from one pier to the other without human intervention. The idea is that the computerized system will always maneuver the ships in the optimal manner, saving energy—a key issue for these battery-powered vessels.

“This is the first step on the road to ferry automation,” says Levander. With higher levels of automation in the near future, such ferries will be able to dock themselves, too. Eventually, cargo ships will be able to navigate the high seas without anyone at the helm, guided either by computers or by remote captains issuing commands from distant facilities on shore.

While the notion of robotic ships might seem revolutionary, it’s really just part of an ongoing evolution in the shipping industry. “The size of ships’ crews has been declining for 150 years,” says Levander. “For some ships, that number will eventually go to zero.” ■

02.17

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SPECTRUM

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Susan Hassler, s.hassler@ieee.org

EXECUTIVE EDITOR

Glenn Zorpette, g.zorpette@ieee.org

EDITORIAL DIRECTOR, DIGITAL

Harry Goldstein, h.goldstein@ieee.org

MANAGING EDITOR

Elizabeth A. Bretz, e.bretz@ieee.org

SENIOR ART DIRECTOR

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SENIOR EDITORS

Stephen Cass (Resources), cass.s@ieee.orgErico Guizzo (Digital), e.guizzo@ieee.orgJean Kumagai, j.kumagai@ieee.orgSamuel K. Moore (News), s.k.moore@ieee.orgTekla S. Perry, t.perry@ieee.orgPhilip E. Ross, p.ross@ieee.orgDavid Schneider, d.a.schneider@ieee.orgDEPUTY ART DIRECTOR Brandon Palacio, b.palacio@ieee.orgPHOTOGRAPHY DIRECTOR Randi Klett, randi.klett@ieee.orgASSOCIATE ART DIRECTOR Erik Vrieling, e.vrieling@ieee.org

SENIOR ASSOCIATE EDITORS

Rachel Courtland, r.courtland@ieee.orgEliza Strickland, e.strickland@ieee.org

ASSOCIATE EDITORS

Celia Gorman (Multimedia), celia.gorman@ieee.orgWillie D. Jones (News), w.jones@ieee.orgAmy Nordrum, a.nordrum@ieee.orgSENIOR COPY EDITOR Joseph N. Levine, j.levine@ieee.orgCOPY EDITOR Michele Kogon, m.kogon@ieee.orgEDITORIAL RESEARCHER Alan Gardner, a.gardner@ieee.org

ADMINISTRATIVE ASSISTANT

Ramona L. Foster, r.foster@ieee.org

CONTRIBUTING EDITORS

Evan Ackerman, Mark Anderson,

John Blau, Robert N. Charette, Peter Fairley, Tam

Harbert, Mark Harris, David Kushner, Robert W. Lucky,

Paul McFedries, Prachi Patel, Richard Stevenson, Lawrence

Ulrich, Paul Wallich

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MULTIMEDIA PRODUCTION SPECIALIST Michael Spector

ADVERTISING PRODUCTION +1 732 562 6334

ADVERTISING PRODUCTION MANAGER

Felicia Spagnoli, f.spagnoli@ieee.org

SENIOR ADVERTISING PRODUCTION COORDINATOR

Nicole Evans Gyimah, n.gyimah@ieee.org

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EDITORIAL CORRESPONDENCE

IEEE Spectrum, 3 Park Ave., 17th Floor,

New York, NY 10016-5997

TEL: +1 212 419 7555 FAX: +1 212 419 7570

BUREAU Palo Alto, Calif.; Tekla S. Perry +1 650 752 6661

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+1 518 238 6514, don.lesem@ieeeglobalspec.com

VP, SALES & CUSTOMER CARE Peter Hauhuth

+1 303 594 8007, peter.hauhuth@ieeeglobalspec.com

SENIOR DIRECTOR, PRODUCT MANAGEMENT & MARKETING

Christian Noe

+1 518 238 6611, christian.noe@ieeeglobalspec.com

SENIOR PRODUCT MANAGER Linda Uslander

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+1 732 562 6399, c.amirat@ieee.org

PUBLICATIONS Michael B. Forster

+1 732 562 3998, m.b.forster@ieee.org

CHIEF MARKETING OFFICER Karen L. Hawkins

+1 732 562 3964, k.hawkins@ieee.org

CORPORATE ACTIVITIES Donna Hourican

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MEMBER & GEOGRAPHIC ACTIVITIES Cecelia Jankowski

+1 732 562 5504, c.jankowski@ieee.org

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+1 732 562 3820, constantin@ieee.org

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EDUCATIONAL ACTIVITIES Jamie Moesch

+1 732 562 5514, j.moesch@ieee.org

CHIEF FINANCIAL OFFICER &

ACTING CHIEF HUMAN RESOURCES OFFICER

Thomas R. Siegert +1 732 562 6843, t.siegert@ieee.org

TECHNICAL ACTIVITIES Mary Ward-Callan

+1 732 562 3850, m.ward-callan@ieee.org

MANAGING DIRECTOR, IEEE-USA Chris Brantley

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CONTRIBUTORS_



Ashok Jhunjunwala

Jhunjunwala is an electrical engineering professor at the Indian Institute of Technology Madras, in Chennai. Two years ago, *IEEE Spectrum* featured him in its "Engineering Heroes" special report, for his efforts to lift up the rural poor of India through innovations in telecom, banking, and power. In this issue, he elaborates on one of those innovations: solar direct-current microgrids, which his group is field-testing in several Indian states [see "The People's Grid," p. 42].



David Kushner

Contributing Editor Kushner's first virtual-world experience was in 1991, shooting arrows at boxy figures in the early virtual-reality game *Dactyl Nightmare*. Last year, he piloted Philip Rosedale's latest social VR venture, which he writes about in "Second Life Founder's Second Act" [p. 30]. When Kushner tries a new VR demo, he isn't picky about the graphics, as long as it draws him in: "You just want to put on the glasses and be somewhere else."



Scott Samuelson

Samuelson is director of the National Fuel Cell Research Center at the University of California, Irvine. In 2002, he helped introduce fuel-cell cars to the United States. A Japanese model drew stares wherever he drove it because the steering wheel was on the right. "They were probably thinking, 'How did he get that thing into the country?'" Samuelson says. In "The Automotive Future Belongs to Fuel Cells," [p. 36] he explores the technology's promise.



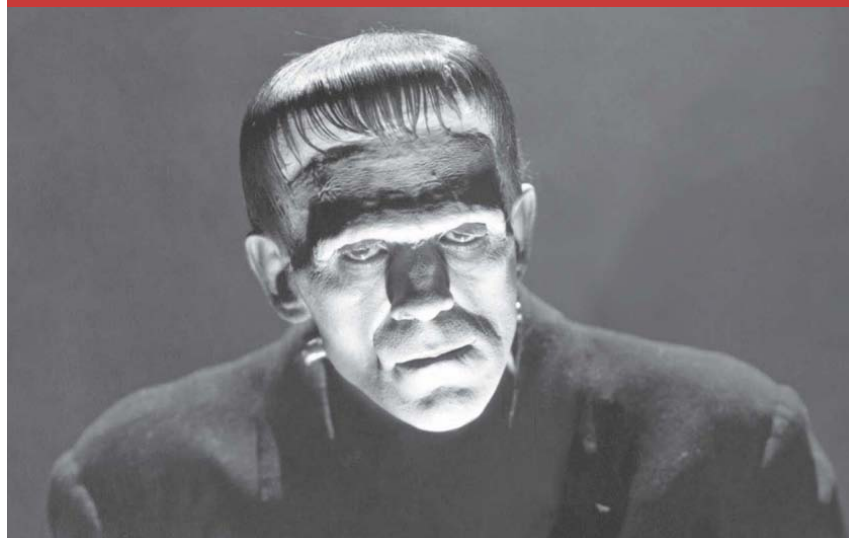
Andrew Silver

Silver, *Spectrum's* former editorial intern, wrote "4 New Ways to Store Renewable Energy With Water" [p. 11]. He took to the topic because, he says, the engineers involved "were taking an existing technology and adapting it to make the world better." Before *Spectrum*, Silver worked at the American Institute of Physics' Inside Science news service. He has now moved on to a data journalism internship at Correctiv, a nonprofit investigative journalism website in Berlin.



Richard Stevenson

Stevenson is a contributing editor of *Spectrum* and the editor of *Compound Semiconductor* magazine. In "Self-Healing Transistors for Chip-Scale Starships" [p. 9], he explores the electronics needed to survive a trip to Alpha Centauri at one-fifth the speed of light. "I'm shocked how fast a chip with a solar sail can go," Stevenson says. The self-healing transistor, he adds, seems "an elegant solution to a space mission to the stars in a reasonable time frame."



What *Frankenstein* Can Teach Engineers

Designing technology with the best intentions can still lead to disaster



When a designer of smartphone cases made a Frankenstein Monster model for the Samsung Galaxy Note 7, the company eerily presaged the fate of what has become the most notorious digital device of the decade. Banned from airplanes and the source of sundry injuries because of a penchant for bursting into flames, the Galaxy 7 deserves to be studied by engineers for lessons about responsible practice.

Samsung discontinued the phone in October 2016 and—at least publicly—has never given a comprehensive explanation as to why the doomed phone produces so many infernos. The mystery serves as a reminder that failure has much to teach engineers—and so does *Frankenstein*; or, *the Modern Prometheus*, the prescient 1818 novel by English author Mary Wollstonecraft Shelley.

This year is the 200th anniversary of Shelley's completion of her novel, in May 1817. Her scenario is simple: A man creates a living being, which, grown monstrous, turns on its creator. The experience of the fictional Victor Frankenstein, who used electricity to give life to an inanimate body, shows how the best intentions can lead to unintended consequences that mock and imperil creators.

To highlight the value of engineers confronting “the fundamental questions of creativity and responsibility,” MIT Press will issue in May 2017 a new edition of *Frankenstein*, specially annotated to illuminate the challenges facing technologists. “Mary was not a Luddite opposed to new technologies,” writes the late Charles E. Robinson, a Shelley scholar, in his lucid introduction. Not only was she tutored in contemporary understandings of electricity and biomedicine, she grasped the risks of acting on “forbidden knowledge and playing God,” Robinson writes.

While engineers and computer scientists don't design and build live, walking, talking monsters, they do create devices that have the qualities of living things. Who has not mistaken the synthesized speech of a networked com-

puter for an actual person? Who hasn't received emails from a bot and thought, Isn't that person nice?

Digital networks don't literally have eyes and ears, but they now hold over us the power of life and death. Many medical procedures depend on the accuracy of digital instruments. So do our electricity systems, commercial airplanes, subways, and of course, the Web. Every minute of every day, in short, the specter of a digital Frankenstein monster looms.

In Shelley's novel, the chemist, Waldman, issues a similar warning, insisting that technologists “have acquired new and almost unlimited powers; they can command the thunders of heaven, mimic the earthquake, and even mock the invisible world with its own shadows.”

Today, few would dismiss this assessment. What then can engineers do to reduce, if not eliminate, the chances

of unwittingly creating a Frankenstein monster? Here are a few ideas:

(1) Resist the temptation to pursue projects simply because they are beautiful or too cool to resist. As the philosopher Heather E. Douglas explains in a companion essay in the new MIT edition of the novel, creative engineering often inspires feelings of awe and wonder that can obscure or erase an awareness of design challenges. When euphoria reigns, stop and take a breath!

(2) Technologists do best when they solve problems of value to people and the planet. Pursuing possibilities without regard to utility invites unforeseen blowback.

(3) Engineers should act as if creation is a shared responsibility, because their knowledge at least partly comes from others and the effects of their work inevitably extend further than themselves.

These dictums are easier theorized than put into practice, so let's give the last words to Mary Shelley, whose sense of complexity still impresses us. “Invention,” she wrote in an introduction to the 1831 revised edition of *Frankenstein*, “does not consist in creating out of void, but out of chaos.” For their own benefit, inventors must “give form to dark, shapeless substances.” —G. PASCAL ZACHARY

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

CORRECTION: In “Self-Driving Cars and Trucks Are on the Move” (Spectral Lines, January 2017), we erroneously stated 50 million as the number of people who work in the infrastructure that supports cars, trucks, and drivers. The actual figure is 15 million.

NEWS



5 LITERS: AMOUNT OF BLOOD IN THE BODY OF A TYPICAL ADULT. 2 LITERS: AMOUNT OF BLOOD LOSS THAT QUALIFIES AS A LIFE-THREATENING CLASS IV HEMORRHAGE.



“NEURAL TOURNIQUET” ZAPS A NERVE TO STOP BLEEDING

First clinical trials will take on postpartum hemorrhage

ISTOCKPHOTO

➤ **A “neural tourniquet” doesn’t sound like a thing that should work.** Even its inventors admit it.

“It’s a real leap of faith: ‘I know, we’ll stimulate a nerve to control bleeding,’” says Chris Czura, a vice president of the Feinstein Institute for Medical Research, near New York City. “When you say this to surgeons, they look at you funny.”

But in the Feinstein team’s 15 years of research, it has gathered ample evidence for this type of bioelectronic medicine, with studies that show neural stimulation can prevent or stop severe hemorrhages in lab animals. Now the researchers are launching a clinical trial in humans to show the world that their strange idea doesn’t just work—it can save lives.

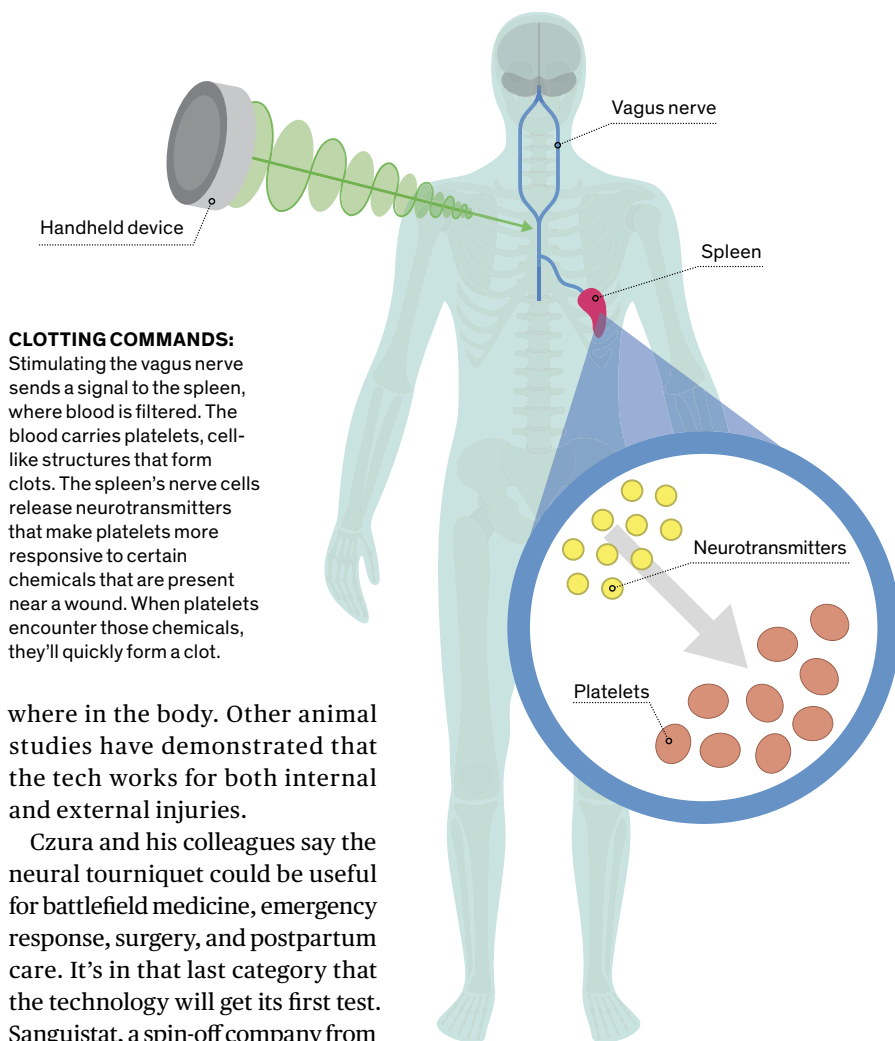
This tech is different from typical tourniquets, which have been used since Alexander the Great’s military campaigns in ancient Persia. When a soldier was wounded, one of Alexander’s physicians would tie a rope around the soldier’s limb above the wound, compressing the blood vessels »

and stopping the blood flow. In today's emergency medicine, first responders use tourniquets in the same way.

With the neural tourniquet, there's no rope and no physical compression of the blood vessel. Instead, doctors press a handheld device against the skin (Czura won't say exactly where, citing proprietary details) to stimulate the vagus nerve, which transmits information between the brain and the major organs. This nerve stimulation conveys a signal to the spleen, where platelets—cell-like structures in blood that form clots—receive their instructions. This signal causes nerve cells in the spleen to release a chemical that “primes” the platelets, prepping them to clot when they encounter a wound anywhere in the body.

“This grabs control of the mechanism the brain uses,” Czura says. “The body has this natural physiologic pathway to control bleeding, and this just ramps it up.”

A 2010 study in pigs found that the neural tourniquet reduced bleeding time by 40 percent and the volume of blood loss by 50 percent. And it worked quickly. Within 3 minutes of jolting the pig's nerve, the researchers measured an increase in an enzyme associated with clotting at the site of injury, while enzyme levels remained steady else-



where in the body. Other animal studies have demonstrated that the tech works for both internal and external injuries.

Czura and his colleagues say the neural tourniquet could be useful for battlefield medicine, emergency response, surgery, and postpartum care. It's in that last category that the technology will get its first test. Sanguistat, a spin-off company from



Tele-Smooching

If you can't be with your loved ones, perhaps you've told them that you're sending a kiss. But if you could really do just that—send a kiss by smashing your lips against a rubber pad that's attached to your smartphone—would you want to? The Kissenger (so named because it's a “mobile kiss messenger”) could give you that awkward option. The brainchild of Emma Yann Zhang and colleagues in London, the Kissenger is a silicone pad, containing force sensors and actuators, that links to a smartphone. With the prototype now built, Zhang is planning a Turing test for kissing, among other experiments.

EMMA YANN ZHANG

the Feinstein Institute, will test the tourniquet as a treatment for postpartum hemorrhage, the leading cause of maternal death worldwide. In Africa and Asia, excessive bleeding kills close to 80,000 new mothers each year. Sanguistat is partnering with the Bill Gates-backed Global Good fund to conduct clinical trials in both the United States and the developing world.

Experts on postpartum hemorrhage note that it's a tricky condition to remedy, requiring the reestablishment of a delicate bodily balance. Andrew Weeks, a professor of international maternal health at the University of Liverpool, in England, explains that pregnant women already have an increased tendency to form clots. Doctors need to guard against thrombosis, he says, a potentially dangerous condition in which a clot forms and blocks a blood vessel.

Weeks also notes that researchers are making progress on pharmaceutical treatments for postpartum hemorrhage. He expects results soon from a worldwide study involving 20,000 women that's testing an inexpensive drug called tranexamic acid. For the neural tourniquet to be widely adopted, he says, "it would need to be easy to obtain and use in an emergency, act rapidly—within a few minutes—and be reversible or transient to prevent thrombosis."

Feinstein researcher and trauma surgeon Jared Huston hopes the neural tourniquet will become a new tool for surgeons. Before an operation, the stimulator could be applied as a protective measure against hemorrhage, he says, in the same way that patients get antibiotics before surgery to protect against infection. Huston would also like to have a better treatment for emergency-room patients, noting that he recently had a 30-year-old patient die from blood loss after a motorcycle accident. "If the surgeon doesn't get in there to stop the bleeding in time, it's game over," he says. —ELIZA STRICKLAND

YANG-KYU CHOI

NEWS

SELF-HEALING TRANSISTORS FOR CHIP-SCALE STARSHIPS

A new design could survive the radiation of a 20-year trip to Alpha Centauri

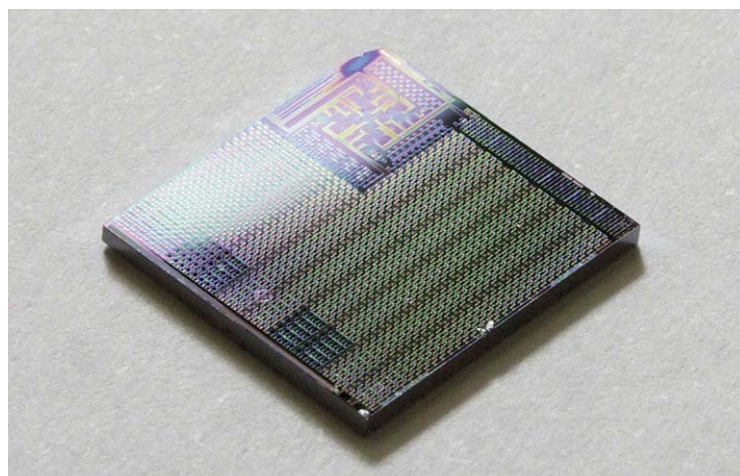
▶ **Working with the Korea Advanced Institute of Science and Technology (KAIST), NASA is pioneering the development of tiny spacecraft, each made from a single silicon chip, that could slash interstellar exploration times.**

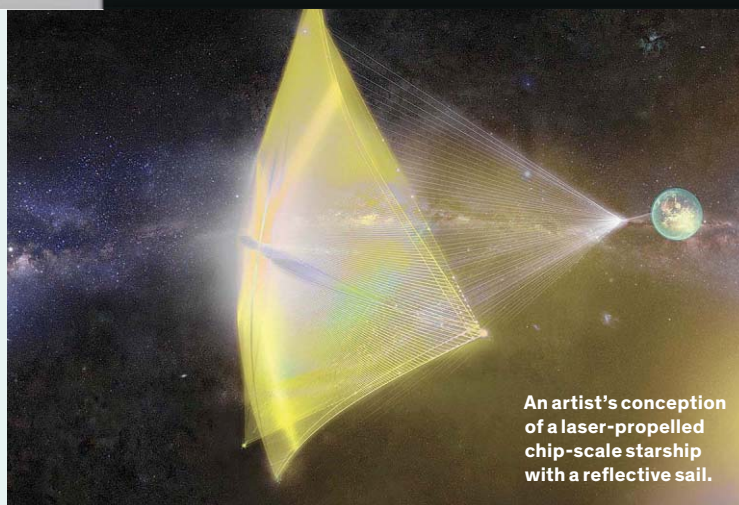
Speaking at the IEEE International Electron Devices Meeting in San Francisco last December, NASA's Dong-Il Moon detailed this new technology, which is aimed at ensuring such spacecraft survive the potentially powerful radiation they'll encounter on their journey.

Calculations suggest that if silicon chips were used to form the heart of a spacecraft powered by a tiny, featherweight solar sail and accelerated by a gigawatt-scale laser system, the craft could accelerate to one-fifth the speed of light. At such high speeds, it would reach the nearest stars in just 20 years, compared with the tens of thousands of years it would take a conventional spacecraft.

Moon and coworkers argue that 20 years in space is still too long for an ordinary silicon chip, because on its journey it will be bombarded by more high-energy radiation than chips encounter on Earth. "You are above most of the magnetic fields that block a lot of radiation, and above most of the atmosphere, which also does a good job of blocking radiation," says Brett Streetman, who leads efforts in chip-scale spacecraft at the Charles Stark Draper Laboratory, in Cambridge, Mass.

COSMIC-RAY-PROOF: A test chip includes DRAM and logic circuits made from self-healing gate-all-around transistors.





An artist's conception of a laser-propelled chip-scale starship with a reflective sail.

5 Hurdles to Reaching the Next Star System

➤ **Light from our sun takes more than four years** to reach our nearest neighbor, the Alpha Centauri star system. Tiny spacecraft, each integrated on a chip and accelerated by laser light, might be able to close the distance in a respectable 20—assuming at least some of them survive the radiation and dust collisions en route. This interstellar scheme, developed with NASA funding, got a big boost last year with the launch of the US \$100 million, privately funded Breakthrough Starshot program. As you might expect, there are myriad technical challenges to overcome. Here are five that top the list for Philip Lubin, a physics professor at the University of California, Santa Barbara, who road-mapped the idea and continues to research it with NASA support. —RACHEL COURTLAND

GETTING IN PHASE: A kilometer-scale array of lasers could be used to create a spacecraft-pushing beam with many gigawatts of power, but the light has to come together very precisely in order to deliver that energy to the spacecraft. Designing an Earth-based array is an added complication because it must quickly adapt to atmospheric perturbations.

REFLECTING THE LASER BACK: Laser light needs to bounce off the spacecraft's sail in order to push it, delivering 10,000 gs or more of acceleration. This sail, which may need to change shape during the mission, will be a tall order. It must be tough but extraordinarily thin, to cut down on mass, and have very low absorption so it won't be blown to bits by the laser.

RIDING THE BEAM: With a mass of a gram or so, a "spacechip" will need to ride a laser beam for only minutes to get up to speed. But the beam needs to stay

pointed at the sail during that critical time. Shaping the sail so the spacecraft can self-stabilize, shifting position or orientation to compensate for pointing errors, could help.

SENDING WORD BACK: As the spacecraft zips by Alpha Centauri, it could use a small onboard laser, perhaps focused by its sail, to send data back. But there will be limited energy for transmission, and an Earth-based receiver will have to discern the dispatch over background noise from solar system dust and the universe at large.

FINDING THE JUICE: Miniaturization will be a challenge for onboard energy generation and storage. A small thermoelectric generator, fueled with plutonium-238, could be a long-lasting source. Solar cells may generate significant power as the spacecraft closes in on its stellar quarry. A thin supercapacitor integrated on-chip could be used for storage.

Radiation leads to the accumulation of positively charged defects in the chip's silicon dioxide layer, where they degrade device performance. The most serious of the impairments is an increase in the current that leaks through a transistor when it is supposed to be turned off, according to Yang-Kyu Choi, leader of the team at KAIST, where the work was done.

Two options for addressing chip damage are to select a path through space that minimizes radiation exposure and to add shielding. But the former leads to longer missions and constrains exploration, and the latter adds weight and nullifies the advantage of using a miniaturized craft. A far better approach, argues Moon, is to let the devices suffer damage but to design them so that they can heal themselves with heat.

"On-chip healing has been around for many, many years," says Jin-Woo Han, a member of the NASA team. The critical addition made now, Han says, is the most comprehensive analysis of radiation damage so far.

This study uses KAIST's experimental "gate-all-around" nanowire transistor. These devices use nanoscale wires as the transistor channel instead of today's fin-shaped channels. The gate-all-around device may not be well known today, but production is expected to rocket in the early 2020s. [See "Transistors Could Stop Shrinking in 2021," *IEEE Spectrum*, August 2016.]

The gate—the electrode that turns the flow of charge through the channel on or off—completely surrounds the nanowire. Adding an extra contact to the gate allows you to pass current through it. That current heats the gate and the channel it surrounds, fixing any radiation-induced defects.

Nanowire transistors are ideal for space, according to KAIST, because they naturally have a relatively high degree of immunity to cosmic rays and because they are small, with dimensions in the tens of nanometers. "The typical size for [transistor dimensions on] chips

devoted to spacecraft applications is about 500 nanometers,” says Choi. “If you can replace 500-nm feature sizes with 20-nm feature sizes, the chip size and weight can be reduced.” Costs fall too.

KAIST’s design has been used to form three key building blocks for a single-chip spacecraft: a microprocessor, DRAM memory for supporting this, and flash memory that can serve as a hard drive.

Repairs to radiation-induced damage can be made many times, with experiments showing that flash memory can be recovered up to around 10,000 times and DRAM returned to its pristine state 10^{12} times. With logic devices, an even higher figure is expected. These results indicate that a lengthy interstellar space mission could take place, with the chip powered down every few years, heated internally to recover its performance, and then brought back to life.

Philip Lubin, a professor at the University of California, Santa Barbara, believes that this annealing-based approach is “creative and clever” but wonders how much danger from cosmic rays there really will be to these chips. He would like to see a thorough evaluation of existing technologies for chip-scale spacecraft, pointing out that there are already radiation hardened electronics developed in the military.

Today, efforts at NASA and KAIST are focusing on the elimination of the second gate contact for heating. This contact is not ideal because it modifies chip design and demands the creation of a new transistor library, which escalates production costs. Those at KAIST are investigating the capability of a different design, called a junctionless nanowire transistor, which heats the channel during normal operation. Separately, at NASA, researchers are developing on-chip embedded microheaters that are compatible with standard circuits.

Cutting the costs of self-healing tech will play a key role in determining its future in chip-scale spacecraft, which will require many more years of investment before they can get off the ground.

—RICHARD STEVENSON

HYDROSTOR

4 NEW WAYS TO STORE RENEWABLE ENERGY WITH WATER

Stash it away in concrete bunkers, undersea bags, and other strange places



If Elon Musk has his way, in the future we'll all be storing

renewable electricity inside big banks of lithium-ion batteries. But let's not forget the energy storage situation today. In the United States, 97 percent of utility-scale storage in 2014 was in pumped-storage hydroelectric plants, according to research by Oak Ridge National Laboratory, in Tennessee.

In traditional pumped hydro, a dam separates a lower reservoir from an upper reservoir. When a utility company needs to store energy, the system pumps water from the bottom to the top. It generates electricity when water flows back down through a turbine. In 2015, Citibank estimated that the cost of power from pumped hydroelectric was about 5 percent of the cost of grid-scale battery-stored electricity. The problem is that there are many places that “consume high amounts of power but don't have geological opportunities to build conventional pumped-storage plants,” says Jochen Bard, an energy processing technology manager at the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), in Germany.

In 2017, a number of new pumped-hydro technologies should achieve

IN THE BAG: Compressed-air bags sit in 55 meters of water off Toronto Island as part of a 660-kilowatt pilot plant commissioned in 2015.



NEWS

NEWS

milestones. They aim to bring the low cost of the technology to geographies that ordinarily wouldn't allow it. Here are four you might hear about:

The Concrete Bunker

Stensea (Stored Energy in the Sea) is a hollow concrete sphere with a built-in pump turbine. It sits on the seafloor and, in its discharged state, is filled with water. To store energy, the system uses electricity to pump water out into the sea. When discharging, the pump works in reverse, generating electricity as water refills the sphere.

In November, Fraunhofer IWES installed a 3-meter-wide pilot sphere in southern Germany's Lake Konstanz at a depth of around 100 meters. It ran a successful four-week test of the system with full charging and discharging. Following a year-long feasibility study, the team is now developing the

EARTH, WIND & WATER:

DNV GL's energy island concept creates a lake in the ocean that stores wind energy by pumping water out.



concept for a 5-megawatt, 20-megawatt-hour full-scale system. The spheres will have certain geographic needs: a water depth from 600 to 800 meters and a surface flat enough to prevent tilting. Potential sites for such a project include locations in the Mediterranean Sea, the Atlantic Ocean, and the Norwegian trench.

Compressed-Air Bags

Hydrostor's system consists of weighted-down balloonlike bags that are placed underwater and connected to a system on the shore. To store energy, it uses electricity to compress the air and fill the

underwater bags. (A heat exchanger and underwater bath capture heat lost during compression to help preserve efficiency.) When electricity is needed, the air flows back out of the bag into a machine that expands it to drive a turbine. [See "Stashing Energy in Underwater Bags," *IEEE Spectrum*, August 2014.]

Hydrostor commissioned a 660-kilowatt pilot plant with undisclosed storage capacity in November 2015 at Toronto

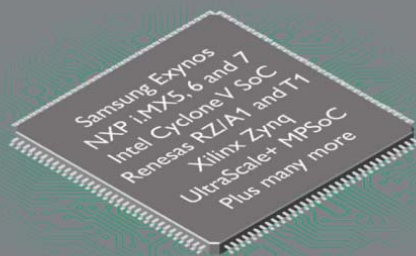
DNV GL

ARMDS

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developer.arm.com/ds-5

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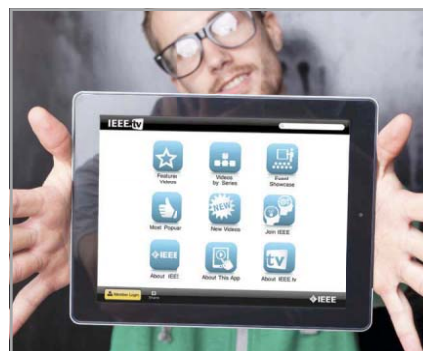
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Island, and the company is currently optimizing the performance. It has proposed new projects in Canada, the United States, and Mexico. And it's now constructing a 2-MW, 7-MWh facility in Goderich, Ontario, that uses underground salt caverns instead of bags, which could be followed by a 1-MW, 6-MWh storage system with bags in Aruba later this year.

Energy Island

In DNV GL's energy island concept, a dike encloses a 10- by 6-kilometer section of the North Sea off the Dutch coast [artist's rendering, left]. To store electricity, the system pumps interior water up and out to sea. Letting water flow through a turbine on its way back generates electricity.

Unlike with traditional pumped storage, the inner lake can be built out in the sea as long as the seafloor has a sufficiently large layer of clay to prevent the ocean from seeping back in. There would also be some trade-off between more energy storage gained from a deeper ocean and increased construction cost.

For now, this energy island is only in the concept stage. DNV GL, based in Norway, is running a business case analysis with partners in the Netherlands and discussing plans to build a large-scale system. It hasn't settled on a power rating or storage duration yet, but a small-scale prototype wouldn't work for something like this, according to the company.

Wind Turbines With Water Storage

In Naturspeicher's system, wind turbines are built on the top of a hill with a pair of water storage reservoirs at their bases that raise them by an extra 40 meters above a typical turbine. A man-made lake sits at the bottom of the hill; energy is stored when the water is pumped up into the reservoirs, and electricity is produced when the water falls back down to the lake.

Adding an extra 40 meters of height should boost generation about 25 percent, but it also requires weight balanc-

ing that would ordinarily be expensive. In this case, however, the company says, water in the reservoirs naturally balances the mechanical load on the cheap.

The system "integrates harmoniously into the landscape without major disruption," the German company says.

It plans to have a wind farm on line by the end of 2017 in the hills of the Swabian-Franconian Forest, in Germany, with pumped storage following by late 2018. It expects the system, when completed, to store 70 MWh and deliver up to 16 MW. —ANDREW SILVER

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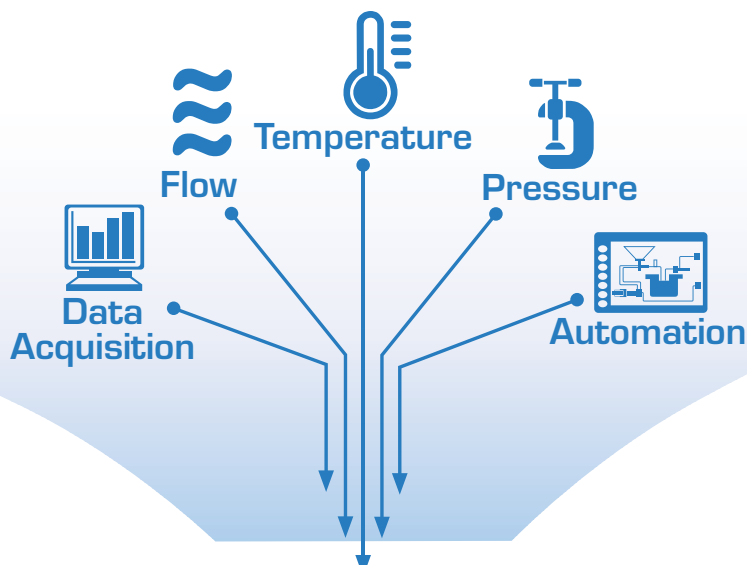
COOL RUNNINGS

LEAGUES OF SERVERS, in giant data centers you never see, provide the muscle that keeps the Internet moving. But as with an athlete performing dynamic feats, if these servers get overheated, their performance suffers. So much importance is placed on keeping these machines from running hot that cooling systems can consume as much as 40 percent of a data center's entire energy budget. But the creators of a data storage facility in Saumur, in western France, found a way to beat the heat without drawing so much power. They built the facility—comprising 160 servers with a capacity of 20 terabytes each—underground, in the man-made cavern of a former quarry. Down there, ambient temperatures—and energy bills—are much lower than on the surface.

THE BIG PICTURE

NEWS

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RESOURCES



RESOURCES_HANDS ON

Like virtually all New York City apartment dwellers, I am occasionally visited by a mouse looking for a new home. However, I was still surprised to hear a familiar scratching sound emanating from behind my desk late last year. This was because 12 months previously my unusually diligent landlord and I searched for every mouse-size gap in my newly renovated apartment and blocked them all with either metal plates or steel wool. • I put down poison and traps, but they were ignored. I started an increasingly frustrated search for the mouse's entry point, until my suspicions fell on the gap between the bottom of our apartment's front door and the sill. It looked just large enough for a small mouse to squeeze under, but I wasn't sure. So, naturally, I set about building my own indoor wildlife camera system to catch the pest in the act of entering. • I could have tried hooking up our Nest Wi-Fi-enabled security camera, and set it for night vision and motion detection, but the Nest is really designed for monitoring rooms, not small areas like my doorsill. I also wondered if I could achieve my goals without sending a stream of live video from my home to some unknown data center. • Fortunately, I'd spotted what promised to be the ideal solution during the 2016 World Maker Faire in New York City last October. Singapore-based Annikken makes a line of shields that let Arduino microcontrollers communicate with a smartphone via Bluetooth. Previously, these shields worked with either Android or iOS mobile devices, but not both. At the Faire however, Annikken was demonstrating its latest product, the US \$79 Annikken Andee U-AIO, which can communicate with both types of device (and the Apple Watch as well). ▶

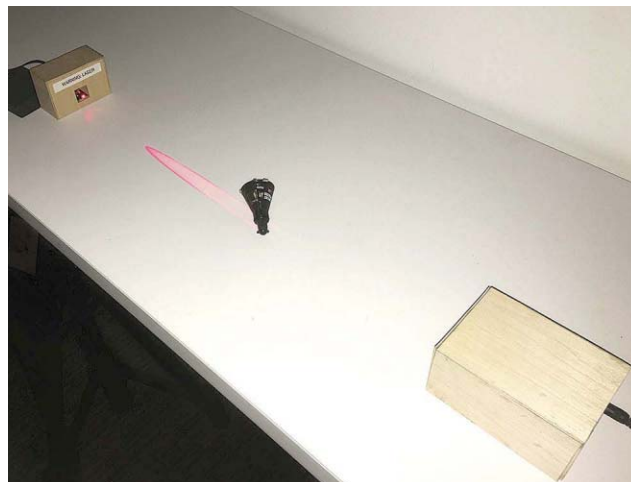
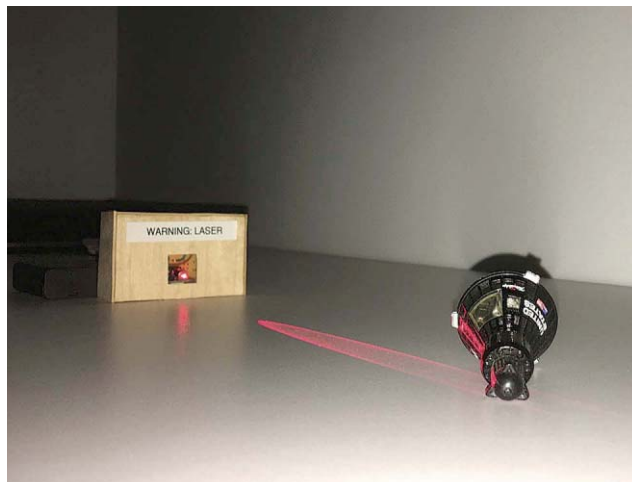


3,660: THE NUMBER OF U.S. PATENTS WITH "MOUSETRAP" IN THE TITLE

BUILDING A BETTER MOUSETRAP

LINK YOUR
SMART-
PHONE
AND YOUR
ARDUINO
WITH THE
ANNIKKEN
ANDEE

RESOURCES_HANDBOOK

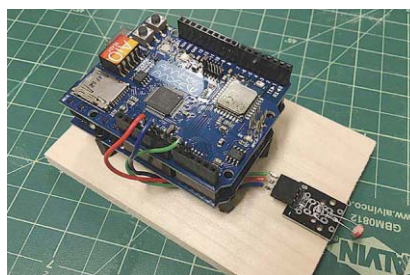
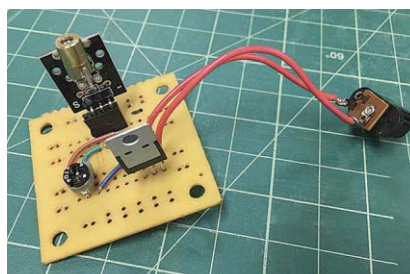


I ordered the shield, and then I dug out a laser diode module and photocell from my \$27 Elegoo 37-in-1 sensor kit. This kit has a miscellany of 5-volt emitters and sensors mounted on little breakout boards, which is very convenient when I want to throw something together quickly.

The laser module doesn't come with a collimating lens, so the light spreads out into a broad cone. This would be a pain if I wanted the beam to travel any real distance. But in my situation, with the door being about a meter across, the wide beam was actually an advantage: I didn't need to be superprecise in positioning the photocell in the path of my optical trip wire. I built a housing for the laser module and hooked up a battery pack, and I connected the photocell to my Arduino Uno board with the Andee shield mounted in place inside another housing.

The Andee U-AIO passes through the Arduino's pin connectors so that you can hook up your projects to the microcontroller, but not every pin is actually usable. The Andee uses pin 8 to communicate with the Arduino, and when using an Uno it is recommended that you not use pins 11, 12, and 13. (To make up for these lost pins, the new U-AIO shield provides an additional eight digital input-output pins. There's also a microSD card slot as well for data that's too big for the Arduino's memory.)

I connected the photocell to one of the Arduino's analog input/output pins. I wrote a short program that dumps the value seen at the photocell's analog pin to the Arduino's serial port, so that I could see what voltage values were reported when the laser was shining di-



The photo at top left was automatically taken by an iPhone when I pushed a mouse substitute (a Mercury capsule model) into the beam of my optical trip wire [top right]. I made the trip wire using a laser module at one end and a photocell attached to an Arduino equipped with an Andee U-AIO shield [above].

rectly on the photocell versus when the beam was blocked. This let me select a suitable threshold value for triggering a camera.

Writing the Arduino software was trivial. I downloaded the software library required to use the Andee from the Annikken website. The library comes with a large set of example programs demonstrating different features, so it was easy to modify the "Automatically Take Photos with Smartphone Camera" example to take a picture with the flash when the analog photocell reading fell below the threshold value.

Once the Arduino, Andee, and photocell were working together, the next step was to set up my smartphone. I used my wife's old iPhone, which had been retired due to a cracked screen and an exhausted battery. I installed the free Andee app. When launched, it spotted my U-AIO shield, and the graphical interface for my Arduino program popped up.

This bit is actually my favorite thing about Annikken's system. Typically, communication hardware and software simply focus on providing a channel between the microcontroller and whatever device you're connecting to. It's up to you to write the software to do anything else on either end. This means becoming familiar with two different systems and understanding the channel well enough to pass unmangled data. But the Andee spared me from having to take a crash course in smartphone app development, because you code how both ends of the connection behave just once in the Arduino software.

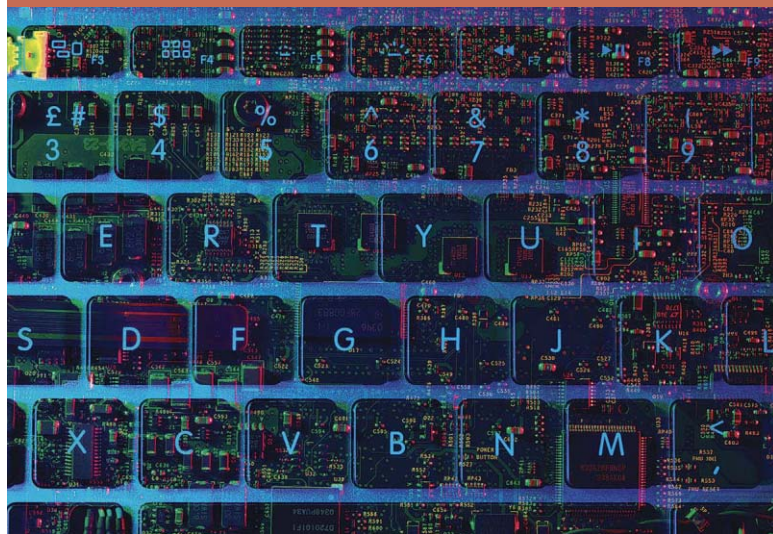
For example, you can specify you want an onscreen message window and a few control buttons for a graphical user interface, and the Andee app will implement those for you. The Andee app can also allow the Arduino to access other hardware present on the mobile device, such as GPS data (exactly what you can access depends on whether you're using an iOS or Android device).

Unfortunately, I then hit a truly fatal snag in my project. Just as I was about to deploy my mouse detector, I noticed that one of my half-forgotten traps had sprung. No more live mouse to detect! But my system lies in wait for the next intruder, and the mystery of from whence it comes... —STEPHEN CASS

RESOURCES CAREERS

FBI AGENT MITCHELL THOMPSON

FIGHTING CYBERCRIME IS A GROWING FIELD



It's not easy to drop in on Mitchell Thompson at work. After removing my shoes for airport-like security, I follow my escort down a hallway to a thick glass door. She scans her badge and punches in a code to gain entry. Behind the door awaits a protected bank of elevators reserved for employees of the U.S. Federal Bureau of Investigation.

High up in the FBI's New York City field office, Supervisory Special Agent Thompson leads a 20-person squad that includes computer scientists and security professionals. They investigate cybercriminals who target the city's largest banks and stock exchanges, as well as scammers who steal from everyday citizens.

In earlier years, occasional investigations into fraud and child pornography were handled by teams with minimal cybertraining. As the number of cases increased, the FBI realized it needed to develop its own cyberleuths. "Historically, people commit crimes at the speed of human," Thompson says in his Texas drawl. "With the Internet, they're able to commit crimes at the speed of the Internet."

Cybersecurity is now one of the agency's top three priorities, right behind terrorism and counterintelligence. The FBI has cybersquads in all 56 of its field offices. Larger offices support multiple squads that specialize in certain types of cybercrime—such as Thompson's group, which focuses on financial misdeeds.

The FBI is not alone in shifting resources toward patrolling the Internet. Law-enforcement agencies around the world are hiring experts to hunt down cybercriminals. Europol, the European Union's law-enforcement agency, established the European Cybercrime Centre in 2013. And its global equivalent, Interpol, once created its own private cryptocurrency and built a fake Darknet to study criminal behavior.

Thompson has been with the FBI for 10 years. In college, he majored in accounting and management information systems, and he later earned his MBA. His first job was as a CPA, auditing financial firms. After six years, he left in search of more rewarding work and became a special agent.

Initially, Thompson knew little about hunting cybercriminals. He learned cybersecurity practices through training with SANS, a specialized security institute, and CompTIA, an industry group for security professionals. The bureau also offers internal cybercertifications and programs on cyberforensics.

Thompson's studies paid off in 2014, when he coordinated a takedown of cybercriminals with agencies in 19 countries that resulted in over 90 arrests. The operation targeted the creators and sellers of malware called Blackshades, which was used to collect victims' keystrokes, steal account information, and spy on thousands of people through their webcams.

To initiate a case, Thompson explores leads from the FBI's Internet Crime Complaint Center. The bureau uses data analysis to search for keywords and identifiers in filed complaints, and it bundles similar cases together, whether they be business owners hit by fraudsters or victims of a romance scam.

If a bank or insurance company in New York City detects an online intruder or a massive distributed denial-of-service attack, they can also call Thompson directly. Depending on the situation, Thompson may immediately deploy a cyberresponse team to start collecting evidence, such as making forensic copies of servers before the attack is over.

Though the FBI has at times rubbed the tech industry the wrong way—many saw its attempt to force Apple to unlock an iPhone as an affront to security and privacy—the bureau is eager to recruit the expertise it needs from the industry.

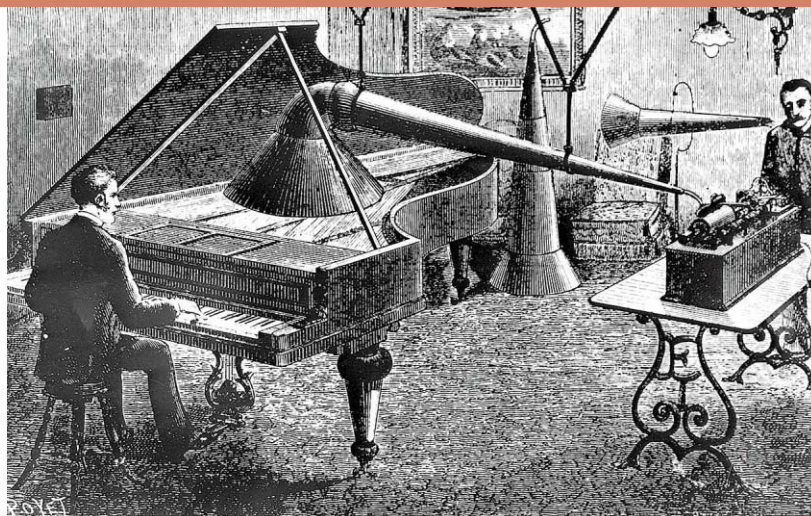
Thompson says he often needs people who can perform specific tasks, such as reverse engineering malware, though he doesn't expect new hires to know it all. "No one is an expert on everything," he says. "As long as you know what your limitations are and know who to ask when you come across your limitations, I'm great with that."

Computer scientists, IT specialists, and engineers can join the FBI right out of college, though some work experience is usually preferred. It also helps to have patience—tracking down cybercriminals often requires months or years of persistent investigation. "When we work a case long enough, we have great success," says Thompson. —AMY NORDRUM

RESOURCES_GEEK LIFE

THE MUSIC MAN

MARC HILDEBRANT REMASTERS THOMAS EDISON'S EARLIEST MUSICAL RECORDINGS



One of the best parts of working for *IEEE Spectrum* is the opportunity to discover intriguing tech

projects that are pure labors of love, whether it's building a 16-bit CPU out of discrete transistors or keeping a collection of vintage personal computers alive. So when I heard about Marc Hildebrant's work on using digital techniques to restore mechanically recorded music to its full glory, I had to know more.

The earliest sound-recording and playback technology was pioneered by Thomas Edison in 1877. The system was purely mechanical: To record a performance, musicians arranged themselves around a recording horn, at the other end of which a diaphragm vibrated in accordance with the incoming sounds. A needle attached to the diaphragm etched a track in the recording medium—first cylinders, and later discs. Playback was simply a reversal of this process, with a needle vibrating a diaphragm at the base of a horn. In the 1920s, the recording switched to an electrical system using microphones. By the 1930s, electrical playback was also available.

HIT IT, MAESTRO: Early sound recording relied on the direct mechanical force of acoustic vibrations to etch patterns in cylinders and discs.

Edison's early mass-market catalog represents a cultural trove: Many famous musicians of the day made recordings. But these recordings have significant sound-quality problems. Most sound-restoration projects eliminate the obvious issues that plague decades-old analog storage media, such as scratches or hissing. But Hildebrant is going deeper and fixing some of the distortions introduced by the original mechanical recording process.

"That area has always been kind of abandoned by the restoration people.... Pretty much what's available today are recordings where they just clean up the noise. They don't really change any of the sound of the music," says Hildebrant.

The distortion comes from the limited frequency response of the mechanical recording system—essentially many high and low frequencies simply couldn't be captured, so even after being cleaned up, the recordings sound tinny. Hildebrant focused on restoring the missing frequencies below 300 hertz to

fill out the bass notes. Trying to simply boost low frequencies below 300 Hz would serve only to amplify noise. Instead, Hildebrant realized that voices or instruments present in the medium frequencies would likely have had harmonics in the missing frequencies originally and so could be used to reconstruct the missing sound signals.

Using commercially available software from Diamond Cut Productions, which can generate subharmonics as part of a digital signal processing chain, Hildebrant was able to generate missing bass frequencies in old Edison recordings, as well as filter out high-frequency noise and make other adjustments.

Because the subharmonic filter will create a low-frequency sound for any strong signal in the midranges, it can produce unwanted frequencies—for example, adding too much bass to a singer's voice—so the process depends to a large extent on Hildebrant tweaking the processing chain for each track, guided in part by his extensive experience with audio recording. The result is a digital file that sounds much more natural than the original recording. (A before-and-after sample of Hildebrant's work is available online.)

Currently semiretired, Hildebrant says he has been working on this audio-rejuvenation project for about five years, after working on restorations of early electrically recorded music. "Like everything in engineering, you're always working on improving," he says. "An engineer's life is never done."

His interest in the recordings goes beyond the merely technical, however, and into the music itself. "It's hard to find decent Edison music because he himself decided what should be played and what not. He didn't like jazz music, so he hardly recorded any," says Hildebrant. But "there's a small window of time where he perfected the [mechanical] process, and this is the area I concentrate on. He didn't really care anymore about who recorded, so the jazz people started recording. You're hearing jazz played by young musicians with Benny Goodman and Tommy Dorsey, and all those people right at their prime when they just started. So I always thought if I could fix that music up, then I'd really have something unique." —STEPHEN CASS

RESOURCES_AT WORK

H-1B VISAS BY THE NUMBERS

NEW TOOLS LET ANYONE EXAMINE THIS CONTROVERSIAL PROGRAM



The H-1B visa program is designed to allow foreign professionals to work in the United States for up to six years. The program's intention is to allow American companies to fill skilled positions for which qualified local candidates cannot be found. However, critics contend that the tech industry is using H-1B visas to depress wages and guarantee a compliant workforce. (If H-1B holders lose their jobs and don't quickly get hired by other companies willing to take on their visas, they must leave the United States.)

About a year and a half ago, I reported on an effort by French software engineer Théo Négri to mine the U.S. Department of Labor's H-1B data for insights into tech salaries. (This set of data covers minimum salaries without any bonuses; the actual salaries paid to H-1B visa holders can be higher.) Négri's tools allow you to browse listings by company, year, job title, and other factors—but it takes some toggling around to get a clear snapshot of trends in engineering salaries at a particular firm.

In a separate effort, software engineer Mahmoud Mechehoul, a former H-1B visa holder from Morocco, took a look at that same data and decided it would be more useful to look at salary distributions, not just aggregated numbers. He reasoned that salaries for similar jobs vary widely, even within the same company. The data, he says, covers 800,000 salaries from 500 (mostly tech and finance) companies and universities for 700 job titles in 1,600 cities.

He came up with a more graphical online tool: H1BPay. It took him about six months to create because he hired contractors to clean up the government data. Their work involved changing formal legal names to more familiar monikers, correcting spelling mistakes, and filtering out salary figures that were extreme outliers. He originally built the tool for use by current and potential holders of H-1B visas, but the picture it paints of engineering salaries can be mined for all sorts of purposes. The tool allows you to browse salaries by company, job, and

city—for some companies, as far back as 2011 (Négri's data goes back to 2000, so it might be worth taking a look there as well if you identify a company you're particularly interested in). The general trend shows that H-1B workers' wages are seeing healthy increases at most companies, but there are exceptions. A few examples:

Salaries for H-1B software engineers at Facebook in Menlo Park, Calif., according to H1BPay, range from US \$85,000 to \$247,200, with a median of \$138,294. The top 25 percent of earners make at least \$150,000. The average salary for H-1B software engineers at the social network increased by an average of 6 percent a year between 2012 and 2016.

H-1B software engineering salaries at Google in Mountain View, Calif., vary between \$92,000 and \$318,240; the median salary is \$126,232. The top 25 percent make a salary of at least \$137,600, and the pay increased by an average of 2 percent annually between 2011 and 2016.

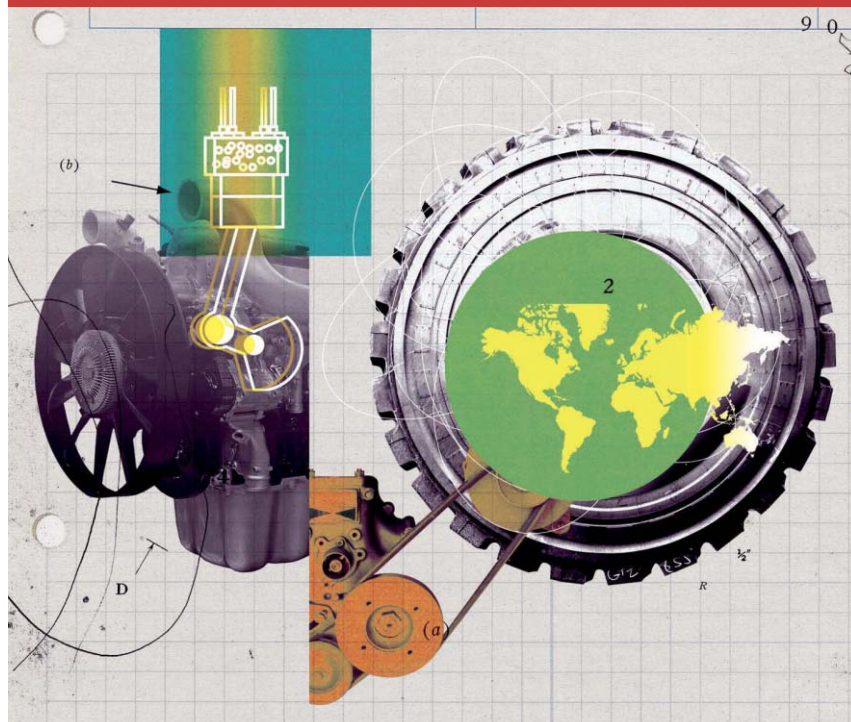
At Uber, H-1B software engineers in the company's San Francisco office are paid from \$76,107 to \$175,000, with a median of \$120,000. The top 25 percent make a salary of at least \$140,000. Software engineering salaries for H-1B visa holders at Uber dropped about 1 percent annually between 2013 and 2016.

According to Mechehoul's tool, salaries for an H-1B software engineer at IBM in San Jose, Calif., range from \$61,735 to \$222,700, with a median salary of \$99,047. The top 25 percent of this group make at least \$140,000, and the average salary went up an average of 12 percent annually between 2014 and 2016. Salaries for H-1B software engineers at IBM's Research Triangle Park, N.C., location range from \$52,998 to \$206,348, with a median of \$83,666; the top 25 percent earn at least \$100,000.

And at Microsoft in Redmond, Wash., H-1B software engineers make from \$78,540 to \$161,000 annually, with a median of \$118,142, and at least \$125,676 for the top 25 percent. These numbers reflect an average annual increase of 5 percent from 2013 to 2016. —TEKLAS. PERRY

NUMBERS DON'T LIE_BY VACLAV SMIL

OPINION



DIESEL ENGINE AT 120



ON 17 FEBRUARY 1897, Moritz Schröter, a professor of theoretical engineering at Technische Universität, in Munich, conducted the official certification test of Rudolf Diesel's new engine. The goal of the test was to verify the machine's efficiency and hence to demonstrate its suitability for commercial development. • The 4.5-metric-ton engine performed impressively: At its full power of 13.4 kilowatts (18 horsepower) the engine's thermal efficiency was 35 percent and its mechanical efficiency reached 75 percent, resulting in a net efficiency of 26 percent. With obvious pride Diesel wrote to his wife, "Nobody's engine design has achieved what mine has done, and so I can have the proud awareness of being the first one in my specialty." Later in that year the engine's net efficiency reached 30 percent, making the machine twice as efficient as the gasoline-fueled Otto engines of the day. • Over time, that efficiency gap has narrowed, but today's diesel engines remain at least 15 to 20 percent more efficient than their gasoline-fueled rivals. Diesels have several advantages: They use fuel of a higher energy density (nearly 12 percent higher than that of gasoline); their self-ignition involves much higher compression ratios (commonly twice as high as in gasoline engines), resulting in a more complete combustion and in cooler exhaust gas; their longer stroke and lower rotational rate reduce frictional losses; they can operate with a wide range of very lean mixtures, burning refined fuel of the lowest quality; they have no throttle valves; and modern common-rail fuel injection systems can spray the fuel into their cylinders at pressures of up to 300 megapascals (up from 60 MPa 50 years ago). • But, disappointingly, in 1897 the record-setting test was not followed by rapid commercial deployment. Diesel's conclusion that he had "a thoroughly marketable machine" and that "the rest will develop automatically on its own worth" was wrong. Only in 1911 did the Danish vessel *Selandia* become the first ocean-going freighter powered by a diesel engine, and diesels dominated shipping only after World War I. Heavy railroad traction was their first land conquest, followed by heavy

road transport, off-road vehicles, and construction and agricultural machinery. The first diesel car, the Mercedes-Benz 260D, came in 1936, but diesels never made it in the United States: Even now they account for just 3 percent of all light-duty vehicles. In the European Union, about 40 percent of all passenger cars are diesels.

Diesel's initial hope was to see small engines used primarily by small, independent producers as tools of industrial decentralization, but 120 years later, the very opposite is true. Diesels are the uncontested enablers of massively centralized industrial production and the irreplaceable prime movers of globalization. Diesels power virtually all container ships and all carriers of vehicles and bulk commodities, such as oil, liquefied natural gas, ores, cement, fertilizers, and grain. They also power nearly all trucks and freight trains.

Most of the items that readers of these essays use, eat, or wear are transported at least once, and usually many times, by diesel-powered machines, often from other continents: clothes from Bangladesh, oranges from South Africa, crude oil from the Middle East, bauxite from Jamaica, cars from Japan, computers from China. Without the low operating costs, high efficiency, high reliability, and great durability of diesel engines, it would have been impossible to reach the extent of globalization that now defines the modern economy.

Over more than a century of use, diesel engines have increased both in capacity and efficiency. The largest machines in shipping are now rated at more than 81 megawatts (109,000 hp), and their top net efficiency is just above 50 percent—better than that of gas turbines, which are at about 40 percent (although in combined-cycle generation, using the exhaust gas to do work, turbines can reach 61 percent net efficiency).

And Diesel's engines are here to stay: There are no readily available mass-mover alternatives that could keep integrating the global economy as affordably, efficiently, and reliably as Diesel's machines, born 120 years ago this month. ■

DATA DIVINATION

To get better at forecasting big political events, we need both better data and sharper reporting, a clearer read on the numbers, and a more penetrating portrait of on-the-ground realities. —Aaron Timms

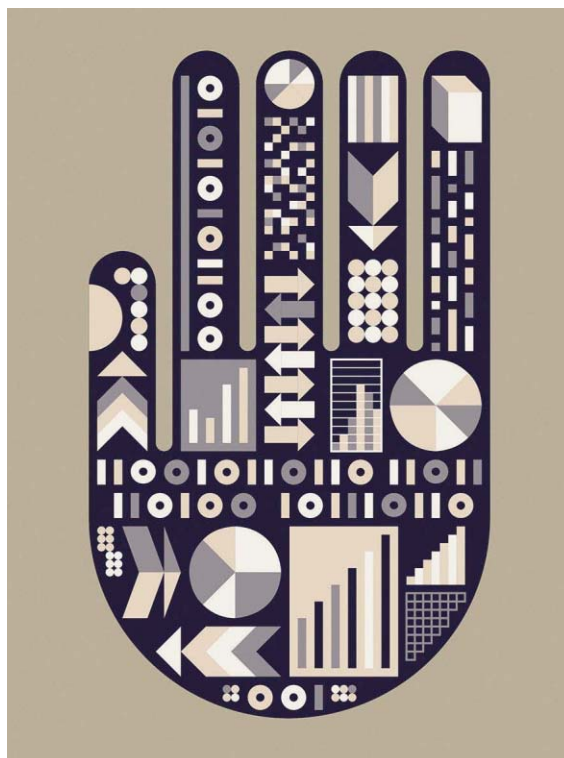


ing information, and **live data**, such as a user's (changing) GPS coordinates. Occasionally, this data can produce **perishable insights**: valuable data that has a very short shelf life (such as when you detect that your roaming user is wandering past one of your brick-and-mortar storefronts). The opposite is **target-rich data**. When tagged, processed, and analyzed, this data offers its owner valuable, long-term insights.

Perhaps there's a way to synthesize both the big picture and the small—that is, to somehow combine both big data and our contributions to that data: **small data**, which arises out of our everyday actions. We'd have to navigate some dangers. For example, we'd need to ensure that our data does not become **cubed data**, where a third party shares our data with another third party and it becomes impossible to predict where it ultimately ends up or how it will be used or interpreted. We'd need some assurances that third parties practice **responsible data**, information that is used and shared sensitively and humanely.

A more promising approach might be one that utilizes **thick data**, which combines both quantitative and qualitative analysis. The pundits could take a cue from **narrative medicine**, which uses the story of a patient's illness combined with traditional medical practices as a way of understanding, diagnosing, and treating the illness. Rather than making guesses about what people will do—for example, that rural voters would stay home on Election Day or that people who told pollsters they'd vote "Leave" would do the opposite in the voting booth—pundits could actually talk to people and listen to their stories rather than just looking at the numbers. Call it *narrative data*. ■

➤ **THE RESULTS OF RECENT VOTES**, particularly the U.S. presidential election and the United Kingdom's referendum on leaving the European Union (better known as *Brexit*) left many surprised. In both cases, the postdecision lament went something like this: "In this age of big data, how could the pollsters and pundits have been so wrong in their predictions?" • I'm just a language guy, so I don't pretend to have an answer, although surely it's an open question whether polls, with their sample sizes in the few thousands, count as "big" data. (Polling statistics probably fall more under the rubric of **medium data**.) Perhaps that was the problem: If preelection and pre-referendum analyses *could* have accessed data points in the millions, then might the results have been less surprising? Or perhaps what's needed isn't big data on its own but an approach that takes advantage of the many new types of data that are available. • For example, **fast data** refers to data that requires near-instantaneous access or analysis or that is relevant for only a very short time. It's an example of **hot data**, which is used constantly, so it must be easily and quickly accessible. On the opposite side of the information coin we have **slow data**, which accumulates over a relatively long time, meaning that at some point it might become **long data**, which extends back in time hundreds of years. It's an example of **cold data**, which is used relatively infrequently, so it can be less readily available. Whether fast or slow, hot or cold, the information isn't much use to anyone if it's **dirty data**, which is incomplete, inconsistent, or just plain wrong. • In the same way that dark matter is an unseen but very large part of the cosmos (some estimates peg dark matter at 27 percent of the mass of the universe), **dark data** represents the unseen but very large part of the data that most corporations collect and store. It's "dark" because corporations don't use it for analysis, insight, or decision making. Some of it is **transient data**, such as unused sensor data or temporary network rout-





AUTONOMOUS SHIPS ON THE HIGH SEAS

**IF ROLLS-ROYCE
HAS ITS WAY, SOME
COMMERCIAL
VESSELS WILL
SOON HAVE NO
CREW ON BOARD**

**By OSKAR
LEVANDER**

It's midnight on the North Atlantic, where a massive container ship receives the latest weather report. There's a nasty storm brewing ahead. Quietly, the ship changes course and speed, to skirt the worst of it and ensure an on-time arrival at its destination. The ship's owners and the harbormaster at its next port of call are advised of the revised route. And as it nears shore, the giant ship must correct course once again, this time to steer clear of a fishing vessel off its starboard bow.



Just another day for trans-Atlantic shipping, it might seem. In fact, it's not. You see, this ship has no one aboard. It's commanded from an operating center on the other side of the world, where technicians are monitoring and controlling this vessel and others like it through a satellite data link—that is, when the ship isn't just controlling itself.

Although robotic ships of this sort are some ways off in the future, it's not a question of *if* they will happen but *when*. My colleagues and I at Rolls-Royce anticipate that the first commercial vessel to navigate entirely by itself could be a harbor tug or a ferry designed to carry cars the short distance across the mouth of a river or a fjord and that it or similar ships will be in commercial operation within the next few years. And we expect fully autonomous oceangoing cargo ships to be routinely plying the world's seas in 10 or 15 years' time.

Remotely controlled ships, piloted by people on shore, and autonomous ships, which can take actions for themselves, are the latest beneficiaries of increasing digital connectivity and intelligence. These developments in electronic sensors, telecommunications, and computing have sparked interest in a range of autonomous vehicles including cars, planes, helicopters, trains, and now ships. Companies and academic researchers around the world are working hard to turn these ideas into reality.

In particular, Rolls-Royce has mounted a joint industry project in Finland called Advanced Autonomous Waterborne Applications (AAWA). The participants hope to create the technology for a remotely controlled or fully autonomous ship that will operate in coastal waters before the end of the decade. And we're not alone.

The European Union's MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) project, led by the Fraunhofer Center for Maritime Logistics and Services, in Hamburg, is assessing the technical, economic, and legal feasibility of operating an uncrewed merchant vessel autonomously during an open-sea voyage. In addition, researchers at DNV GL, an international ship-certification organization, are exploring the feasibility of using uncrewed battery-powered vessels to transport freight along Norway's long coastline. And China's Maritime Safety Administration and Wuhan University of Tech-

nology have partnered in their Uncrewed Multifunctional Maritime Ships Research and Development Project. Their goal is to find ways for autonomous ships to be used within China's own commercial and military maritime sectors.

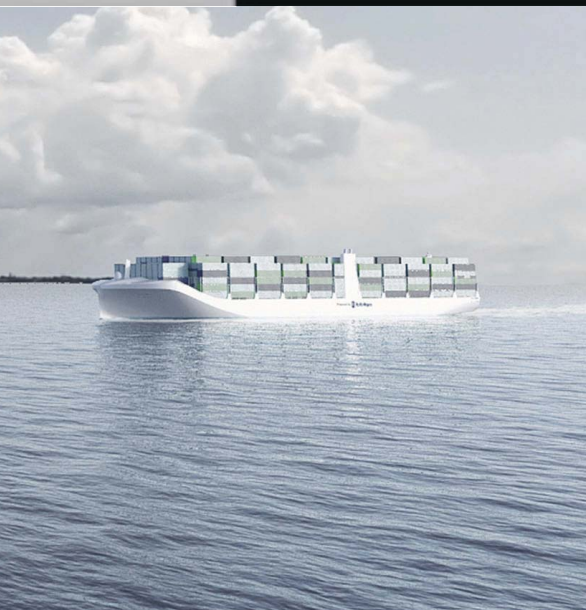
Clearly, there's a lot of work being done on robotic ships. I'd like to give you here an insider's perspective about the nature of these efforts and why they are so exciting.

THAT PEOPLE SHOULD BE SERIOUSLY INTERESTED in robotic ships is easy enough to explain: Such ships are expected to be safer, more efficient, and cheaper to run. According to a report published by the Munich-based insurance company Allianz in 2012, between 75 and 96 percent of marine accidents are a result of human error, often a result of fatigue. Remotely controlled and autonomous ships would reduce the risk of such mistakes and along with it the risk of injury and even death to crew members, not to mention the dangers to the ship itself.

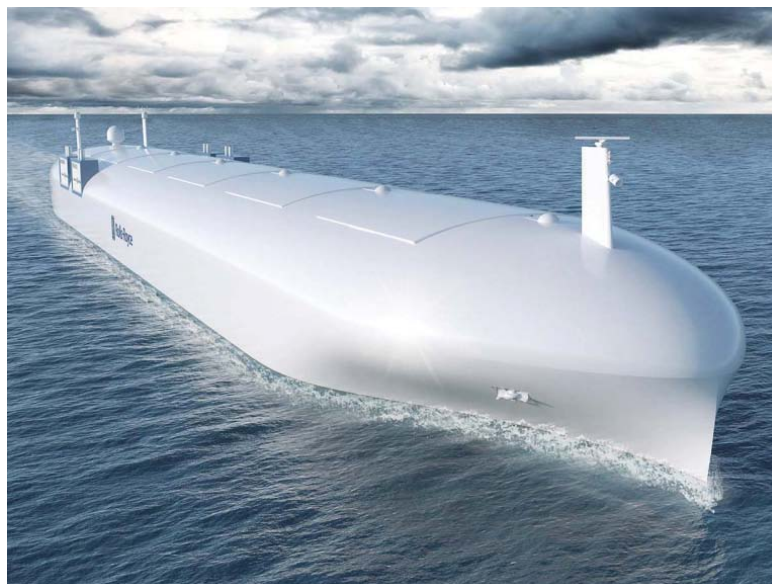
The threat posed by piracy to ships and their crews would also be reduced. That's because uncrewed ships could be built so that they'd be very difficult to board on the high seas. Even if pirates got aboard, access to the controls could be made unavailable. Indeed, the computers in command could immobilize the ship or have it steam in a circle, making it relatively easy for naval authorities to reach it. Recapture would also be easier than is usually the case in such situations because there would be no crew held hostage. And without a captured crew to ransom, the target of the piracy is significantly less valuable.

Another advantage of remotely controlled and autonomous ships is that they can be designed with a larger cargo capacity and lower wind resistance. That's because, with no crew to accommodate, certain features of today's ships can be eliminated—for example, the deck house, the crew quarters, and elements of the ventilation, heating, and sewage systems. This will make the ship lighter and sleeker, cutting fuel consumption, reducing operating and construction costs, and facilitating designs with more space for cargo.





TOMORROW'S ROBOTIC VOYAGERS: The size of ships' crews has been decreasing for centuries, and soon some large vessels may sail without anyone on board. Ships designed to be controlled remotely or to navigate themselves will look distinctly different from today's ships, as suggested by these artist's illustrations [left and below]. Even sooner, advanced automation will help battery-powered ferries now being built for the Norwegian company Fjord1 to make their crossings using electrical energy in the most efficient manner possible [lower left].



Finally, intelligent ships will provide owners and operators with a way to respond to the growing shortage of people who have the requisite maritime skills. With more and more mechanical and electronic systems on board, ships are becoming increasingly complex, needing skilled technicians to keep them working. At the same time, seafaring as a career is growing less attractive, with fewer people from developed nations wanting to spend weeks or months at a time away from home and family. Remote and autonomous operations could facilitate the transfer of jobs requiring high levels of education and skills to ports of call or to operations centers on land, making such careers more interesting to young people entering the industry.

A **LL THE TECHNOLOGICAL BUILDING BLOCKS** are in place to construct and control robotic ships. What could prove to be more challenging, though, are the regulatory changes required to allow such ships to operate. At the moment, global shipping regulations are unclear about whether these ships would be permitted, how they could be insured, and who would be legally liable in the event of an accident.

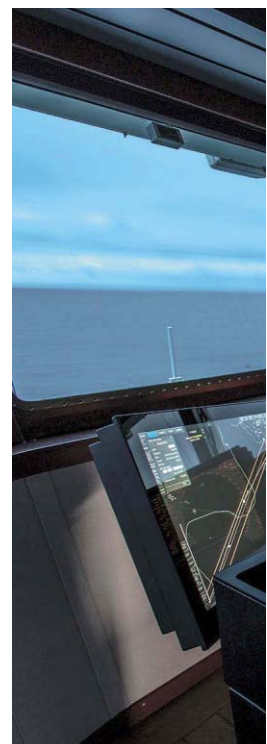
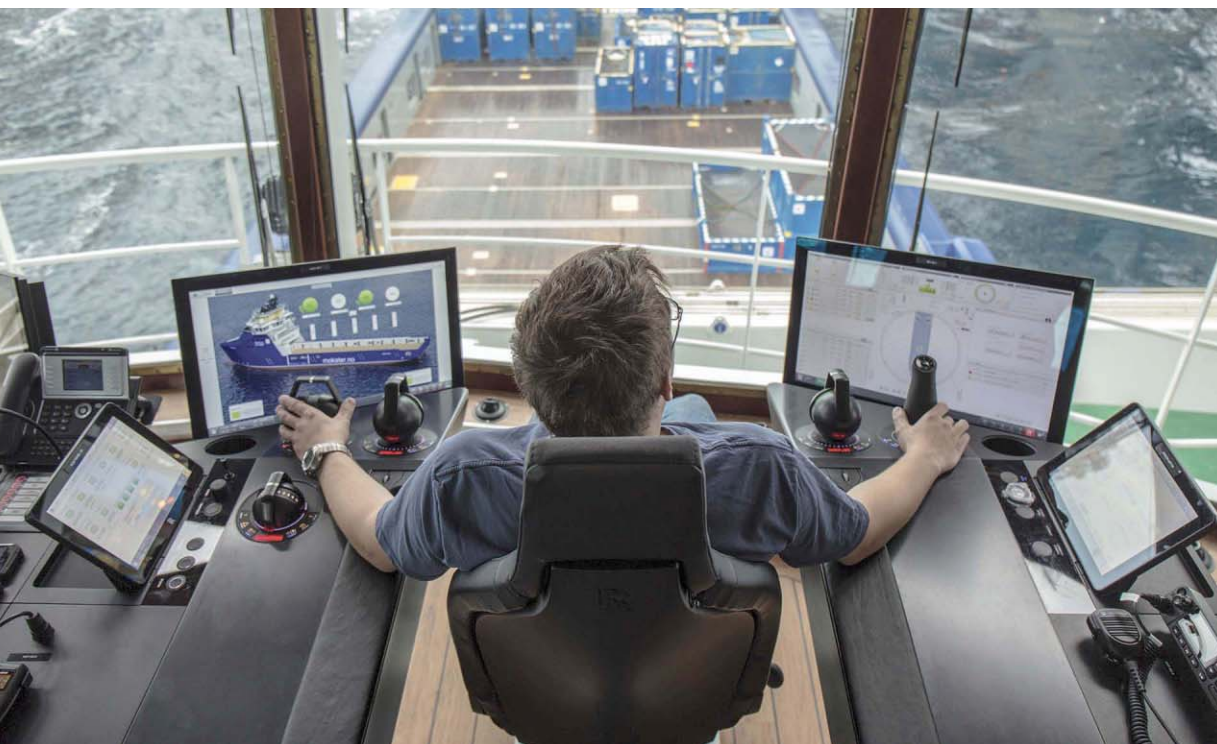
Along with members of the AAWA project, at least two other groups in Europe are looking at changes to regulations that would clarify these questions. A group called SARUMS (Safety and Regulations for European Unmanned Maritime Systems), led by Sweden with six other participating countries, is one. In the United Kingdom, the Maritime Autonomous Systems Regulatory Working Group has been carrying out similar efforts.

The ultimate aim is to ensure that the next substantial iteration of the International Convention on Safety of Life at Sea—the rules that govern international shipping—reflects these technological developments.

The regulators debating these issues will clearly want to know just how safe robotic ships will be. So the challenge for engineers now is to combine relevant technologies to best effect to avoid all possible dangers.

Vital to the development of remotely controlled and autonomous operations will be a ship's ability to sense and communicate what's going on around it so that it can navigate to its destination, avoid collisions along the way, and perform complex maneuvers, such as docking when it finally arrives. We at Rolls-Royce are working on situational-awareness systems that integrate imagery from high-definition visible-light and infrared cameras with lidar and radar measurements, providing a detailed picture of the ship's immediate environment. This information can then be either transmitted back to a remote-operations center—where it would be presented to an experienced skipper—or used by the ship's onboard computers to generate the appropriate next action.

The ship's remote commander or its autonomous-navigation system would also take advantage of many other sources of information: fixes from satellite navigation, weather reports, broadcasts from other ships about their positions and identity. Ships' crews today are already using multiple data sources and electronic aids as part of their daily activities. Systems already exist to plot other vessels, assist with navigation decisions,



BRIDGE TO THE FUTURE: When the time comes to control large oceangoing ships from facilities on shore, the centers set up for such remote operations might resemble Rolls-Royce's Unified Bridge, which was installed initially on the platform-supply vessel *Stril Luna* [right]. That ship's bridge offers panoramic views backward [left] and forward [center], with computerized controls and monitoring systems all within easy reach. Maintaining good situational awareness and keeping the bridge uncluttered both help to improve the safety of operations.

monitor the ship's main machinery, and ensure that the engines and other key mechanical components are performing properly.

In the future, ever more data will be available from sensors embedded deep in the ship's key systems—its main engines, cranes and other deck machinery, propellers and bow thrusters, electrical generators, fuel-filtration apparatus, and so forth. This information will help determine whether these systems are working correctly and in the most efficient manner possible. When a critical part starts to fail, preventative maintenance can be scheduled at the next port of call or, if need be, by dispatching people to make repairs while the ship is still at sea.

Of course, when the ship involved is autonomous or remotely operated, getting this data to shore in a timely manner is vital. Such ships will thus require constant real-time communications links. While satellite communications have been available to ships on the high seas for many years, service is now getting really good. In particular, AAWA partner Inmarsat launched its third Global Xpress satellite in August 2015, which gave the company the ability to support broadband data links almost anywhere in the world. So Inmarsat can provide future uncrewed ships with high-speed broadband connections from space, just as it is doing for today's vessels.

Protecting those data streams and the ship's systems to which they connect from hackers will, of course, be crucial. You don't want troublemakers to divert ships from their routes, or worse, make them collide with something. While providing it will be no small task, we at Rolls-Royce are confident that such security can be achieved.

Even when ships are able to operate completely on their own, there will have to be somebody on land who is able to take charge if conditions demand it. Different types of ships, or ships at different stages of their voyages, will likely require very different levels of oversight and control. A cargo carrier far out at sea will normally need little human supervision, with a single captain overseeing many ships at the same time. A vessel operating in a congested shipping lane, close to shore, or while entering or leaving port, will require much more diligence and the full attention of an individual captain.

As a consequence, an important technological component in all this is the development of remotely controlled systems and control centers. Building on the experience gained from work in aviation, nuclear energy, and space exploration, and from constructing simulators used for training mariners, my Rolls-Royce colleagues and I have been studying how to design such centers. Their configuration must take into account not just ergonomics but also ease of use and how to convey a realistic portrait of what is happening around the ship.

To construct such remote-operations centers, Rolls-Royce will also take advantage of what its engineers have learned while designing and building its Unified Bridge, which is a complete redesign of the traditional ship's bridge, one that provides a more comfortable, clutter-free, and ultimately safer working environ-



ment for mariners. The initial example of Rolls-Royce's Unified Bridge sailed for the first time in August 2014 on the *Stril Luna*, a vessel owned by Simon Møkster Shipping and used to supply oil-drilling platforms. Since then, the Unified Bridge system has been incorporated into tugs, megayachts, polar research vessels, even a new type of cruise ship.

IT'S UNLIKELY THERE WILL BE A SINGLE SCHEME for building and operating robot ships. Some of these vessels could operate without any crew at all, and those will look radically different from current designs. Others will rely on a blend of autonomous and remote control, sailing autonomously in open water but falling back on remote control where more advanced maneuvers are required. Some, such as cruise ships, are always likely to need crew if only for customer service, safety, and reassurance. I expect that the crewed ships of the future will feature many of the same technologies as the uncrewed ones. That is, they'll provide the people on board with improved situational awareness, increasing safety.

I can't point to examples in the water, but Rolls-Royce is working now on the specifications and on preliminary designs for the first generation of advanced intelligent ships. My colleagues and I are bringing together researchers at universities, ship designers, equipment manufacturers, and classification societies to explore the economic, social, legal, regulatory, and technological factors that need to be addressed.

The first intelligent ship to go into commercial operation will use mostly technology that already exists. That vessel will likely ply the coastal waters of a single "flag state," a seafarer's term for a country that can provide the legal basis for

a ship's operation. The ship could be a ferry, a tug, or other coastal vessel traveling within a very confined area. It could still have a crew on board, although they will be carrying out duties other than navigating the vessel.

Indeed, the testing of such ships is not far off. The Norwegian Maritime Authority and the Norwegian Coastal Administration have signed an agreement that allows for relevant sea trials to take place in the Trondheim Fjord, the first place in the world to be designated for the testing of autonomous ships. Meanwhile in Finland, an association called Finnish Marine Industries, the Ministry of Transport and Communications, and Tekes (the Finnish Funding Agency for Innovation) have joined Rolls-Royce and other companies to develop and explore autonomous marine transport in the Baltic Sea.

Expect such a ship by 2020. By 2025, some forward-thinking shipping companies will be operating remotely controlled, completely uncrewed vessels on the high seas. Five years beyond that, uncrewed oceangoing vessels will be commonplace.

These ships will represent some of the most fundamental changes seen by the shipping industry in a long time. But other changes are probably in store as well. The shift from having a crew on board to having land-based technicians manage ships remotely will no doubt revolutionize the operation of the global supply chain, creating new services, more-efficient schemes for leasing and pooling vessels, the emergence of online marketplaces for cargo delivery by sea, and other clever innovations for the digitally connected age. These changes will probably be disruptive, as new players enter a rather staid market, the same way as Uber, Spotify, and Airbnb have done in other realms. So it won't just be the robotic ships that are making waves. ■



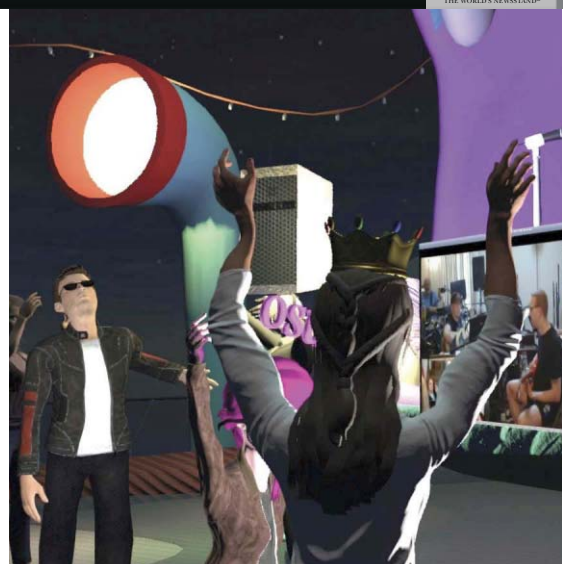
Second Life Founder's Second Act

By **David Kushner**

Photo-illustration by **Sinelab**

Original photo: **Gabriela Hasbun**

**Virtual-reality pioneer
Philip Rosedale
is back with an even
bigger plan**



Philip Rosedale, the Willy Wonka of virtual reality, is giving me a tour of his bustling office in San Francisco in August when his blue eyes sparkle with a better idea. “Let’s just go in-world instead,” he suggests. I follow him to a windowless back room. Waiting there for us are a large HDTV screen, a computer, a few cardboard boxes, and two small, black infrared light-emitting beacons that point down from the high corners.

We slip on our beveled, black HTC Vive headsets, and my eyes adjust to the virtual world. Instantly, I’m teleported to a large living room filled with playthings. A dart board hangs on the wall, a jukebox sits in the corner, a craps table stands beside me. Bows and arrows litter the floor. “My God, it’s a mess in here,” he says through my headset.

In the physical world, Rosedale is a graying 48-year-old in Converse sneakers. Here, Rosedale’s avatar is an almond-eyed woman with short dark hair and blue jeans. I follow Rosedale outside by pushing a button on a controller in my hand and feel a woozy disparity between the motion in-world and my actual stasis. “We’re going to fix that,” Rosedale reassures me.

Rosedale relishes the surreal possibilities of life inside VR. He hands me a garden gnome and suggests we play tetherball. He uses a sword to smack the ball in my direction and urges me to whack it back with the gnome. Tossing the sword on the ground, Rosedale shows me how I can “rez”—or create—my own objects to play with by selecting them from a menu. I use my controller to click something called the Floating Space Cantina, and a huge purple gazebo crashes from the sky onto

the lawn before me. “Wow, that’s cool,” Rosedale says, marveling at the structure. “I guess someone just made that.”

This is a beta demonstration of High Fidelity, open source software created by Rosedale’s company of the same name that lets you build and deploy your own virtual world. Rosedale calls this “social VR.” Most VR experiences—such as games and films—are designed for a single person. Social VR is all about sharing moments with others. The concept is an evolution of his pioneering virtual world, Second Life, which he created in 2003.



VR PRO: Serial entrepreneur Philip Rosedale fell in love with virtual reality as a teen. Now, he’s obsessed with building his new social-VR company, High Fidelity.

HOUSE PARTY: In High Fidelity, users build their own homes and invite friends to join them in-world or through streaming video.

Having seen, and monetized, the first Internet boom, Rosedale wants High Fidelity to do for VR what the World Wide Web did for the Internet: provide a new means through which people can stake out ground online. Instead of surfing to people’s Web pages, you’ll be teleporting to virtual worlds they’re running on their own computer servers. To get from one place to the next, rather than clicking on a hyperlink, people will simply click on a 3D object or “portal.” Coded using that favorite of Web programmers, JavaScript, it will connect them to another’s server, allowing them to open the door of someone’s castle or step into the hut of someone’s tropical island. “What we believe is going to happen is the Internet all over again,” he declares.

This master plan is similar to the one that inspired Second Life, which supported 1.1 million active users per month at its peak. But despite the hype, Second Life never reached mass adoption. Achieving full Internet-scale VR, Rosedale has realized, comes down to the servers.

Second Life had at least 10,000 servers around the country all run by his former company, Linden Lab. As Second Life’s popularity grew, his employees became bogged down with maintenance and capacity issues. The question for High Fidelity became how to break that model and put the servers out in the wild. By distributing High Fidelity online for free, Rosedale wants to foster a do-it-yourself, interconnected community that transforms our virtual lives. “We are



closer than probably people think to having an Internet-scale set of servers that present interconnected personal spaces,” he says.

Rosedale has a knack for painting utopian visions of the future. But to reach the masses, High Fidelity will need to develop far beyond quirky gnome-and-gazebo demos. His team must create sophisticated synchronization software that is also easy to use, writing code that lets people transform their laptops into VR servers while also handling the job of instantly coordinating people’s actions across worlds. Ultimately, these systems must be able to scale to handle the millions whom he hopes will join him in his funky alternative universe.

Weaned on science fiction and “Star Trek,” Rosedale had an early fascination with the potential of virtual worlds and tried to build his own head-mounted display in his teens. Studying physics at the University of California, San Diego, he devoted himself to solving the soft-

ware challenges of VR instead. The video compression technology he coded caught the attention of RealNetworks, an early streaming company in Seattle, which bought his wares and made him its chief technology officer. But it was seeing the simulated future presented in the seminal sci-fi film *The Matrix*, in 1999, and reading the 1992 science fiction novel *Snow Crash* (which popularized the use of the term “avatar” to mean an online stand-in), that inspired Rosedale to leave Real, move to San Francisco, and make his own virtual world. “I was obsessed,” he says.

In 2003, his company, Linden Lab, launched Second Life as the Net’s first free-form virtual reality community. People could create their own avatars and online homes. Fueled by media buzz, Second Life attracted individuals, corporations, and governments (even the IEEE invested in a Second Life island). Users spent over US \$500 million annually worth of virtual cash (in lindens), and developed their own political systems, newspapers, and in-world design firms. It was like virtual reality’s pioneer town—predating the kind of activity we’d later see with large community games like *Minecraft* or *World of Warcraft*.

By 2009, however, Rosedale realized the pressure of running a \$100 million company with about 200 employees was distracting him from his lifelong goal of making a truly immersive VR experience, so he resigned as CEO (though he remains a shareholder). He had seen Second Life run up against its natural limits in employee and server capacity and was eager to obliterate those limits.

“How do we do the kind of thing that Second Life did so well for a million people with mice and keyboards but scale that up to a billion?” Rosedale recalls asking himself.

Part of the answer, it turns out, was to wait for virtual reality to go mainstream. Serious research into virtual reality dates back to the late 1960s, but for decades the goggles were unwieldy, the graphics too unconvincing, and the latency—the lag between making a movement and getting visual feedback on that movement—was too stomach-churning to reach the masses. But improvements in device design and new software for producing 3D objects and environments have made it a far more compelling technology. As gaming, Hollywood, the military, theme parks, and others race to cash in, Goldman Sachs predicts virtual and augmented reality (the latter differs in that it displays a layer of computer-generated graphics over a view of the real world) will become an \$80 billion industry by 2025.

Now, Rosedale is betting his software is best positioned to make social VR a reality. And he’s persuaded others of this too. In 2015, High Fidelity secured an \$11 million investment from Microsoft cofounder Paul Allen. In December, Rosedale said the company has raised an additional \$22 million from investors, and a total of \$37 million to date.

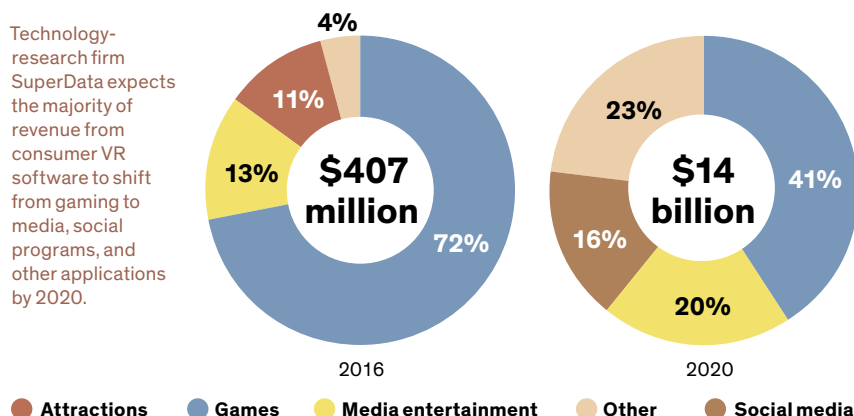
Jaron Lanier, the pioneer who popularized the term *virtual reality*, has tried High Fidelity and hopes it can deliver the kind of shared experiences he’d always imagined. “I like the idea of networked virtual worlds a lot,” he says. “I’d love to see one take off in a huge way.”

In the High Fidelity office, which has the kind of geeky funhouse vibe indigenous to a San Francisco startup, a team of 25 engineers, including several recruits from Linden Lab, have been working like elves to bring Rosedale’s dream to life. Scruffy coders rattle at their computers as multi-colored balloons from a birthday party nudge the ceiling. A telepresence robot—a wheelie machine with an iPad affixed on top—rolls around so that the chief technology officer in Seattle can tune in.

Consumer VR Software Revenue

Technology-research firm SuperData expects the majority of revenue from consumer VR software to shift from gaming to media, social programs, and other applications by 2020.

SOURCE: SUPERDATA RESEARCH



Since 2013, when the company was founded, this team has focused largely on creating the software that provides the technology's essential structure: its distributed client-server system. This means that people can readily deploy it on their own computer servers, without having to rely on a hosting service.

Such a client-server system allows people to essentially put up anything they want—just as if they were running a Web server. High Fidelity allows people to transform their own computers into servers that can support up to 20 people at a time. To run the program, a computer needs access to a broadband connection with a speed of 10 megabits per second or higher. That's well within reach of many people in the United States, where broadband networks currently provide an average connection speed of 15.2Mb/s (some other countries, such as Norway and South Korea, do considerably bet-

ter). Over time, Rosedale thinks Internet service providers everywhere will readily offer enough bandwidth to support a massive virtual world because customer demand will be so great.

All of the content exchanged on these servers can be user generated, built on JavaScript. Users can design basic objects through graphical interfaces, or create more advanced objects and environments by writing code. Programmers wanting to tinker with the underlying High Fidelity client/server platform can do so: The platform is open source, written in the popular programming language C++, and licensed under the Apache 2.0 open source software license.

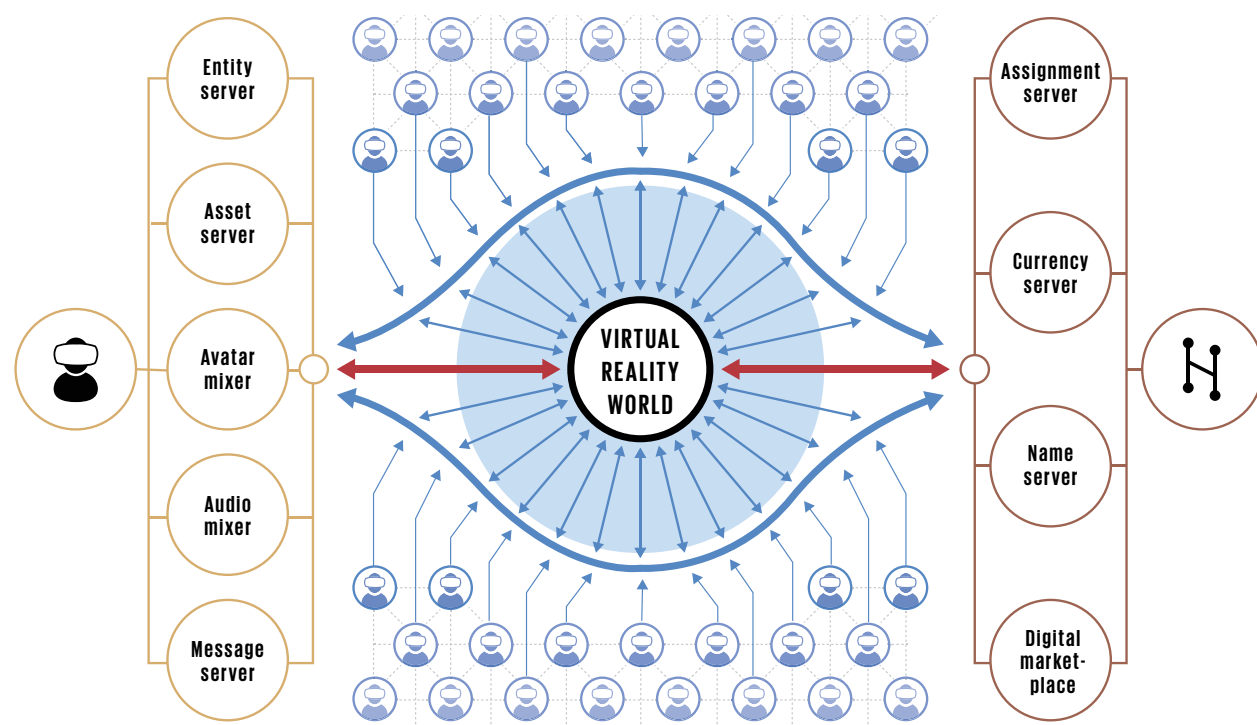
For ease of use, the High Fidelity platform supports two popular file formats called FBX and OBJ, which let people open 3D-vector graphics that were originally created in different formats. The platform will also be compatible with emerging stan-

dards like the GL Transmission Format (also known as "the JPEG of 3D") so people can quickly load 3D scenes and move models around in their virtual worlds.

Alternatively, instead of wading into 3D coding, nonprogrammers can simply download materials from a marketplace. People can even earn virtual cash by selling their own digital objects through the marketplace (High Fidelity will not take a cut of these sales). This leaves High Fidelity, the company, to make money by providing services like domain name translation, user identification, and possibly advertising to all these personal worlds.

Back in-world, Rosedale shows me how someone can drag and drop objects from the marketplace into the world. In his virtual backyard, he calls up another menu which connects us to Clara.io, a library of free 3D models. All I have to do is click on, say, a cactus, a conga, or a steam locomotive and drop it into my

High Fidelity Network Architecture



1. HIGH FIDELITY users install Sandbox, a free software platform. It includes a domain server and five other servers to handle in-world elements, such as an audio mixer for 3D sounds and an entity server to track objects.

2. PROGRAMMERS can write their own code to create objects that they can sell or give to other users, and earn virtual cash by completing tasks that High Fidelity assigns to them.

3. HIGH FIDELITY runs a name server, an assignment server, and a currency server that all support its many virtual worlds. It also manages a digital marketplace where users buy or sell new scenes and items.

world, and it's ready for use. For now, the marketplace is focused on digital objects—such as furniture and toys—but it could include textures and color palettes that people can use to build their own scenery at some point.

A key challenge here is keeping the appearance and behavior of objects consistent and synchronized among all the users visiting a given world. If a high school art teacher holds a distance learning class inside High Fidelity, students need to be able to smoothly hand each other their virtual sculptures.

To facilitate this, Rosedale's team wrote their own "synchronization engine" software. It relies on an "entity server"—a database that maintains, tracks, and manages all virtual objects, or entities. Once a person has connected, the entity server performs lookups to find out what a client is able to see based on the person's position and viewing direction. Then it sends information back to the client about which entities are in view and describes any changes as they occur. For example, if someone fires a gun, Rosedale says, the client will send a message to the entity server to request that it create a "bullet" entity at the client's location and move it along a specific path through the air.

This is something Rosedale's crew first had to tackle in Second Life but now aims to get working with a latency of under 100 milliseconds, so that the action feels smooth and cohesive. Rosedale admits High Fidelity can't guarantee such low latency across all the worlds added to its online universe, but he expects that the builders of the most popular virtual locations will use high-performance servers and network connections to minimize delays. But, as in the early days of the Internet, the results may not always be perfect. "If one server is slower, information from that space might show up more slowly," Rosedale says.

In addition to the delivery issues, High Fidelity's software must also cope with a slew of demands inherent in any virtual reality within its distributed architecture. One of the biggest challenges, Rosedale says, is creating three-dimensional audio so that noises and voices in-world sound



A STRANGE LAND: High Fidelity operates a marketplace for creators to share tools, toys, and unique avatars.

as though they are actually coming from the places where objects and people appear. To create an illusion of space—such as the sound of a ball dropping far across a room—High Fidelity employs its own patented process.

It starts with a database of thousands of standard WAV files, including, for example, the sounds of dropped balls of various sizes and shapes. An audio-mixing server measures the distance and angle of each sound relative to a person's position inside the virtual world, and then mixes it, adjusting the frequency and delay for the desired effect before sending it out to the client.

By opting to release the platform under an open source license, Rosedale let developers outside the company help engineer solutions that work for everyone. And he's not worried about competitors. "If we're successful and I'm right," he says, "it doesn't matter that it's open source because everybody's going to want to deploy a standard system because they want to interconnect to each other."

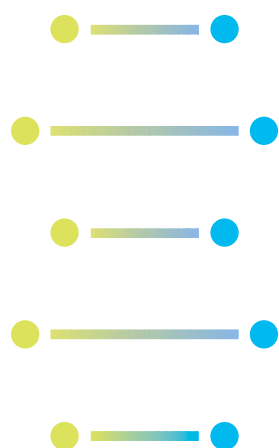
After using my garden gnome to play a xylophone in Rosedale's virtual backyard, I wander toward a side wall, where a whiteboard hangs on the bricks. Rosedale shows me how I can pick up one of the virtual markers and draw a smiley face. "This is what I like best," he tells me, through my headset, "just seeing people drawing on here."

This seems like a far cry from the guy who spent the previous decade ruling the minions of Second Life. But while Rosedale is engineering a democratic social future of VR, he's no less bombastic. By his calculations, if he can get his software on each of the billion Internet-connected machines deployed in the last four years, the virtual world—in sheer landmass—would exceed that of our actual world. "You'd have a space the size of Earth," he says, eyes widening, "so talk about high fidelity. I mean, we're going to go beyond planet Earth!"

But even though High Fidelity software is free, people will still need to buy their own headsets to join Rosedale's dream world and find enough free time to dilly-dally around inside. A \$600 Oculus Rift headset, for example, also requires a high-end PC with a central processing unit equivalent to an Intel Core i5-4590 processor and a powerful graphics card. Such a PC costs \$800 or more.

If we join him, though, Rosedale's convinced that we'll never look at our old planet the same way again. He thinks we'll spend most of our time immersed in VR, and drop back into reality only when we want to do things we simply can't do in-world. "When you think about the Earth in 20 years," he says, "you're going to think of it as a museum."

And, he goes on, the days of me coming out here to do this interview are numbered. "You won't have to drive here. That's nuts," he says. He motions to the screen—"You'll just be able to sit with me in there." ■



THE AUTOMOTIVE FUTURE BELONGS TO FUEL CELLS

RANGE, ADAPTABILITY,
AND REFUELING TIME
WILL ULTIMATELY
PUT HYDROGEN FUEL
CELLS AHEAD
OF BATTERIES

BY SCOTT
SAMUELSEN





PHOTOGRAPH BY Patrick T. Fallon/Bloomberg/Getty Images



You'd have to be completely uninterested in cars or any other type of transportation not to recognize that automobiles are undergoing a major transition. They no longer run solely on internal-combustion engines and burn petroleum-based fuels. Nowadays, consumers routinely purchase vehicles that run in part or entirely on electricity.

There are different forces behind this colossal shift. For one, electrically powered vehicles reduce the emissions of pollutants that degrade local air quality as well as carbon dioxide emissions, which raise significant worries about altering the climate.

Another reason to favor electrically powered vehicles involves national security. Ample supplies of petroleum are found only in select regions of the world. So countries that lack these natural resources will remain at a political and economic disadvantage if they continue to utilize vehicles that burn gasoline or diesel fuel.

The final reason stems from the fact that exploitable sources of petroleum are slowly running out. Once society reaches the point where production cannot keep up with demand, prices will skyrocket. So it's no wonder, really, that the transition to electric vehicles is speeding up.

Electric vehicles can be divided into three groups. Most common today, of course, are hybrids, which combine batteries, electric motors, and internal-combustion engines. Although these vehicles have many virtues, in particular high efficiency, all but the plug-in hybrids ultimately draw all of their power from petroleum-based fuels.

The second group is battery electric vehicles, or BEVs, such as the Nissan Leaf and the Tesla Model S, which are now reasonably common. While the electricity they use to charge their batteries comes primarily from fossil fuels, BEVs are advantageous because they use that energy more efficiently than a car with an internal-combustion engine. The grid is also moving to more renewable power, further reducing the carbon signature associated with BEVs.

A third budding category consists of fuel-cell electric vehicles, or FCEVs, which are just emerging but, as I argue below, represent the electric vehicle that most people will ultimately select as their principal car. Forward-looking carmakers are now producing both BEVs and FCEVs, but

not without considerable controversy and competitive posturing, which only makes the situation more confusing. So here I would like to clarify the relative benefits of the different technologies and relate how I see electric personal transportation evolving.



HYBRID AND BATTERY electric vehicles are common enough now that I needn't say much about their principles of operation. Fuel-cell electric vehicles are still a rarity, though, so let me describe more fully how they work.

Rather than relying on combustion to drive pistons that then power an electric generator as in a hybrid car, a fuel-cell vehicle uses electrochemistry to generate electricity directly. This is done by taking compressed hydrogen gas stored on board and combining it with oxygen from the air. The products of the reaction are electricity to power the vehicle and water, which is discharged through the tailpipe along with the nitrogen that entered the fuel cell with the air. Because there is no combustion, high temperatures are avoided, and oxides of nitrogen, a smog-inducing pollutant from conventional vehicles, are not produced. And because there is no carbon in the fuel to begin with, no hydrocarbons, carbon monoxide, or carbon dioxide are emitted from the tailpipe.

In addition, a fuel-cell electric vehicle is remarkably efficient, more than three times as efficient as today's average gasoline-powered automobile. Its range and fueling time are comparable to those of conventional automobiles, its fuel can be produced in a variety of straightforward ways, and its drivetrain produces practically no vibration.

Sounds attractive, doesn't it? You might be wondering how you can start driving one. If you're in the right location, you now can. A fuel-cell version of the Hyundai Tucson SUV has been offered for lease in my home state of California since June 2014. And an FCEV has been both sold and leased here by Toyota since October 2015, a four-door sedan called the Mirai. Honda released a new FCEV in California in December, a commercial version of its Clarity fuel-cell prototype.

Of course, you need more than just the car—you also need a place to fuel it. In my state, the requisite hydrogen-fueling infrastructure is being developed by the California Energy



COOKING WITH GAS: Honda's new Clarity fuel-cell-powered car [far left] is soon to be joined by electric and plug-in hybrid versions of this model. Since 2014, drivers in California have been able to lease a fuel-cell-powered Tucson SUV [left] from Hyundai. Toyota's fuel-cell-powered Mirai [above] has been both sold and leased in California since October 2015. And just two months ago the Nikola Motor Co. unveiled its fuel-cell-powered Nikola One [right], which is able to travel more than 1,200 kilometers on a single fill-up of hydrogen.

Commission, which projects that there will be more than 44 hydrogen filling stations operating here by the end of 2017 and 74 by 2020. The need for a hydrogen-fueling infrastructure elsewhere in the country is being addressed by H₂USA, an initiative supported by the U.S. Department of Energy.

In Europe, there are currently a few dozen hydrogen-fueling stations in operation, and a program called Hydrogen Mobility Europe is leading efforts to increase that number. As of mid-2016, there were 80 hydrogen stations operating in Japan, where the government is keen to boost the number of such facilities considerably before the 2020 Summer Olympics in Tokyo.

HYUNDAI'S, TOYOTA'S, AND HONDA'S fuel-cell electric vehicles may be new to the streets, but much of the technology they carry is not at all new because these cars have a great deal in common with existing battery electric vehicles. Both FCEVs and BEVs have electric drivetrains and battery packs. And both use regenerative braking, a key energy-saving attribute of electric vehicles. Where they fundamentally differ is in the source of electricity, the time required to recharge or refuel, the driving range, and the ability to scale up the size of the vehicle.

Consider first the source of electricity. BEVs are powered solely by electricity generated elsewhere and then stored in a battery pack, whereas FCEVs are powered by hydrogen, which is transformed to electricity by a fuel-cell engine on board the vehicle. Although the hydrogen fuel cell generates electric power, FCEVs also require a battery pack to supply surges of energy to the drive motor and to absorb electricity created by regenerative braking. In contrast to



BEV batteries, however, FCEV batteries are only of modest size, like those in hybrid cars today.

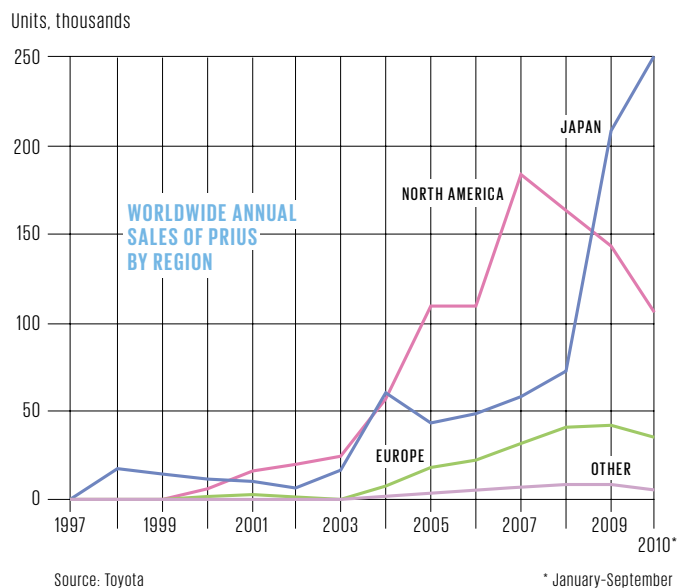
The range of most BEVs falls somewhere between 65 and 320 kilometers (40 and 200 miles), depending on the model, the cooling and heating loads, the speed at which the vehicle is driven, and how often the headlights and other electric accessories are used. Affluent electric-car enthusiasts can purchase a Tesla Model S or Model X, which are reported to have ranges of nearly 480 km. That's approaching the range of FCEVs and conventional vehicles, which can typically travel from 480 to 640 km on one tank.

A BEV takes an hour to more than 4 hours to charge when a high-voltage source is available and more than 6 hours using a standard 120-volt household outlet. Cars equipped to accept DC "fast" charging take roughly 30 minutes. An FCEV fills up with a full charge of hydrogen in less than 5 minutes.

BEVs are well suited for light-duty vehicles and are emerging for use in delivery trucks and buses on routes of modest range. The problem with trying to power larger, longer-distance vehicles with batteries is that more battery mass must be added to do so. That in turn requires the vehicle to be outfitted with a bigger motor, a stronger suspension, and better brakes to maintain the same performance—all of which add more weight, which means even bigger batteries are required. It's a vicious circle, one that eventually becomes unsupportable when designing a large vehicle with the range to which drivers are accustomed. In contrast, fuel cells can be used to power virtually any size vehicle, from compact cars to long-distance tractor-trailer rigs.

THAT DIFFERENCE IN CAPABILITY is well illustrated by what happened at Nikola Motor Co., which at one time had intended to produce a BEV tractor-trailer. After the realities of trying to engineer such a vehicle became apparent, the truck's designers switched to using a hydrogen fuel cell for power. And just two months ago, the company introduced its fuel-cell-powered tractor-trailer, called the Nikola One.

While fuel-cell cars are just now gaining a toehold in today's market, I believe that within the next quarter century, the majority of car buyers entering the showroom will select an FCEV as their primary means of transport.



HYBRID VIGOR: Sales of the Toyota Prius, which pioneered the hybrid drivetrain, took about a decade to really take off. The same will presumably be true of fuel-cell-powered cars.

tation, and because of limitations in range and recharging speed, they will consider a BEV only as an option for their second car.

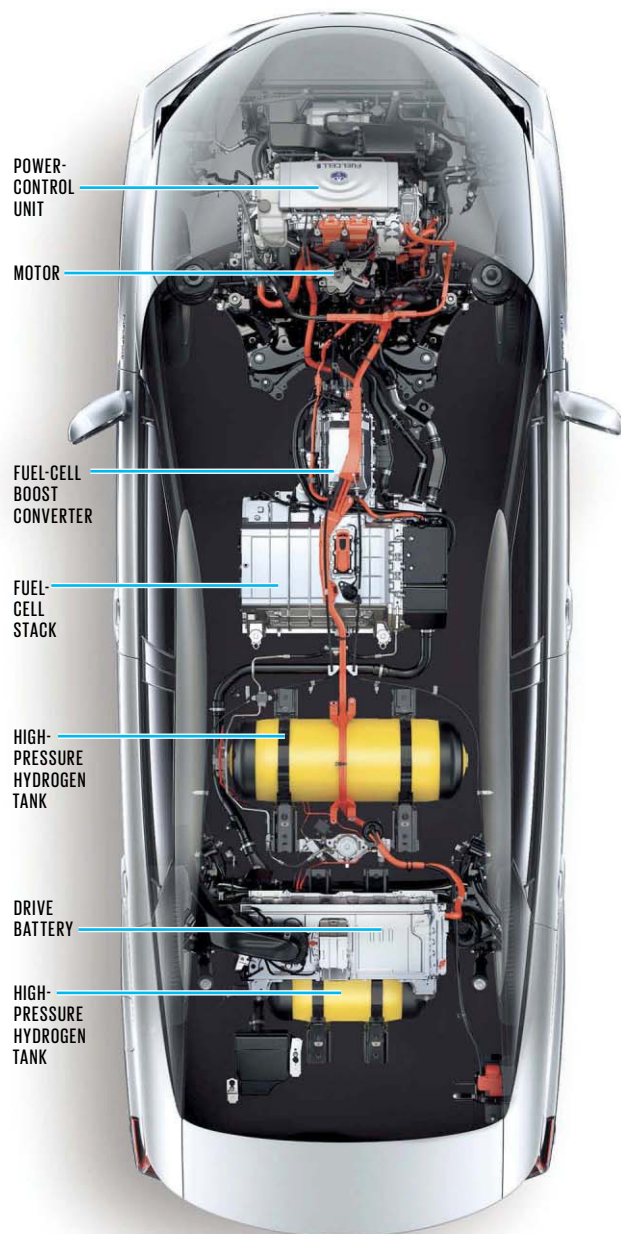
Some strongly disagree with my position here. Most prominent among them, perhaps, is Tesla CEO Elon Musk, who has deridingly referred to FCEVs as “fool-cell vehicles.”

On one occasion in 2015, Musk gave three specific reasons for his position: concerns about the safety of hydrogen, the lack of fueling infrastructure for providing that hydrogen, and its nonrenewable nature. I suspect that Musk’s stance is colored by his desire to promote Tesla’s emerging line of BEVs, a bias that is a disservice to both the public and the environment.

So let me explain why I think Musk’s remarks are off base. First, his statements about the dangers of hydrogen are overblown. All sources of vehicle energy—whether it’s hydrogen, gasoline, diesel fuel, natural gas, or the electricity stored in a battery—have safety issues associated with them. Each must be addressed with the appropriate caution, codes, and standards.

Hydrogen is no different in that regard from other fuels except for certain features that, in some ways, make hydrogen *safer* than the gasoline fuel with which we’ve grown so comfortable over the decades. In particular, hydrogen is lighter than air and rapidly dissipates upward and outward. This is very different from gasoline, which in a breach can accumulate under the vehicle and, if ignited, engulf the entire vehicle in flame.

Musk’s criticism about the lack of fueling stations for hydrogen is similarly exaggerated. Both BEVs and FCEVs require comprehensive changes to our transportation infrastructure, to be sure. For FCEVs, existing gasoline filling stations must be capable of dispensing hydrogen, which requires costly equipment. But not all filling stations would need to have that capability initially (just as not all filling stations



INNER WORKINGS: Toyota’s fuel-cell-powered Mirai has many of its key components located beneath or behind the passenger compartment, although the electric motor is situated up front, under the hood.

dispense diesel fuel). A study carried out for the California Energy Commission in 2013 found that the state needed only 68 hydrogen filling stations for people to start buying FCEVs in substantial numbers. Within Southern California, only 38 such facilities would be required. At full build-out, only 15 percent of current gasoline filling stations operating in the state need to transition to hydrogen. From such a base, the hydrogen-fueling infrastructure would no doubt expand with the numbers of FCEVs to add additional convenience and capacity.

BEV charging, unlike hydrogen fueling, does not have the filling station as the natural home for deployment. The



ACTUAL GAS STATION: Iwatani Corp. opened Japan's first commercial hydrogen filling station in the city of Amagasaki in July 2014. At such facilities, cars can tank up in a few minutes, in much the same fashion as they do at today's "gas" stations.

reason, clearly, is because charging takes so long. Charging stations are, however, being installed at major destination points such as shopping centers and office complexes. Home charging is also possible, but it's a challenge for the increasing numbers of drivers living in apartments and condominiums. And the long periods required to recharge a vehicle at a public charging station are problematic, often creating episodes of "charge rage," when one vehicle is denied access to a charging port because it's occupied by another vehicle that is either taking hours to charge or is fully charged but waiting for its driver to return from shopping or completing a day's work.

Musk's final criticism is that the hydrogen used in FCEVs is not produced from renewable sources. He is again not correct. Today, 33 percent of the hydrogen dispensed in California must, by law, be produced from renewable sources. Going forward, the percentage of renewable hydrogen dispensed will increase, and, most likely at some point in the not-too-distant future, *all* the hydrogen put into vehicles will fall into this category.

Here's why that makes sense: There are already multiple sources of renewable hydrogen, including the combined generation of hydrogen, heat, and power (known as trigeneration) from stationary fuel cells operating on renewable fuels. Another source, electrolysis, is well established and, as it expands, will be able to capture and store solar and wind energy that would otherwise be curtailed when the power generated exceeds the demands of the grid.

That stored energy would then be available for FCEVs or for stationary fuel cells to meet a call for power by the grid.

WHERE THE HYDROGEN STATIONS ARE

California and the Northeast contribute most to the fledgling hydrogen infrastructure for fuel-cell vehicles in the United States. To learn more about where stations are located, go to <http://spectrum.ieee.org/hydrogenstations0217>

Batteries will play a role as well, but they do not have the energy density to absorb the massive amounts of energy available, whereas hydrogen does.

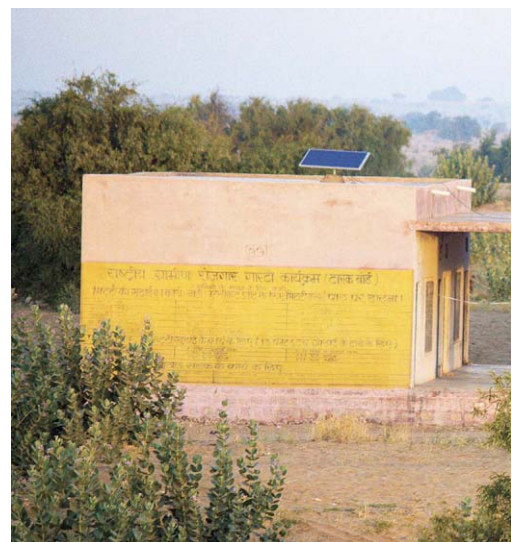
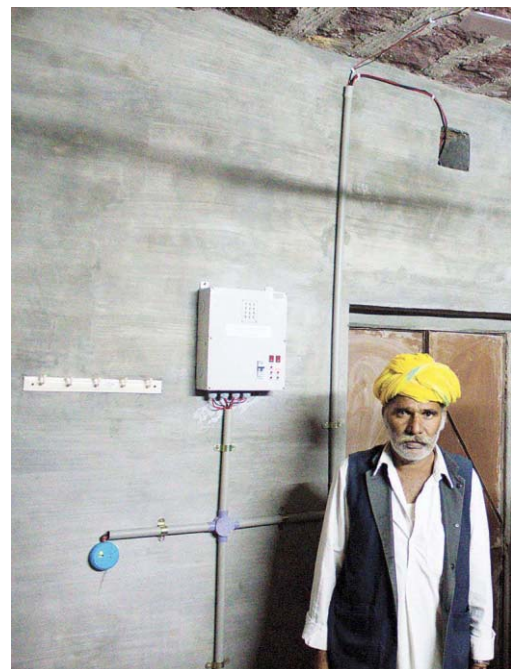
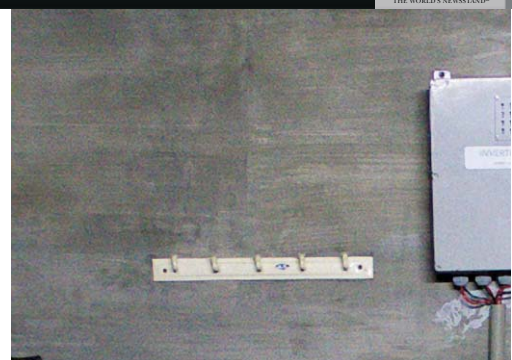
Musk argues that electrolysis squanders energy because it's only half as efficient as charging batteries. But rather than squandering renewable-energy resources, producing hydrogen from wind and solar could—despite its relative inefficiency—make available a great deal of energy that would otherwise never have been captured in the first place.

DESPITE THE VERY PUBLIC POSTURING of Musk and other hydrogen naysayers, most automobile manufacturers are readying themselves for a time when FCEVs dominate. These companies realize that the size and costs involved generally preclude the use of battery storage for large passenger vehicles as well as medium- and heavy-duty trucks, whereas FCEVs are well positioned to serve all these segments. Mainstream carmakers are also acutely aware that, for many people, BEV charging is just really inconvenient.

That said, I don't want to suggest that BEVs will be completely replaced by FCEVs as the models available and hydrogen-fueling infrastructure expand. Some people don't need large cars or vehicles that can travel long distances without lengthy recharging stops. For many homeowners, charging a car in the garage at night is easy enough, and BEVs will serve that portion of the market very well.

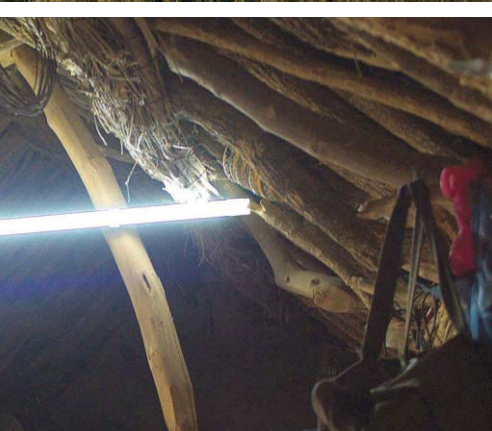
So it's not a matter of one type of electric vehicle prevailing over the other. Based on the current fleet and evolving market trends, I expect FCEVs eventually to be more common than BEVs, but that will take decades, no doubt. And even when that happens, the number of BEVs, many representing a second vehicle, will undoubtedly be substantial.

Elon Musk needn't feel so threatened by the many attractive features of the FCEVs that are just now breaking into the mainstream automobile market, thanks to the efforts of Hyundai, Toyota, Honda, and other manufacturers. Yes, it's taken a long time, but the age of the hydrogen-fuel-cell electric vehicle has begun. ■



POWER TO THE PEOPLE: Starting in 2015, about 4,000 rural households in the Indian state of Rajasthan received solar direct-current microgrids. Each microgrid consists of a 125-watt solar panel, a lead-acid battery, and a special inverterless controller. While modest by Western standards, the setup provides enough power for LED lighting, a DC ceiling fan, and a cellphone charger.

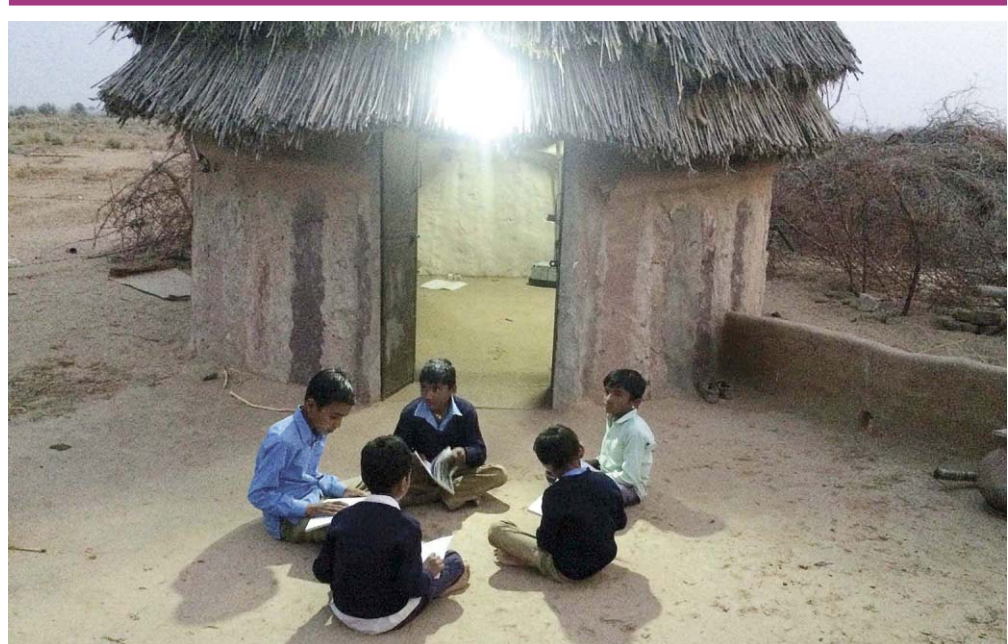




By **ASHOK JHUNJHUNWALA**

THE PEOPLE'S GRID

SOLAR DC MICROGRIDS can do what conventional grids can't: bring reliable electricity to the world's rural villages





I

In the industrialized world, the power grid is so reliable that we take it for granted.

But in India, where blackouts are a sad fact of daily life, being connected to the grid is no guarantee of reliable electricity. In a 2015 study of villages in six Indian states, for example, the vast majority reported having fewer than 4 hours of electricity per day; nearly half of the households that reported having a grid connection nevertheless had effectively no electricity. Chief among the reasons they cited were poor reliability, quality, and affordability. In many parts of the country, even middle-income households still find themselves held hostage to frequent power cuts that can last anywhere from a few hours a day to most of the day. Those who can afford to often install diesel generators, an expensive and polluting option.

Then, too, roughly a quarter of a billion Indians, or one-fifth of the population, live without access to any

OFF GRID: The Rajasthan village of Bhom Ji ka Gaon was the first to be electrified using solar DC microgrids, at a fraction of what it would have cost to extend the traditional power grid to such a remote site.

electricity at all, according to the International Energy Agency. For a country where science and technology has otherwise advanced at a breathtaking pace, this sorry state of electrification is a disgrace.

In recent years, the Indian government has invested heavily in electricity generation (including solar- and wind-power plants), state-of-the-art high-voltage transmission lines, and a multitude of household electrification projects. And yet these efforts have made only a modest dent in the problem. A government Web portal that tracks rural electrification efforts shows that in only four of the country's

29 states do all of the households have access to electricity.

The problem is this: The Indian government has taken a traditional approach to electrification, which focuses on building up generation, transmission, and distribution. But there's a better way that's more affordable, more efficient, and much faster and easier to deploy. It can also address all aspects of the electrification problem at once, reducing the gap between demand and supply, bringing down electricity costs, and providing reliable, always available electricity to everyone.

This strategy, developed by my group at the Indian Institute of Technology (IIT) Madras in conjunction with industrial partners, relies on solar-powered direct-current (DC) microgrids. For homes not connected to the grid, a 125-watt microgrid can serve as the sole source of electricity. For connected households, the microgrid acts as a backup power supply to let lighting, fans,

TV sets, and cellphone chargers continue operating even during brownouts.

In 2014, we began field-testing our DC microgrid systems in dozens of homes, offices, and dormitories at IIT Madras. The following year, we expanded deployments to about a thousand homes in three cities and multiple villages. Now, with funding from India's Ministry of Power, we have two large-scale projects under way that will eventually reach more than 100,000 households.

By Western standards, the 125-W load provided by our microgrids is quite modest—an ordinary household vacuum cleaner uses anywhere from 500 to 3,000 W. Indeed, in the typical northern California home, the “idle” load—that is, the electricity used by devices that are plugged in but turned off—far exceeds 125 W. And yet, in every place we've deployed our system, the recipients have been immensely satisfied because they now have electricity around the clock. They appreciate having lights to prepare a meal or study at night, watching an entire TV program without having it interrupted by a power outage, sleeping through a hot night under the cooling breeze of a fan.

And while India faces a unique challenge in the sheer number of homes that lack electricity, our technology could find uses far beyond India. In fact, we believe every household in the world, whether in Cincinnati or São Paulo, could benefit from having a solar DC microgrid. Here's why.

Let's first consider how to shore up the power supply to households that already have a grid connection. As in the rest of the world, India's main power grid is based on alternating current (AC). Our system, by contrast, relies on DC because PV panels and batteries as well as consumer electronics, LED lighting, and a growing range of appliances all work with direct current, and we thus avoid the losses that come with converting back

and forth between AC and DC. Each conversion incurs a power loss of 5 to 20 percent, so for the sake of efficiency, you want to minimize the conversions.

We start by running an additional power line in the home. It is a 48-volt DC line and provides about 10 percent of the typical household load. LED lightbulbs, electronics, or small appliances that have been designed to run on DC can be fed directly by this line. We also replace the traditional electricity meter with what we call an uninterrupted direct-current (UDC) power meter, which has the same control and communications capabilities of a smart meter, along with an AC-to-DC converter for converting a portion of the incoming AC to DC.



POWER 24/7: In the Indian city of Sasaram, residents can have a separate DC line installed, controlled by the circular device above. Called an uninterrupted DC power meter, it replaces the traditional meter.

Now let's say that demand on the grid is peaking, and generation can't keep up. The typical practice in India is for the grid operator to cut power completely in some areas until the careful balance of supply and demand has been restored. In areas where our UDC system has been deployed, the grid operator instead institutes a brownout, cutting power by 90 percent. The remaining 10 percent may not sound like much power, but bolstered with current from some storage batteries (more on them below), it's actually enough for the household to keep the lights on and perhaps a few DC appliances, too. At the start of the brownout, the local substation signals each UDC meter, which instantly cuts off the home's main AC power line but maintains the DC power. When the brownout

is over, the substation signals the UDC meter again, and it restores regular AC power in the home.

Since 2015, we've been collaborating with the Hyderabad-based solar power company Cygni Energy to roll out UDC systems in the city of Sasaram, in the northeastern state of Bihar. There, up to 100,000 households will soon receive DC microgrids. Although these homes are connected to the existing AC power grid, the reliability is poor, and residents are desperate for an alternative. Bihar has the largest deficit between peak demand and supply of any Indian state and the lowest per capita electricity consumption. Eventually, Sasaram could become the first city in the world to have a DC power line installed in every home.

To supplement the power coming from the main grid, each UDC household can also install a 125- to 500-W photovoltaic panel, which connects through the UDC meter to a low-cost but high-performance lead-acid battery developed by Amara Raja Batteries. The battery supplies electricity at night and during brownouts.

Unlike the vast majority of residential solar installations being deployed these days, ours is an entirely DC system.

We thus avoid the inefficiency of converting the panel's direct current to AC for synchronizing to the main grid, the conversion back to DC to charge the battery, and a third conversion from DC back to AC when the battery is discharged.

Taken together, the DC line from the main grid and the solar microgrid are enough to power five fans, eight LED lights, two small flat-screen TVs, several cellphone and tablet chargers, and a laptop. These are all DC-compatible devices, of course, and use much less power than do AC appliances. The fans use brushless DC motors; where an AC fan might consume 72 W, a DC fan with comparable airflow will use just 30 W. Similar brushless DC motors could one day be used in refrigerators, air conditioners, and washing machines. As for LED lighting,

LCD TVs, computers, and the like, they already run on DC; to plug them into a traditional AC outlet, manufacturers add on an AC-to-DC converter. So configuring them to operate on a DC line mostly involves replacing the AC-to-DC converter with a much more efficient DC-to-DC controller.

By using DC-compatible lights and devices instead of their AC alternatives, homeowners can dramatically reduce their electricity usage and thus their monthly bills. We ran simulations to compare the costs of a solar-powered AC microgrid and a solar DC microgrid. We calculated the consumption for a small home equipped with two LED tube lights, two LED lightbulbs, two fans, a mobile phone, and a 24-inch LED TV. With an AC solar microgrid running AC lights and appliances, the home used 3.3 kilowatt-hours a day, at a cost of 16.3 rupees (24 U.S. cents). With a DC microgrid, the usage was just 1.2 kWh at 6.5 rupees (9.5 U.S. cents) because of the higher efficiency of the DC appliances and the lack of conversion losses.

We then looked at how the microgrids would perform during a load-shedding brownout that occurred every day and lasted 4 hours—a common pattern in many parts of India. In such a situation, the microgrid's battery would be discharged and then later recharged. As noted above, the solar-powered AC microgrid would see significant losses associated with converting from AC to DC and back again. Factoring in the load shedding would raise the daily cost for the AC microgrid to 28.9 rupees (42 U.S. cents), while the DC grid's cost would go up only slightly, to 7.3 rupees (11 U.S. cents). Over a month's time, the potential savings from the DC system could amount to more than 400 rupees (\$5.90). That may not sound like a lot of money to an affluent resident of a developed country. But in many parts of India, it is. It could mean the difference between

keeping the lights on or sitting in the dark, between having a working fan or sweating in one's bed.

Solar DC microgrids are also starting to have an impact in Indian villages that have never had grid-provided electricity. Our largest installation to date involves 71 villages in the western state of Rajasthan, where we have been working with the utility company Jodhpur Vidyut Vitran Nigam to electrify some 4,000 homes for the Ministry of Power. [For another example of electrification of a remote Indian

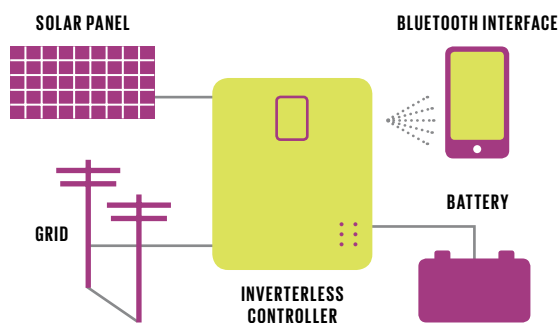
water to irrigate their crops and raise their livestock. Most residents don't venture out of the village except when they need to grind wheat or millet.

For the conventional power grid to reach this remote site would require building substations and power lines—a difficult and economically unfeasible proposition given the uneven terrain, long distances, and occasional severe sandstorms. What's more, the chances of recovering such an investment would be slim at best: Although the villagers are self-sufficient, they don't earn much money and so wouldn't be able to buy a lot of electricity even if it were available.

What Rajasthan does have are clear skies and abundant sunlight for most of the year. So it's ideal for solar power and indeed has already attracted several large PV power plants, most notably a proposed 4,000-MW facility near Sambhar Lake that would be the world's largest. But these plants have many of the same problems of a traditional grid connection: They require transmission and distribution infrastructure to channel the captured power to nearby villages, and they suffer conversion losses when the DC power generated by the solar panels is converted to AC power.

In our deployments in Rajasthan, each home is given a 125-W solar panel, a specially designed 1-kWh lead-acid battery with an expected life span of 1,600 cycles (compared to about 800 cycles for a normal battery), and an inverterless controller box. Each house also gets a complement of devices: a full-size DC fan, a dimmable LED tube light, a remote for controlling the fan and tube light, an LED lightbulb, and a cell-phone charger. The homeowner can add extra lights or a TV set, as long as the overall load doesn't exceed 125 W. The entire system is being manufactured and installed for a fraction of the cost of traditional grid electrification.

We've also done installations outside of Rajasthan in which groups of two



JUST ENOUGH: A grid-connected home where power is unreliable can benefit from having a separate DC line, which provides about 10 percent of the usual household load during brownouts.

village in the Himalayas, see "Lights for the Enlightened," *IEEE Spectrum*, December 2016.]

Before the project began, the villagers basically lived in darkness at night. Rajasthan actually has enough power to meet the needs of its entire population; the problem is delivering that power to every household.

Our first village was Bhomji ka Gaon, a community of 120 households that lies among the mighty sand dunes of Rajasthan. The village is 90 kilometers from the nearest town and 300 km from the nearest city, Jodhpur. The homes are spread out over an area of about 10 square kilometers. With no paved roads, crossing the sand dunes is best done by camel cart, tractor, or four-wheel drive. The people collect rain-



NIGHT LIGHT: After the sun goes down, the solar DC microgrid's batteries power an efficient LED streetlamp, which provides plenty of illumination for cooking, conversing, and moving about.

to four houses share a single 500-W microgrid and one installation in which about 30 houses now share a 7,500-W microgrid. With these larger networks, the amount of electricity allotted to each household can be remotely varied, to accommodate different-size households, via a wireless connection to the UDC meter in each home. The shared equipment reduces the installation and operating costs for each household.

For villages like Bhom Ji ka Gaon, conventional electrification is many years away, at best. In the meantime, DC appliances will keep getting better and a wider range of products will come to market, including evaporative coolers, small DC refrigerators, and solar stoves. At the same time, solar panels, batteries, and other microgrid components will continue to become cheaper and more efficient. In the end, the villagers may find that their off-grid systems provide all that they need.

India's power problems are deep and pervasive. And yet the country's experience with telephony offers a glim-

mer of hope. Until the mid-1990s, not even 5 percent of Indian homes had a phone, and in many places you'd wait for years just to get a landline installed. The main problem was the cost of copper cable, which made such connections prohibitively expensive for most people.

Then came cellphones and the rapid expansion of the cellular network. Today, nearly every adult in India has a mobile phone, which provides so much more functionality than a landline phone ever could. And the number and range of mobile services continue to grow all the time.

So too could India's electrification follow an unconventional, disruptive path. We hope that solar DC microgrids paired with UDC meters evolve like India's cellular network, leapfrogging over traditional infrastructure. Introducing DC

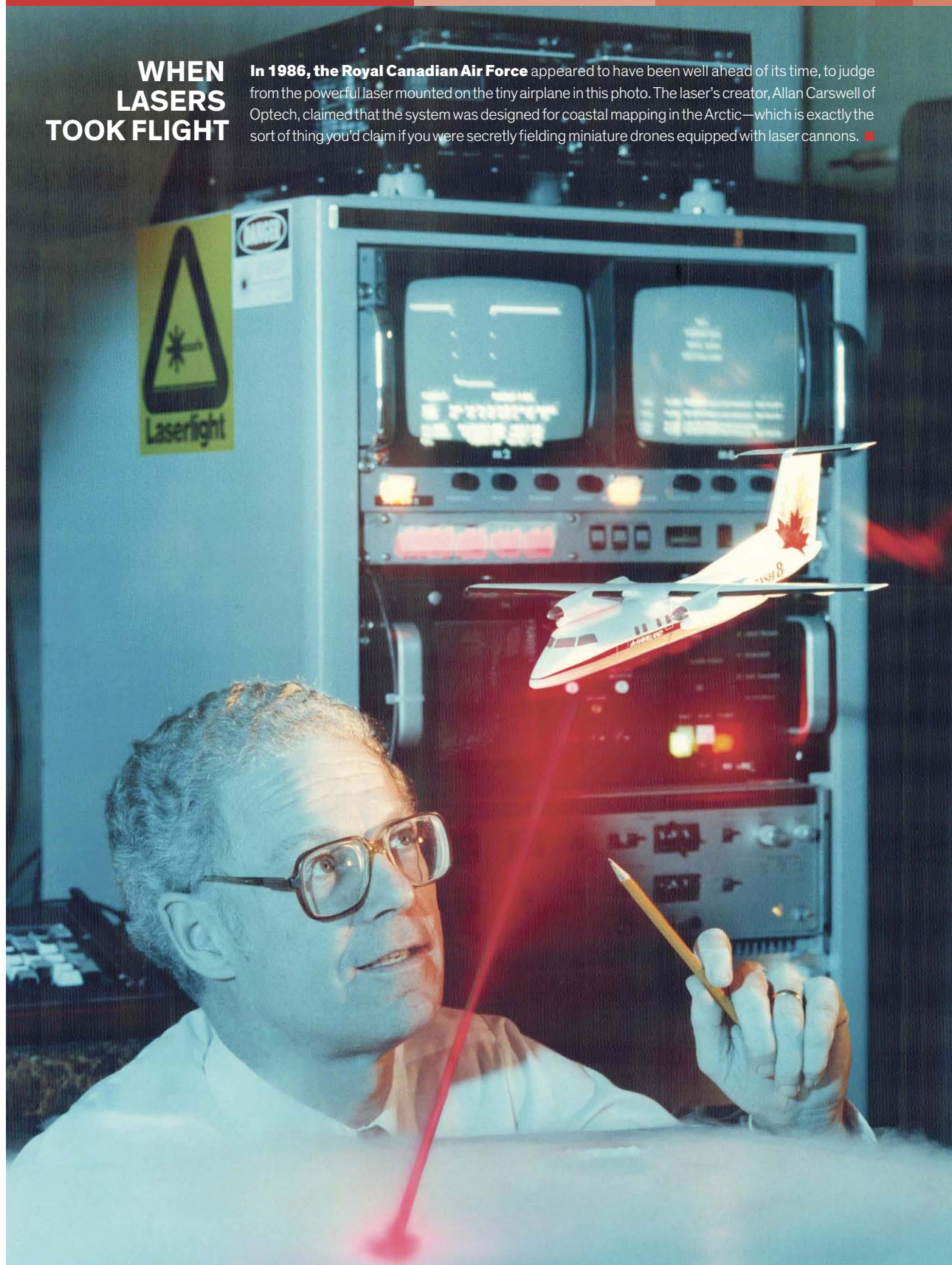
lines into the home will naturally boost the market for DC appliances, which in turn will begin to edge out more power-hungry AC alternatives. Over time, those appliances as well as the microgrid equipment will become more affordable, even for rural villagers with little income. And as households consume far less energy and generate that energy right where it's used, their utility bills will drop. As homes become less dependent on the traditional grid, they'll be less affected by power cuts; eventually, such outages will disappear, as gaps between supply and demand go away.

We know that this technology can transform lives. We've seen what even a modest level of access to electricity can do, and we've heard many moving and inspiring stories from villagers who now enjoy comforts, conveniences, and security that they never thought they'd have. This is one of those rare moments when technological breakthroughs can come together to make it possible to do good on a massive scale. For the 1.2 billion people in this world who still live without electricity, it cannot happen soon enough. ■

PAST FORWARD_BY EVAN ACKERMAN

WHEN LASERS TOOK FLIGHT

In 1986, the Royal Canadian Air Force appeared to have been well ahead of its time, to judge from the powerful laser mounted on the tiny airplane in this photo. The laser's creator, Allan Carswell of Optech, claimed that the system was designed for coastal mapping in the Arctic—which is exactly the sort of thing you'd claim if you were secretly fielding miniature drones equipped with laser cannons. ■



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