IEEE SPECTRUM

FOR THE TECHNOLOGY INSIDER | 12.14

PEEL BACK for Career Tools, Discounts & More!

Time to renew your **IEEE membership!**

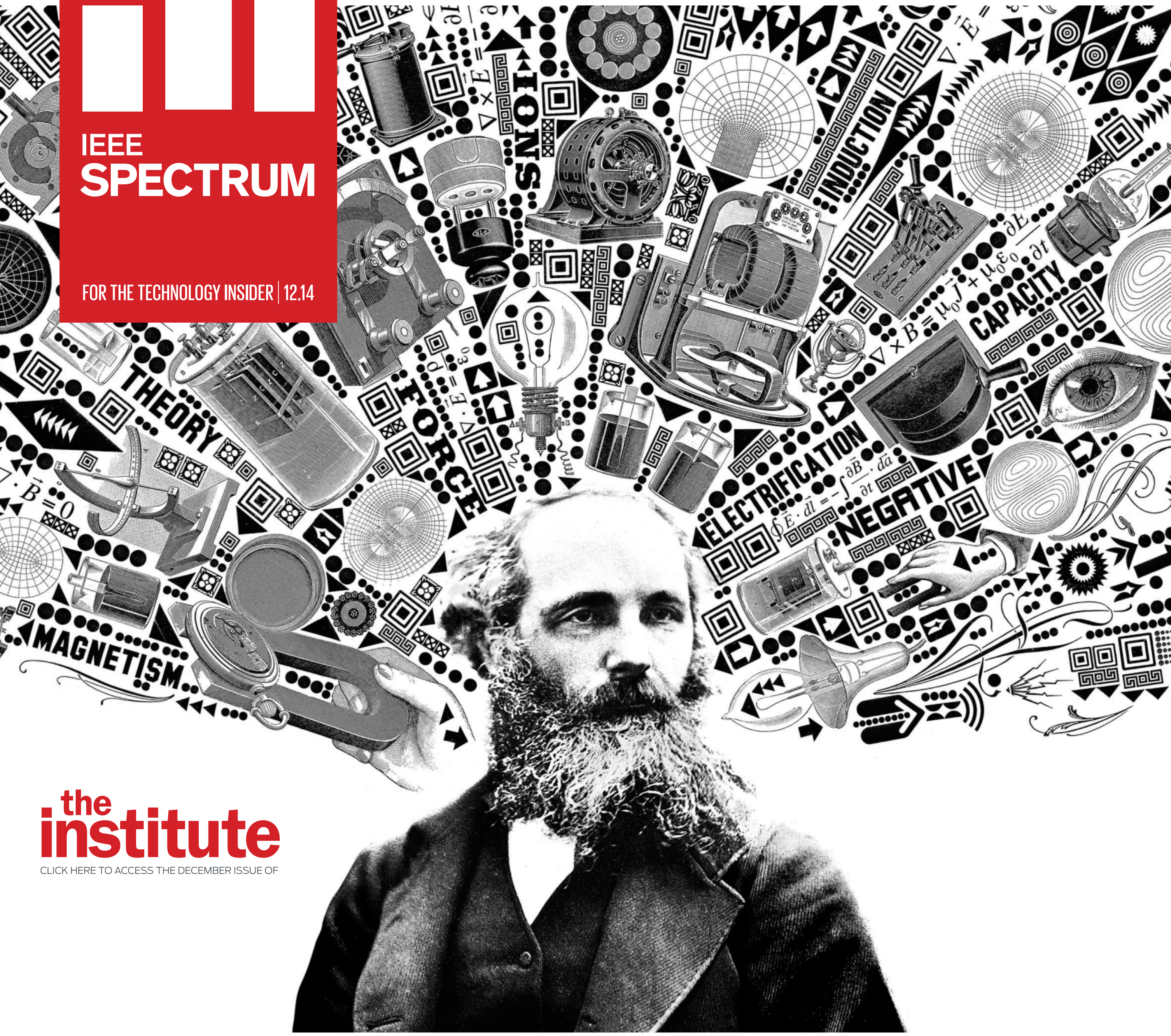
Don't lose *IEEE Spectrum* and other great IEEE benefits.
Renew today at **www.ieee.org/renew**

If you have already renewed—**thank you.** No action is needed.

IEEE
Advancing Technology for Humanity

IEEE SPECTRUM

FOR THE TECHNOLOGY INSIDER | 12.14

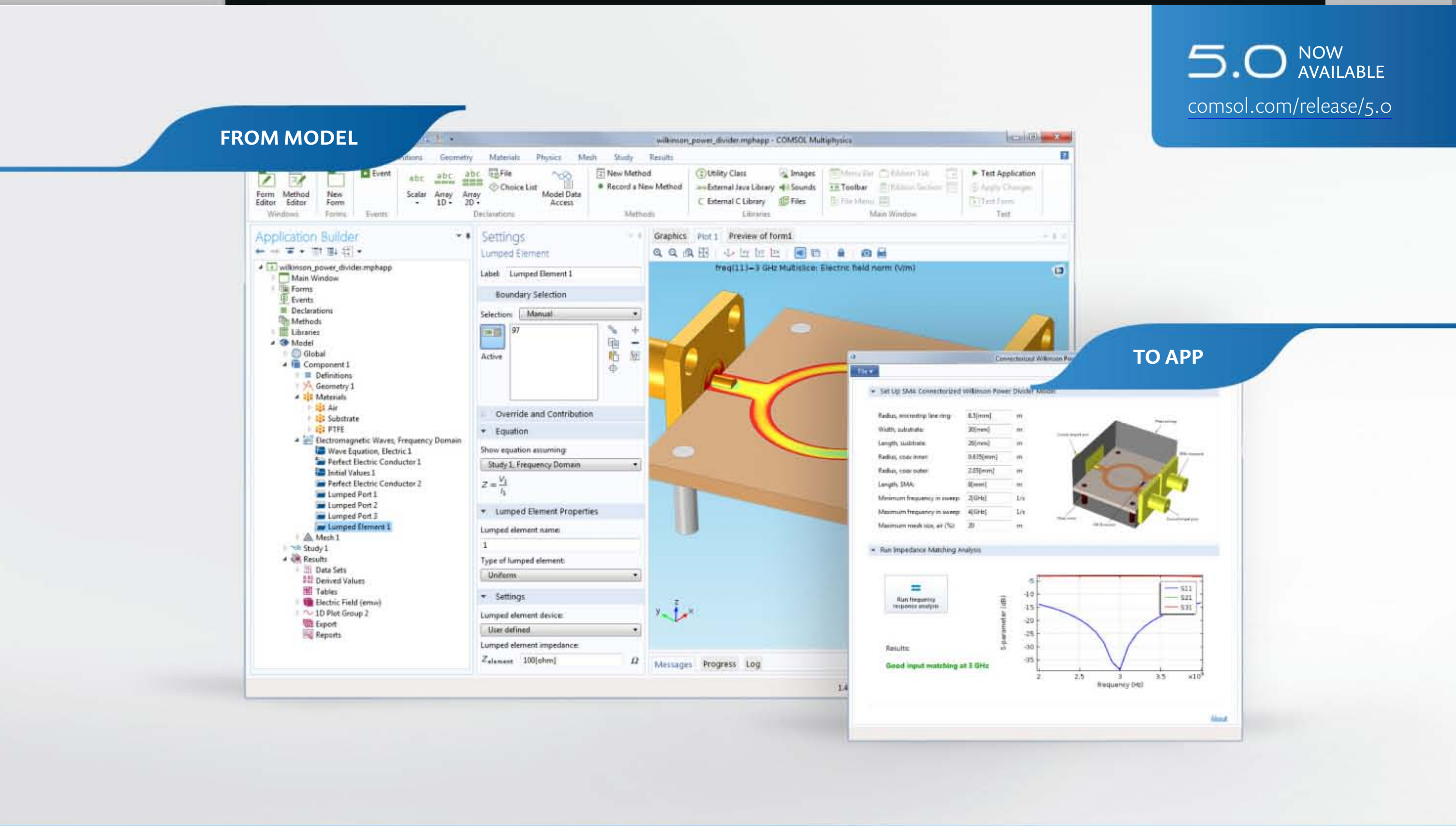


the institute
CLICK HERE TO ACCESS THE DECEMBER ISSUE OF

JUST 4 EQUATIONS

150 years ago, James Clerk Maxwell showed the way toward modern science and technology **P. 32**

IEEE



Verify and Optimize your Designs with COMSOL Multiphysics®

NOW FEATURING THE APPLICATION BUILDER

The Application Builder provides you with tools to easily design a custom interface for your multiphysics models. Use COMSOL Server to distribute your apps to colleagues and customers worldwide.

Visit comsol.com/release/5.0

PRODUCT SUITE

COMSOL Multiphysics
COMSOL Server

ELECTRICAL
AC/DC Module
RF Module
Wave Optics Module
Ray Optics Module
MEMS Module
Plasma Module
Semiconductor Module

MECHANICAL
Heat Transfer Module
Structural Mechanics Module
Nonlinear Structural Materials Module
Geomechanics Module
Fatigue Module
Multibody Dynamics Module
Acoustics Module

FLUID
CFD Module
Mixer Module
Microfluidics Module
Subsurface Flow Module
Pipe Flow Module
Molecular Flow Module

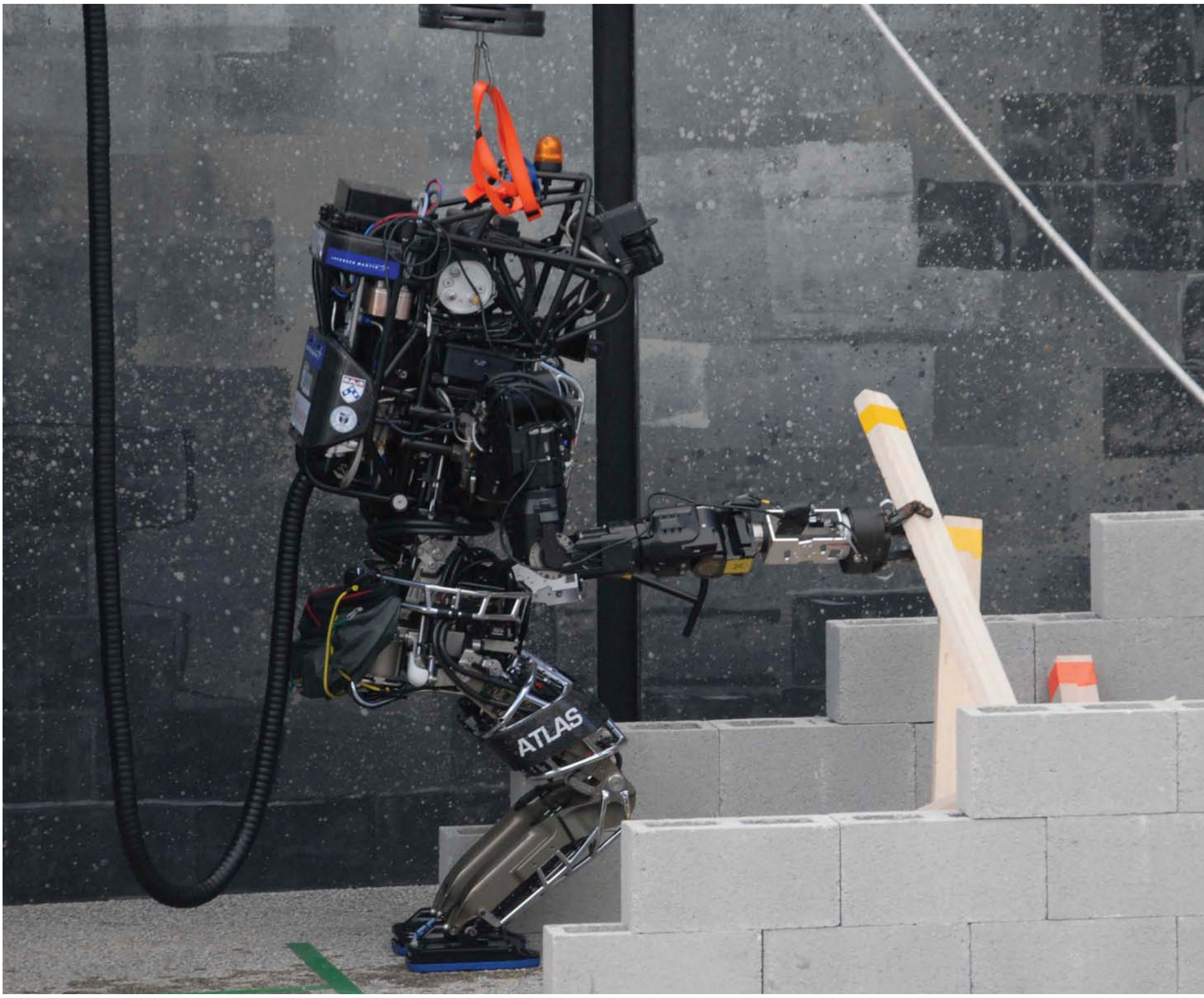
CHEMICAL
Chemical Reaction Engineering Module
Batteries & Fuel Cells Module
Electrodeposition Module
Corrosion Module
Electrochemistry Module

MULTIPURPOSE
Optimization Module
Material Library
Particle Tracing Module

INTERFACING
LiveLink™ *for* MATLAB®
LiveLink™ *for* Excel®
CAD Import Module
Design Module
ECAD Import Module
LiveLink™ *for* SOLIDWORKS®
LiveLink™ *for* Inventor®
LiveLink™ *for* AutoCAD®
LiveLink™ *for* Revit®
LiveLink™ *for* PTC® Creo® Parametric™
LiveLink™ *for* PTC® Pro/ENGINEER®
LiveLink™ *for* Solid Edge®
File Import *for* CATIA® V5

COMSOL

IEEE SPECTRUM

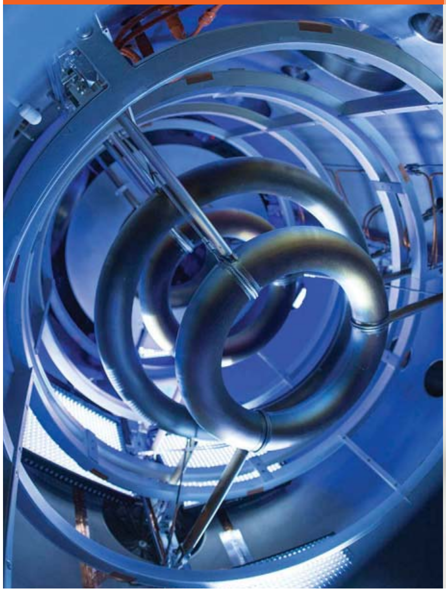


LOCKHEED MARTIN CORP.

On the Cover **Illustration for *IEEE Spectrum* by Lorenzo Petrantoni**

DEPARTMENTS_12.14

IEEE SPECTRUM



ADDITIONAL RESOURCES

Tech Insider / Webinars

Available at spectrum.ieee.org/webinar

- Antennas for Automotive Applications—4 December
- Introduction to Antenna Simulation With COMSOL—11 December
- Thinking Past the Plug: Integrating Electric Vehicles With the Smart Grid—11 December

- **NEW PRODUCT RELEASE LIBRARY**
  http://spectrum.ieee.org/static/new-product-release-library
- **WHITE PAPERS**
  http://spectrum.ieee.org/whitepapers

The Institute

Available 8 December at theinstitute.ieee.org

TRANSFORMING COMMUNICATIONS NETWORKS The December issue delves into software-defined networks, or networks of equipment that decouple hardware from software. SDNs will give operators the ability to create or program flexible and dynamic networks capable of integrating and monitoring terminals and intelligent machines. Read about IEEE's SDN Initiative and the products, standards, and other resources to get up to speed.

MANAGING SOFTWARE-DEFINED NETWORKS Find out what skills IT and network professionals will need to successfully deploy SDNs.

PART-TIME PASSIONS One IEEE member spends his time creating attention-grabbing—and sometimes controversial—street art, while another enjoys designing, building, and launching high-powered rockets.

FROM LEFT: LOCKHEED MARTIN CORP.; DIGITAL BOLEX; ISTOCKPHOTO

IEEE SPECTRUM
(ISSN 0018-9235) is published monthly by The Institute of Electrical and Electronics Engineers, Inc. Volume No. 51, issue No. 12, International edition. The editorial content of IEEE Spectrum magazine does not represent official positions of the IEEE or its organizational units. Canadian Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40013087. Return undeliverable Canadian addresses to: Circulation Department, IEEE Spectrum, Box 1051, Fort Erie, ON L2A 6C7. Cable address: ITRIPLEE. Fax: +1 212 419 7570. INTERNET: spectrum@ieee.org. ANNUAL SUBSCRIPTIONS: IEEE Members: $21.40 included in dues. Libraries/institutions: $399. POSTMASTER: Please send address changes to IEEE Spectrum, c/o Coding Department, IEEE Service Center, 445 Hoes Lane, Box 1331, Piscataway, NJ 08855. Periodicals postage paid at New York, NY, and additional mailing offices. Canadian GST #125634188. Printed at 120 Donnelley Dr., Glasgow, KY 42141-1060, U.S.A. IEEE Spectrum circulation is audited by BPA Worldwide. IEEE Spectrum is a member of the Association of Business Information & Media Companies, the Association of Magazine Media, and Association Media & Publishing. IEEE prohibits discrimination, harassment, and bullying. For more information, visit http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html.

BACK STORY_

JEAN RAUTIO

Giving Electromagnetism Its Due

WHEN JAMES RAUTIO was building up his company, Sonnet Software, in the mid-1990s, he needed some noncopyrighted imagery to use in his marketing materials. A friend lent him an 1882 copy of a biography of physicist James Clerk Maxwell. Rautio scanned a portrait in the book, and that image of Maxwell became the fledgling company's emblem.

Rautio picked the picture of Maxwell largely because it was in the public domain. But it was also a fitting choice: His software, which is used to design radio-frequency circuitry, relies on the four equations, known as Maxwell's equations, that describe the fundamental rules of electromagnetism.

Rautio says he knew little about Maxwell himself at the time. But he read up on Maxwell's life and was soon hooked. He began visiting relevant sites, including one in Dublin, shown above. It is the grave of George Francis FitzGerald, one of the physicists who helped put Maxwell's theory on solid footing.

Over the past decade, Rautio has become a champion of Maxwell and his legacy. He's given 116 talks to date on Maxwell's life and work at conferences, workshops, and IEEE chapter meetings. In 2007, after a visit to Maxwell's ancestral home, Glenlair, in southwest Scotland, he convinced the IEEE Microwave Theory and Techniques Society to contribute matching funds to help restore the building, which was heavily damaged in a 1929 fire.

Rautio says he's come to realize that Maxwell's theory is not just about "equations on a piece of paper. It's a four-dimensional story." That "fourth dimension" is a reference to the several dozen years it took for Maxwell's ideas to be developed and confirmed. He describes that time in "The Long Road to Maxwell's Equations," in this issue. ■

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes an international and a North American edition, as indicated at the bottom of each page. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, Dataflow is in *IEEE Spectrum*, Vol. 51, no. 12 (INT), December 2014, p. 60, or in *IEEE Spectrum*, Vol. 51, no. 12 (NA), December 2014, p. 80.

12.14

IEEE
SPECTRUM

EDITOR IN CHIEF
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
Mark Montgomery, m.montgomery@ieee.org

SENIOR EDITORS
Stephen Cass (Resources), cass.s@ieee.org
Erico Guizzo (Digital), e.guizzo@ieee.org
Jean Kumagai, j.kumagai@ieee.org
Samuel K. Moore (News), s.k.moore@ieee.org
Tekla S. Perry, t.perry@ieee.org
Philip E. Ross, p.ross@ieee.org
David Schneider, d.a.schneider@ieee.org

DEPUTY ART DIRECTOR Brandon Palacio, b.palacio@ieee.org
PHOTOGRAPHY DIRECTOR Randi Klett, randi.klett@ieee.org
ASSOCIATE ART DIRECTOR Erik Vrielink, e.vrielink@ieee.org

ASSOCIATE EDITORS
Ian Chant, i.chant@ieee.org
Rachel Courtland, r.courtland@ieee.org
Celia Gorman (Multimedia), celia.gorman@ieee.org
Eliza Strickland, e.strickland@ieee.org
ASSISTANT EDITOR Willie D. Jones, w.jones@ieee.org
SENIOR COPY EDITOR Joseph N. Levine, j.levine@ieee.org
COPY EDITOR Michele Kogon, m.kogon@ieee.org
EDITORIAL RESEARCHER Alan Gardner, a.gardner@ieee.org

EXECUTIVE PRODUCER, SPECTRUM RADIO Sharon Basco
ASSISTANT PRODUCER, SPECTRUM RADIO Francesco Ferorelli, f.ferorelli@ieee.org

ADMINISTRATIVE ASSISTANTS
Ramona Foster, r.foster@ieee.org
Nancy T. Hantman, n.hantman@ieee.org
INTERN Neel V. Patel

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

DIRECTOR, PERIODICALS PRODUCTION SERVICES Peter Tuohy
EDITORIAL & WEB PRODUCTION MANAGER Roy Carubia
SENIOR ELECTRONIC LAYOUT SPECIALIST Bonnie Nani

SPECTRUM ONLINE
PRODUCT MANAGER, DIGITAL Shannan Brown
WEB PRODUCTION COORDINATOR Jacqueline L. Parker
MULTIMEDIA PRODUCTION SPECIALIST Michael Spector

EDITORIAL / ADVERTISING CORRESPONDENCE
IEEE Spectrum
3 Park Ave., 17th Floor
New York, NY 10016-5997
EDITORIAL DEPARTMENT
TEL: +1 212 419 7555 FAX: +1 212 419 7570
BUREAU Palo Alto, Calif.; Tekla S. Perry **+1 650 752 6661**
ADVERTISING DEPARTMENT +1 212 705 8939

CONTRIBUTORS_

Brian J. Cantwell

Cantwell is a professor in Stanford's department of aeronautics and astronautics, where he and his colleagues have been studying paraffin-fueled hybrid rockets, as he describes in "The Wax Rocket" [p. 44]. As a kid, he had attempted to build his own rockets, but his parents forbade such activities—for good reason. "What I was building would have blown up right away," he admits. His rockets today, despite being vastly bigger, are considerably safer.

Robert Howe

The head of the Harvard Biorobotics Laboratory, Howe investigates how engineers can take cues from nature to build more effective robots. In general, he says, inspiration is preferable to mere imitation. "For generic manipulation, the human hand is not a great model," Howe says. "It brings along a lot of biological baggage." That kind of thinking led to the three-fingered iHY robotic hand [p. 38], which he designed with coauthors Aaron Dollar of Yale and Mark Claffee of iRobot.

Ross Koningstein

Koningstein and coauthor David Fork are engineers at Google who worked on a bold renewable energy project that ultimately failed. In "Energy's Creative Destruction" [p. 26], they share lessons learned from that experience. They dedicate this article to the memory of Tim Allen, who led their green-energy initiative. Allen inspired them to question their assumptions about what it would take to reverse climate change. "He wasn't married to one approach," Koningstein says. "He was intent on solving the problem."

Lucas Laursen

A frequent contributor to *IEEE Spectrum*, Laursen is a globe-trotting freelance journalist who has reported from more than a dozen countries on five continents. Soon after he moved to Oaxaca, Mexico, earlier this year, he learned of the country's vast expansion into wind energy and other renewable sources, a contentious development for one of the world's biggest oil producers. For his article on the subject [p. 12], "reporting was easy," Laursen says. "Mexicans have strong opinions about their energy resources."

Lorenzo Petrantoni

Petrantoni, who created the illustrations for "The Long Road to Maxwell's Equations" [cover, p. 32], is known for his intricate and playful collages. Working with photocopies of graphics from 19th-century books, he painstakingly cuts out each element and glues it onto a composition board. For this assignment, he researched James Clerk Maxwell and "was amazed by his work on color," Petrantoni says, "especially the fact that he was the first person to create a color photograph."

12.14

IEEE

IEEE MEDIA
SENIOR DIRECTOR; PUBLISHER, IEEE SPECTRUM
James A. Vick, j.vick@ieee.org
ASSOCIATE PUBLISHER, SALES & ADVERTISING DIRECTOR
Marion Delaney, m.delaney@ieee.org
RECRUITMENT AND LIST SALES ADVERTISING DIRECTOR
Michael Buryk, m.buryk@ieee.org
BUSINESS MANAGER Robert T. Ross, r.ross@ieee.org
IEEE MEDIA/SPECTRUM GROUP MARKETING MANAGER
Blanche McGurr, b.mcgurr@ieee.org
IEEE MEDIA GROUP DIGITAL MARKETING SENIOR MANAGER
Ruchika Anand, r.t.anand@ieee.org
LIST SALES & RECRUITMENT SERVICES PRODUCT/ MARKETING MANAGER Ilia Rodriguez, i.rodriguez@ieee.org
REPRINT SALES +1 212 221 9595, EXT. 319
MARKETING & PROMOTION SPECIALIST Faith H. Jeanty, f.jeanty@ieee.org
SENIOR MARKETING ADMINISTRATOR Simone Darby, simone.darby@ieee.org
MARKETING ASSISTANT Quinona Brown, q.brown@ieee.org
RECRUITMENT SALES ADVISOR Liza Reich +1 212 419 7578
ADVERTISING SALES +1 212 705 8939

ADVERTISING PRODUCTION MANAGER Felicia Spagnoli
SENIOR ADVERTISING PRODUCTION COORDINATOR
Nicole Evans Gyimah
ADVERTISING PRODUCTION +1 732 562 6334

IEEE STAFF EXECUTIVE, PUBLICATIONS Anthony Durniak

IEEE BOARD OF DIRECTORS
PRESIDENT J. Roberto B. de Marca, president@ieee.org
+1 732 562 3928 FAX: +1 732 465 6444

PRESIDENT-ELECT Howard E. Michel
TREASURER John T. Barr **SECRETARY** Marko Delimar
PAST PRESIDENT Peter W. Staecker

VICE PRESIDENTS
Saurabh Sinha, Educational Activities; Gianluca Setti, Publication Services & Products; Ralph M. Ford, Member & Geographic Activities; Karen Bartleson, President, Standards Association; Jacek M. Zurada, Technical Activities; Gary L. Blank, President, IEEE-USA

DIVISION DIRECTORS
Ellen J. Yoffa (I); Jerry L. Hudgins (II); Harvey A. Freeman (III); Jozef W. Modelski (IV); Susan K. Land (V); Bogdan M. Wilamowski (VI); Wanda K. Reder (VII); Roger U. Fujii (VIII); Marina Ruggieri (IX); Stephen Yurkovich (X)

REGION DIRECTORS
Vincent P. Socci (1); Parviz Famouri (2); Mary Ellen Randall (3); Karen S. Pedersen (4); J. Derald Morgan (5); Michael R. Andrews (6); Amir G. Aghdam (7); Martin J. Bastiaans (8); Norberto M. Lerendegui (9); Toshio Fukuda (10)

DIRECTORS EMERITUS Eric Herz, Theodore W. Hissey

IEEE STAFF
EXECUTIVE DIRECTOR & COO James Prendergast
+1 732 502 5400, james.prendergast@ieee.org
PUBLICATIONS Anthony Durniak
+1 732 562 3998, a.durniak@ieee.org
CORPORATE ACTIVITIES Elena Gerstmann
+1 732 981 3452, e.gerstmann@ieee.org
EDUCATIONAL ACTIVITIES Douglas Gorham
+1 732 562 5483, d.g.gorham@ieee.org
ACTING CHIEF INFORMATION OFFICER Donna Hourican
+1 732 562 6330, d.hourican@ieee.org
MEMBER & GEOGRAPHIC ACTIVITIES Cecelia Jankowski
+1 732 562 5504, c.jankowski@ieee.org
HUMAN RESOURCES Shannon Johnston, SPHR
+1 732 562 6343, s.johnston@ieee.org
STANDARDS ACTIVITIES Konstantinos Karachalios
+1 732 562 3820, constantin@ieee.org
GENERAL COUNSEL & CHIEF COMPLIANCE OFFICER
Eileen M. Lach, +1 212 705 8990, e.m.lach@ieee.org
CHIEF MARKETING OFFICER Patrick D. Mahoney
+1 732 562 5596, p.mahoney@ieee.org
CHIEF FINANCIAL 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
+1 202 530 8349, c.brantley@ieee.org
IEEE PUBLICATION SERVICES & PRODUCTS BOARD
Gianluca Setti, *Chair*; John Baillieul, Babak Beheshti, Herbert Bennett, Jennifer Bernhard, Stuart Bottom, Jean-Luc Gaudiot, David Allan Grier, Glenn Gulak, Lawrence Hall, Sheila Hemami, David Hodges, Hulya Kirkici, Khaled Ben Letaief, Carmen Menoni, Paolo Montuschi, Lloyd A. "Pete" Morley, William Moses, Michael Pecht, Sorel Reisman, Charles Rubenstein, Tariq Samad, Gaurav Sharma, Curtis Siller, David Tian, Joel Trussell, Leung Tsang, Stephanie White, Timothy Wong

IEEE OPERATIONS CENTER
445 Hoes Lane, Box 1331, Piscataway, NJ 08854-1331 U.S.A.
Tel: +1 732 981 0060 Fax: +1 732 981 1721

PHOTO-ILLUSTRATIONS BY **Gluekit**

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

RANDI KLETT

My Favorite Things

These articles capture *IEEE Spectrum* at its best

IN THE HALF CENTURY of its existence, *IEEE Spectrum* has published roughly 3,700 feature-length articles. We covered the fall of the vacuum tube and the rise of the integrated circuit, the decline of the mainframe and the ascent of the personal computer. We wrote about robots, the Internet, lasers and LEDs, code-breaking and compound semiconductors, wireless and weapons, transistors and transhumanism.

Among those many feature articles are a dozen or two that became a critical part of my apprenticeship in this business and, more than that, a part of the mythos of my young adulthood. They're like old friends, in no small part because I saw them come into the world, in the office and at a pub called Murphy's where, decades ago, *Spectrum* staffers used to gather to lick our wounds, plot strategy, and celebrate the glow that came from knowing stuff that nobody else knew.

IEEE SPECTRUM 1964 / 2014

Suffice it to say, my recollections here will be personal and, given the space constraints, seriously abridged.

I first became a staffer at *Spectrum* in 1984, around the time when the magazine was reaching a new level of sustained excellence with a young, smart, and energetic staff. Fred Guterl, now the executive editor of *Scientific American* magazine, was a junior editor at *Spectrum* in those days. He got wind of a project to build a state-of-the-art but affordable personal computer at a company called Apple Computer and decided to write a case study on the new machine. Guterl described how a young man named Burrell Smith—a liberal-arts-school dropout who had started at Apple as a computer repairman—wound up leading the design of the Macintosh computer, on which Apple's future fortunes would be built.

The story appeared in our December 1984 issue. To help with Guterl's research, Apple was kind enough to send a prerelease version of the original Macintosh. It appeared in our office in the summer of 1984, like a spiffy appliance from the future. Which it basically was.

Not long after, Trudy E. Bell, another of *Spectrum*'s talented crew in the 1980s, helped organize a special issue that analyzed the effects of the divestiture of AT&T. Published in November 1985, the issue went on to win our third National Magazine Award, the highest honor in our business. During her reporting for the article, Bell had interviewed almost all the big names associated with the antitrust case that precipitated the breakup of the Bell system. But the biggest name of all, Judge Harold H. Greene, remained elusive. Greene, the federal district court judge who had presided over the antitrust case, had a policy of never speaking to the press.

Bell's repeated calls to Greene's office were always politely rebuffed. But she saw her opportunity when a source from the U.S. Department of Justice told her that the officials and attorneys from the DOJ and AT&T—bitter adversaries during the trial—had established a tradition of meeting every year in Washington, D.C., for a friendly softball game. The next game was just a couple of weeks away.

True to his habit, Greene was a spectator at the game (which, unlike the trial, AT&T won). Bell did not approach Greene at first and took pains to appear as a mere casual spectator herself. "I wanted to get quotes," she says, "but I didn't want to be seen taking notes." How did she manage it? She memorized what was being said and then periodically excused herself to record the dialogue on paper she had secreted in her clothes. "I went to the bathroom an awful lot," Bell says.

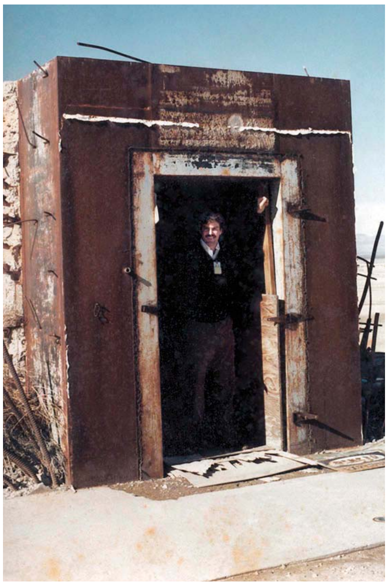
After the game was over, Bell handed a copy of her draft manuscript to Greene,

Editor's note: In this 50th anniversary year of IEEE Spectrum, *we are using each month's Spectral Lines column to describe some pivotal moments of the magazine's history. Here, Executive Editor Glenn Zorpette reminisces about some of his favorite articles. An extended version of this article is at http://spectrum.ieee.org/favorites1214*

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

ostensibly as a courtesy. A few days later, sitting at her desk at 1:30, Bell answered her phone and heard a woman say, "Please hold for Judge Greene." Greene's first words to her were, "I found your article so interesting I felt I just had to contribute to it." For the next half hour, Greene gave Bell one of the very few press interviews he ever granted and left Bell with an enduring memory. "Of all the articles I've ever done, this was one of my career highlights," she says.

Another article from the same period also broke new journalistic ground. Early in 1986, John Horgan traveled to the Nevada Test Site (NTS), where the United States tested nuclear weapons. The U.S.S.R. had just announced it would unilaterally cease testing nuclear weapons, and the pressure was on the United States to follow suit. Although testing was in the news, very few journalists had been to the U.S. test site, and none had written a comprehensive article on the technology of weapons testing.



NUKE THE VAULT: In 1986, *Spectrum* associate editor John Horgan posed in a bank vault that had been heavily damaged by a nuclear bomb.

Horgan, then an associate editor at *Spectrum*, jumped at the chance. "I had written my master's thesis on the antinuclear movement," he recalls. "I thought the nuclear arms race was imperiling all of humanity and that it absolutely had to be stopped. And the testing of the weapons at NTS was a really crucial part of the arms race.

"I went into this assignment wanting to criticize this stuff," adds Horgan, who is now director of the Center for Science Writings at Stevens Institute of Technology, in Hoboken, N.J. But something funny happened after he arrived at the remote desert site and started interviewing engineers there: "I ended up falling in love with it. There's something exhilarating about nuclear weapons," he says. "They're just so insane."

Shortly after Horgan's article ran, in the April 1986 issue of *Spectrum*, remarkably similar stories on the very same topic were published in *The New York Times* and *Discover* magazine (the latter even used our main illustration, for which *Discover* graciously reimbursed us).

Two other articles have proven prescient, with a quarter century's perspective. One was written by Karen Fitzgerald and published in December 1989. "Technology in Medicine: Too Much, Too Soon?" posited that emerging medical technologies would push health-care costs to considerably higher levels in the United States. They did, and that surge was just the start of an elevation in U.S. medical costs that has developed into something of a national crisis. When Fitzgerald wrote her article, the emerging technologies included defibrillators, magnetic resonance imaging, ultrasound, and computer tomography. Today it's robotic and other minimally invasive surgical techniques, bone replacements, fertility treatments, and others. I've read few forward-looking articles in my career that were as insightful and absolutely spot-on as Fitzgerald's.

In 1991, as the United States led a coalition into war in the Persian Gulf, a big assortment of new weapons were unleashed for the first time. Many technologies registered blows on the Iraqi military, including cruise missiles, smart munitions, stealth aircraft, the Joint Surveillance Target Attack Radar System aircraft, antimissile missiles, and vast tactical and command-and-control networks. The embedded press corps, many of them relatively uneducated when it came to technology, were fed a diet of impressive-looking bomb-cam video from the U.S. Defense Department. The result, particularly early on in the war, was fawning press coverage.

John A. Adam, *Spectrum*'s military editor in those days, knew better. Adam is one of the best reporters I've met in 30 years in this business. His article, "Warfare in the Information Age," published in September 1991, is a model of careful and insightful reporting done in a turbulent environment and against a low signal-to-noise ratio. Amid the breathless reports of the day, Adam noted soberly that "pilots were sent to attack targets that did not exist or were long evacuated"—and that the proportion of so-called friendly fire deaths, at 23 percent, was "the highest ratio ever."

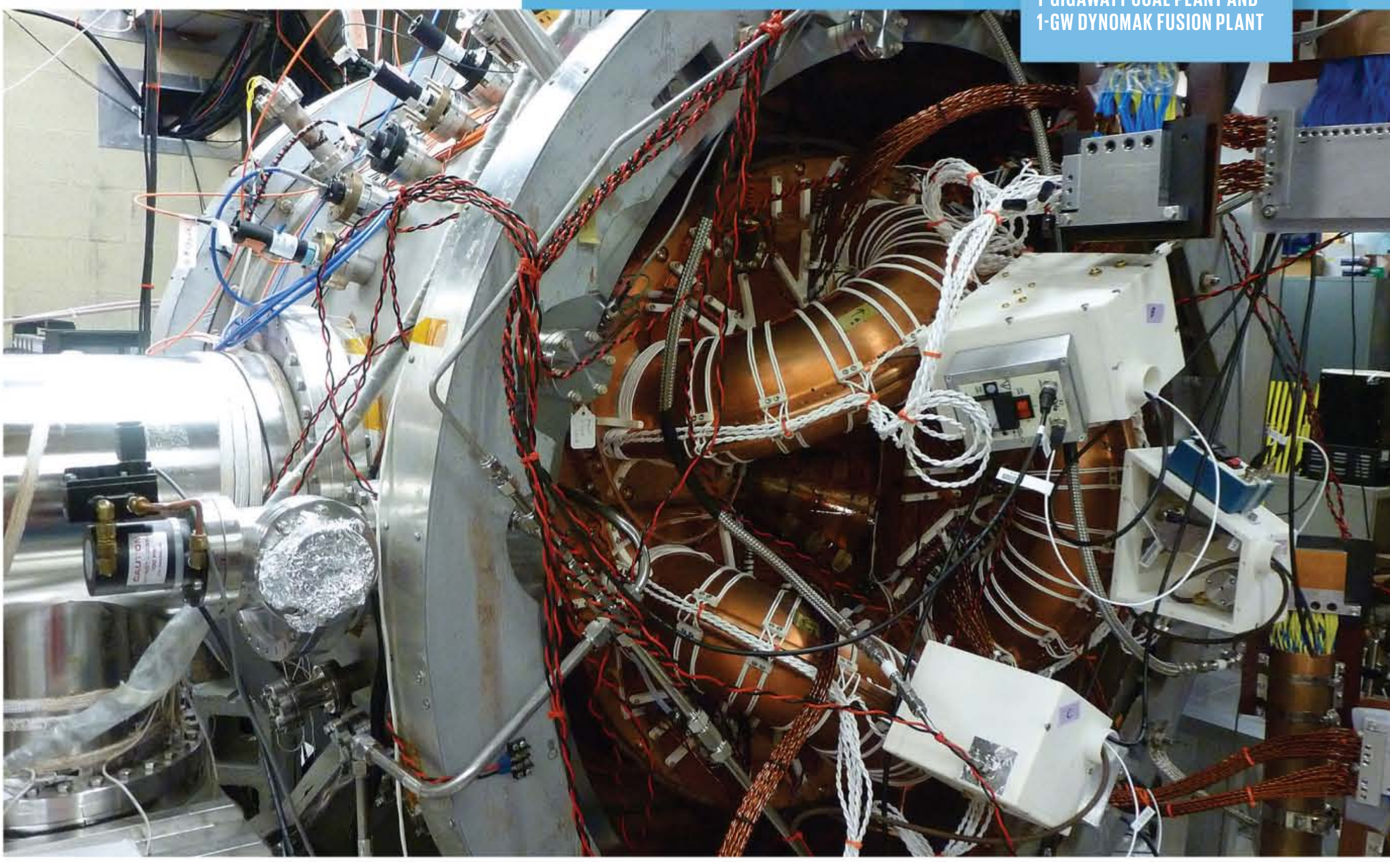
Whereas Fitzgerald's and Adam's articles anticipated the future, another of my favorites took a fond look backward. In our August 1998 issue, *Spectrum* published an article called "The Cool Sound of Tubes," about the improbable resurgence of vacuum tubes in audio. The story was conceived and edited by Michael J. Riezenman, an MIT graduate, bon vivant, and raconteur, whom I was fortunate to have as a friend and colleague. Riezenman, who died this past January, was a great rarity: a person who had a deep understanding of technology and could really write.

I'll mention one more article. It will always be special for me, even if it wasn't all that good. It was about aluminum house wiring. Really. I wrote it in February 1984, in a drafty one-room attic apartment in Arlington, Va., when I was 22 years old. I wrote it for *Spectrum*, hoping to get a job there—I did—and dreaming of a career as a journalist. Darned if I didn't get that, too. —GLENN ZORPETTE *Twitter: @Electric_Genie*

JOHN HORGAN

NEWS

US $266 MILLION: DIFFERENCE IN ANNUAL FUEL COST BETWEEN 1-GIGAWATT COAL PLANT AND 1-GW DYNOMAK FUSION PLANT



HELICITY HERO: A trio of "magnetic helicity injectors" are the key to the University of Washington's HIT-SI3 fusion experiment.

MICHELLE MA/UNIVERSITY OF WASHINGTON

ENTER THE DYNOMAK

Could this fusion technology be cheaper than coal?

Fusion power has many compelling arguments in its favor. It doesn't produce dangerous, long-term toxic waste, like nuclear fission. It's far cleaner than coal, with a supply of fuel that's virtually unlimited. And unlike with wind and solar, the output of a fusion power plant would be constant and reliable.

The primary argument *against* fusion power has been that despite decades of work, it still doesn't exist. But that's no hindrance to a fresh crop of enthusiasts from academia, government, private industry, and even venture capital firms.

In October, Lockheed Martin Corp. revealed that it's been working on a type of fusion reactor that could be made small enough to transport by truck. Lawrenceville Plasma Physics raised money through crowdfunding in June to advance its alternative proton-boron fusion. Helion Energy is developing a type of fusion based on magnetic compression, and General Fusion is working toward a power system that involves shock waves inside a vortex of liquid metal.

A particularly promising approach was unveiled recently by a University of Washington research group, led by plasma physicist Tom Jarboe. They've been developing a type of fusion reactor called a dynomak. The researchers involved say the technology is unique in that it offers a path to a power plant that's backed »

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

up by demonstrated physics and because such a reactor also promises to be even more economical than a coal-fired power plant.

The dynomak is a variation of the most popular type of research fusion machine, the tokamak. Essentially, a tokamak is a doughnut-shaped machine that generates helical magnetic fields by combining toroidal fields (which go around the doughnut's equator) with poloidal fields (which wrap around the outside of the doughnut). These fields have to be strong enough to keep plasma stable and contained indefinitely at the tens to hundreds of millions of degrees Celsius necessary to induce fusion.

In practice, tokamaks are hollow, doughnut-shaped vacuum chambers with interior walls made of heat-resistant metals or ceramics. Outside the chamber are massive superconducting coils that generate the toroidal magnetic fields that stabilize the plasma. The European Union, China, India, Japan, Russia, South Korea, and the United States are collaborating to build a giant US $50 billion tokamak in France called ITER (originally International Thermonuclear Experimental Reactor), which may lead to a fusion power plant in the 2030s. But the University of Washington group—and its alternative-fusion competitors—are hoping to beat it to commercialization.

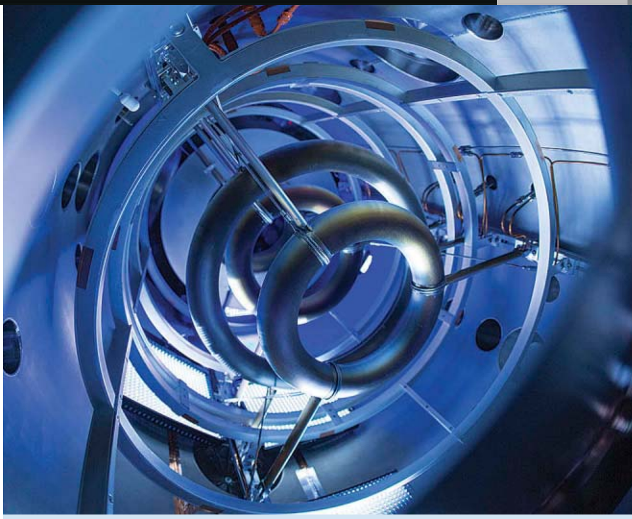
The University of Washington's dynomak is a refinement of a subtype of tokamak called a spheromak. The most important difference is that the spheromak does away with most of the tokamak's expensive superconducting magnetic coils. Instead, a spheromak uses the electric currents flowing though the plasma *itself* to generate the magnetic fields needed to both stabilize and confine the plasma.

This is tricky, as UW graduate student Derek Sutherland explains. For it to work, you need not only a sophisticated understanding of the physics underlying the behavior of the plasma but also a very efficient way of driving the current. If you're not careful, you'll end up dumping all the energy that your reactor is producing right back into the plasma just to keep it contained—resulting in a very expensive machine that will power itself and nothing else.

According to Sutherland, the big breakthrough was UW's experimental discovery in 2012 of a physical mechanism called imposed-dynamo current drive (hence "dynomak"). By injecting current directly into the plasma, imposed-dynamo current drive lets the system control the helical fields that keep the plasma confined. The result is that you can reach steady-state fusion in a relatively small and inexpensive reactor. "We are able to drive plasma current more efficiently than previously possible," says Sutherland. "With that efficiency can come higher current and a more compact, economical design."

How economical? According to projections by Sutherland's group, a dynomak has the potential to cost less than a tenth as much to build as a tokamak like ITER, even as it produces five times as much power. This massive boost in efficiency is very compelling: According to UW's analysis, it makes the total cost of a dynomak fusion power plant with an output of 1 gigawatt slightly cheaper than the total cost of a coal power plant with the same output—$2.7 billion versus $2.8 billion.

The UW researchers are particularly optimistic about their dynomak because it's not much of a deviation from established systems. "I think we've blended the



FUSION ALTERNATIVES

Lockheed Martin Corp.

Funding: Internal. **How does it work?** The device [above] is similar to a tokamak, but it uses a new type of self-tuning feedback mechanism to control its magnetic field geometry. **What's the advantage?** Very efficient reactors will be small enough to fit inside trucks and shipping containers, and they could even power an airplane indefinitely. **When will it be commercial?** Currently testing operational theories; functional reactor by about 2025.

Helion Energy

Funding: US $7 million from NASA, the Department of Energy, and the Department of Defense, plus $1.5 million in seed funding. **How does it work?** Plasma fuel forms stable toroids at either end of a chamber. The toroids are then slammed together at more than1.6 million kilometers per hour. **What's the advantage?** All solid-state electronics make for small, modular power plants. Fusion energy is directly converted to electricity. The plant generates its own helium-3 fuel as a by-product. **When will it be commercial?** Currently developing a reactor-scale fusion core; 50-megawatt pilot plant in 2019.

Lawrenceville Plasma Physics

Funding: $3 million from private investors, plus $180,000 from a crowd-funding campaign on Indiegogo; currently applying for a two-year, $2 million Advanced Research Projects Agency-Energy grant. **How does it work?** A strong pulse of electricity generates filaments of plasma. The filaments are combined, and natural instabilities cause them to twist into a plasmoid. The plasmoid self-heats to reach a fusion state. **What's the advantage?** Instead of trying to control plasma instabilities with magnetic fields, the system uses the instabilities to create fusion. Hydrogen-boron fusion reactions do not create radioactive by-products. **When will it be commercial?** Currently performing test shots to increase plasma density; garage-size 5-MW generators by 2020 costing $300,000 to $500,000 each.

General Fusion

Funding: $55 million, primarily venture capital. **How does it work?** Magnetic fields briefly confine plasma inside a vortex of liquid metal. Steam-powered pistons create a spherical shock wave, which collapses the liquid metal vortex, compressing the fuel to achieve a burst of fusion energy. **What's the advantage?** Plasma needs only a brief confinement, and steam-powered pistons lead to a simple, cheap reactor. **When will it be commercial?** Currently testing reactor subcomponents; successful prototype in 2015 could lead to commercial reactor in 2020.

mainstream and alternates into a pathway that is completely plausible but different enough to really start addressing the economic issues facing fusion power," says Sutherland.

"The spheromak–and the dynomak is a species of spheromak–in particular has not received the level of attention that it warrants," says University of Iowa physicist Fred Skiff. "The potential advantages are significant: a lower magnetic field–and therefore lower cost and complexity–and a smaller reactor." The lower magnetic field requirements are important because "large superconducting coils are not trivial to produce and protect in a reactor environment."

However, "there are significant unknowns," says Skiff. "The ability to control the current profile, the plasma position, and the ability to maintain high confinement will have to be demonstrated."

The next steps for the dynomak are straightforward. The experimental device Jarboe's group is working with right now, called HIT-SI3, is about one-tenth the size that a commercial dynomak fusion reactor would be. It includes three helicity injectors, which are the coils that control the delivery of twisting magnetic fields into the plasma. "The eventual dynomak reactor will have six injectors according to the current design," says Sutherland. With $8 million to $10 million in funding, the group hopes to construct HIT-SIX, a six-injector machine that will be twice as large as HIT-SI3.

At that size, things start to get interesting, says Sutherland. HIT-SIX is designed to reach millions of degrees Celsius using a mega-ampere of plasma current. If imposed-dynamo current drive works well in HIT-SIX, he'll be "much more confident going forward that our development path will be successful," he says.

That entire path, including an electricity-generating pilot plant, would require about $4 billion, Jarboe's group projects. Compared with ITER's $50 billion, that's a bargain. —EVAN ACKERMAN

OPPOSITE: LOCKHEED MARTIN; THIS PAGE: PETER TUFFY/THE UNIVERSITY OF EDINBURGH

NEWS

LI-FI GETS READY TO COMPETE WITH WI-FI

Visible light communications could outshine Wi-Fi in industrial settings

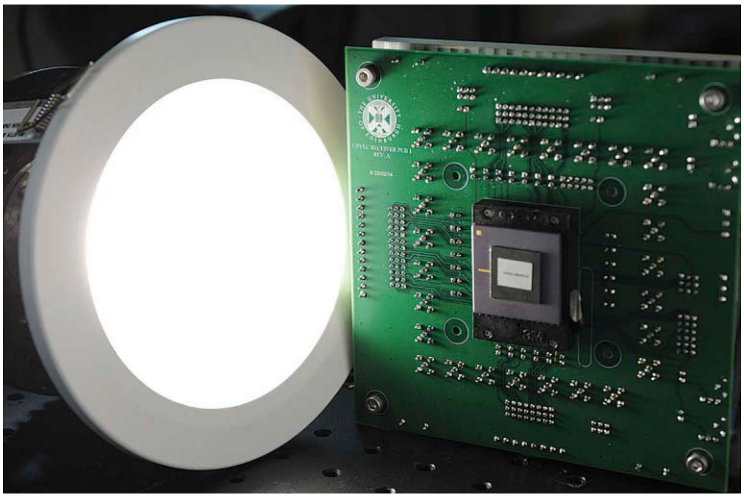
As LEDs become a more common source for room lighting, they're opening a new pathway for linking mobile devices to the Internet, with the potential for wider bandwidth and quicker response time than Wi-Fi. At least that's what researchers such as Harald Haas, chair of mobile communications at the University of Edinburgh, are hoping.

"All the components, all the mechanisms exist already," Haas says. "You just have to put them together and make them work."

Haas's group, along with researchers from the Universities of Cambridge, Oxford, St. Andrews, and Strathclyde, are halfway through a four-year, £5.8 million project funded by the Engineering and Physical Sciences Research Council, in the United Kingdom. They are pursuing ultraparallel visible light communication, which would use multiple colors of light to provide high-bandwidth linkages over distances of a few meters. Such a Li-Fi system, as it's been dubbed, could supplement or in some instances replace traditional radio-based Wi-Fi, they say. But taking on such a broadly used radio technology is an uphill battle.

At the IEEE Photonics Conference in October, members of the consortium showed off the progress they're making. For instance, the team has used commercially available red, green, and blue LEDs as both emitters and as photodiodes to detect light. By doing that, they created a system that could both send and receive data at aggregate rates of 110 megabits per second. When transmitting in one direction only, they reached a rate of 155 Mb/s.

But Haas says that this version is limited by existing LEDs, and by the use of LEDs as transmitters and detectors at the same time. Members of the consortium, however, have created a better LED, which provides a data rate



LIGHT FANTASTIC: A CMOS digital-to-analog converter developed at the University of Edinburgh helps LEDs act as communications devices.

close to 4 gigabits per second operating on just 5 milliwatts of optical output power and using high-bandwidth photodiodes at the receiver. With a simple lens to enhance the distance, they can send data 10 meters at up to 1.1 Gb/s, and soon they will increase that to 15 Gb/s, Haas says. The 802.11ad Wi-Fi standard for the 60-gigahertz radio band reaches just under 7 Gb/s, so Li-Fi would more than double that rate.

They're also using avalanche photodiodes to make better receivers. In an avalanche photodiode, a single photon striking the receiver produces a cascade of electrons, amplifying the signal. Haas's team at the Li-Fi R&D Centre has created the first receiver chip for Li-Fi with integrated avalanche photodiodes on CMOS. The 7.8-square-millimeter IC houses 49 photodiodes.

Separately, the Fraunhofer Institute for Photonic Microsystems, in Dresden, Germany, had announced plans to demonstrate a Li-Fi hot spot in November (after press time) at the Electronica 2014 trade show in Munich. Frank Diecke, who leads the team developing Li-Fi at Fraunhofer, says that the system would most likely use infrared light and is aimed at industrial users rather than consumers. The hot spot was set to be a point-to-point link with a data rate of up to 1 Gb/s.

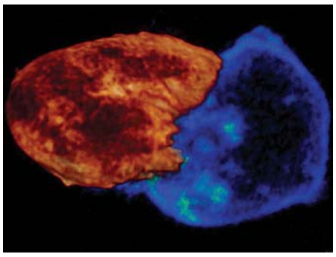
"You can have more or less the same data rate as over a USB cable," Diecke says. "That's very challenging for most wireless technologies, like Wi-Fi and Bluetooth." Another advantage, says Diecke, is that the latency of Wi-Fi–the time between when a signal is sent and when it's received–is measured in milliseconds, whereas Li-Fi's latency is on the order of microseconds. In industrial applications, where data has to flow between sensors, actuators, and a control unit, low latency and high data rates would make Li-Fi useful in places where Wi-Fi is not. "We don't want to replace Wi-Fi," he says. "That's not our goal."

But Diecke says Li-Fi could complement existing communications technologies, including Wi-Fi and gigabit Ethernet. For now, his group is not focusing on combining it with general lighting, as Haas proposes.

A group of European academic researchers and networking companies is aiming for the consumer market, though. The group is working on a project called Advanced Convergent and Easily Manageable Innovative Network Design (ACEMIND) to develop ways to manage local networks in homes and small businesses. ACEMIND includes a number of demonstrator projects to test different technologies, including Li-Fi. Dmitris Katsianis at the University of Athens, who is a participant in ACEMIND, thinks Li-Fi might be in practical use within the next five years. "Li-Fi has the advantage of being useful in electromagnetically sensitive areas such as in hospitals, aircraft cabins, and power plants," he says.

Haas is counting on a much bigger market. He expects LEDs to evolve past just being light sources, much the same way the cellphone evolved from a communications device to a mobile computer. "In 25 years, every lightbulb in your house will have the processing power of your cellphone today," he says. "It will in the future serve illumination as just one of many purposes." —NEIL SAVAGE

LIFE IN ACTION



This month Eric Betzig, of the Howard Hughes Medical Institute, is expected to fly to Stockholm to receive his share of the 2014 Nobel Prize in Chemistry for expanding the frontiers of microscopy. It seems he just couldn't leave those frontiers alone. Betzig (an engineer by training) and his collaborators have come up with a brand new microscopy trick. Called lattice light-sheet microscopy, it generates extraordinarily sharp 3-D images and videos of live organisms at scales ranging from single molecules to early-stage embryos. (Here it's showing an immune system cell [left] attacking an invader.) It works by illuminating the biological sample using a thin sheet of light that's manipulated by an ultrafast LCD to create a lattice of high and low intensity.

See the full story at http://spectrum.ieee.org/betzig1214

BETZIG LAB/HHMI

MEXICO'S RENEWABLES REVOLUTION CREATES TENSION

Demand for wind energy brings opportunities to engineers but angers some locals

Men died in gun battles over the installation of windmills in the state of Oaxaca, Mexico, three years ago. Opponents argued that energy companies misled them and that community leaders rented out collective lands without consulting everyone they should have. Today, protests continue, but the growth of wind farms and other renewables seems assured: Mexico boasts almost 2 gigawatts of installed wind power capacity and plans to install perhaps another 12 GW by 2022. All that clean energy is a big change for this country, which is the world's ninth-biggest oil producer and perhaps the 11th-biggest emitter of carbon dioxide.

Yet at a conference in the city of Oaxaca de Juárez in August 2014, audience members asked the state's renewable energy coordinator, Sinaí Casillas Cano,

MARK STEVENSON/AP PHOTO

WINDY WELCOME: In 2009, people gathered in Oaxaca for the inauguration of a US $550 million wind farm. The benefits of Mexico's renewables boom have been uneven, triggering protests.

what benefit the foreign-built windmills had brought. Few of the farmers who have rented their land to wind companies are qualified—or needed—to maintain the multimegawatt windmills. The benefits will arrive unevenly as Mexico races to reform its fast-growing energy sector, experts say. Better-educated Mexicans will win the first jobs, and industrial power buyers will be the first to see their electricity bills fall, according to energy strategist Eduardo Reyes of PricewaterhouseCoopers, in Mexico City.

Casillas won applause from the crowd, saying, "Oaxaca needs to keep construction and maintenance jobs here." But to do that, Mexico needs to train engineers capable of working with—and someday competing with—the foreign firms that are leading the renewable energy boom here.

The country has now begun to mobilize its workforce. In October, the federal government launched a national program for energy-job training. The government predicts that the overall sector's job demand will grow from about 20,000 jobs in 2015 to 50,000 by 2018, with about one-fifth of those for people with bachelor's degrees or higher levels of training. It will provide educational grants to up to 60,000 technicians, engineers, and postgraduates.

The country's universities have already ramped up a response as well. In 2011, the National Autonomous University of Mexico (UNAM) launched a new major in renewable energy engineering. "Our graduates have a very high potential of finding jobs in the private sector and in government," says the program's director, Octavio García Valladares. The UNAM program has been stable at around two dozen students per class since 2012, and there are now 22 such programs nationwide.

Still, such efforts have a long way to go, says electrical engineer Santiago Barcón, a columnist for *Energy Hoy* in Mexico City. Unlike in the United States, where competition among companies has created a deeper, if sometimes redundant, talent field, Mexico's history of monopoly means that fewer people have experience in each niche of the energy marketplace. And it will take a decade to get fresh graduates up to speed, Barcón says. The result will be a short-term salary bubble in the energy sector, he predicts.

PricewaterhouseCoopers expects "clean" energy production to triple from 53 terawatt-hours in 2012—around a fifth of Mexico's generation—to 160 TWh by 2024. That gain will be thanks to a 2012 law requiring electricity generators to produce or buy 35 percent of their energy from clean sources. "Clean" in this case includes certain natural-gas plants, but large contracts for non-fossil-fuel energy are proliferating: Wind projects announced this year outside Oaxaca include a 66-megawatt, US $120 million farm in Esperanza and a 252-MW, $650 million project near General Bravo. The country's first utility-scale solar plant, a 39-MW, $100 million facility in La Paz, opened in March. Also, a major constitutional reform of the country's energy sector and regulations enacted this past August make it easier for producers to reach buyers.

Those projects should help unstick the country's stagnant economy, but it may take a long time for benefits to reach Mexicans in the poorest parts of the country, such as the Isthmus of Tehuantepec, where the first major wind farms were installed and gun battles broke out. To counter accusations that foreign wind companies took advantage of illiterate people with little basis for judging their offers, the companies have begun to invest in social development programs.

At the August conference, Claudia Toledo Matus, a corporate-responsibility representative for the Spanish energy company Acciona, said the company's goal was to spend 5 percent of its budget on social development over the 20-year life of the project. Yet in the first four years, Acciona spent only one-tenth of 1 percent of its Oaxaca wind budget on social programs, or around $913,000, according to Toledo. "We have to revise it every year to decide how to allocate it," she says, but she did not provide a schedule for spending the remaining $78 million.

UNAM's García and others criticize Mexico's government for its delays on reforming the renewable energy sector, too. "Unfortunately, the energy reform approved in Mexico barely mentions renewable energies," he says. Government officials will turn their attention to clean energy next, said Megan Reilly Cayten, coauthor of an August Atlantic Council report on the reform, during a conference call: "The issue has essentially been punted to the fall," she says. By *IEEE Spectrum* press time, no new rules had been established. The government will need to resolve issues such as how to assign clean energy credits and how to ensure that renewables can compete with ever-cheaper natural-gas generation on the new electricity grid.

Mexico's first university class of renewables engineers, due to graduate next year, had better study hard: They will arrive in a fast-changing market for their skills. —LUCAS LAURSEN

NEWS

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

SIX-STATE MEMRISTOR OPENS DOOR TO WEIRD COMPUTING

A new memristor-based device could be used to build brainlike systems and base-10 computers

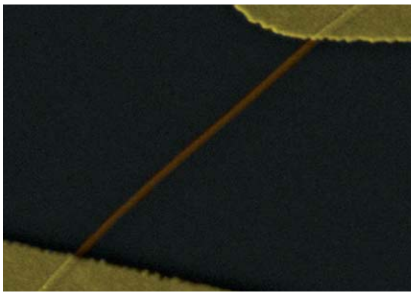
The newest fundamental electronic component, the memristor, still holds some surprises, it seems. Since researchers built the first memristor six years ago, this mysterious device has promised a host of applications—denser nonvolatile memories, new universal logic gates, and brainlike computers, among other things. Add to these another, according to Trinity College Dublin physicists: base-10 memory.

Unlike transistor-based memories, which are designed to assume only binary states, the memristor can hold much more. The Trinity researchers constructed one that can remember six states, and there's nothing to stop expanding that to 10 or more, they claim.

Instead of maintaining a bit as charge, the way flash and dynamic RAM do, memristors (or RRAM, for resistive RAM) hold memory as resistance. The device "remembers" the level of current that has flown through by altering its internal resistance. The resistance decreases when current flows in the other direction.

The Trinity memristor is a bit different. For one thing, unlike other memristors, it also acts as a diode: The resistance levels can be controlled only by current flowing in one direction. The diode effect comes from a postproduction processing step, called electroforming. The device consists of a titanium dioxide semiconducting nanowire sandwiched between two metal electrodes. Once the memristor is constructed, prolonged exposure to 10 volts boosts the population of charge carriers near the interface with the cathode, creating a diode junction.

Apart from conducting in one direction,



ONE-WAY MEMORY: A titanium oxide nanowire acts as both a diode and a memristor.

the new memristor stores bits differently, too. A normal memristor would need two different voltages to store two different levels of resistance: "You apply 5 V and you get one resistance level; you apply 10 V and that gives you the other level," says Curtis O'Kelly, a physicist at Trinity College, who with John Boland and Jessamyn Fairfield discovered the new properties. "In our device, you apply 7.5 V once, and that will take you up one resistance step, and when you apply another pulse of 7.5 V, that will take you up another step." After six such pulses the researchers found that their device reached a saturated state, and no more changes in the resistance took place. You can stop at any level, which remains stored, and later apply another pulse, which will bring you to the next level, or you can reset the device by applying a single negative 7.5-V pulse, explains O'Kelly. Because the memristor is a diode, you can reset the memory cell without current flowing, something that cannot be done with a "normal" memristor, he says.

The researchers say that the mechanism of the memory effect can be explained by a physical change that takes place in the nanowire at the interface with the electrode. "When you apply a positive voltage to one of the contacts, you generate a population of oxygen vacancies—you are removing oxygen from the lattice of the wire—and this allows electrons" to move into the metal more easily, says O'Kelly. The negative 7.5-V pulse injects electrons from the gold electrode into the nanowire, destroying the oxygen vacancies at the interface and making the nanowire less conductive.

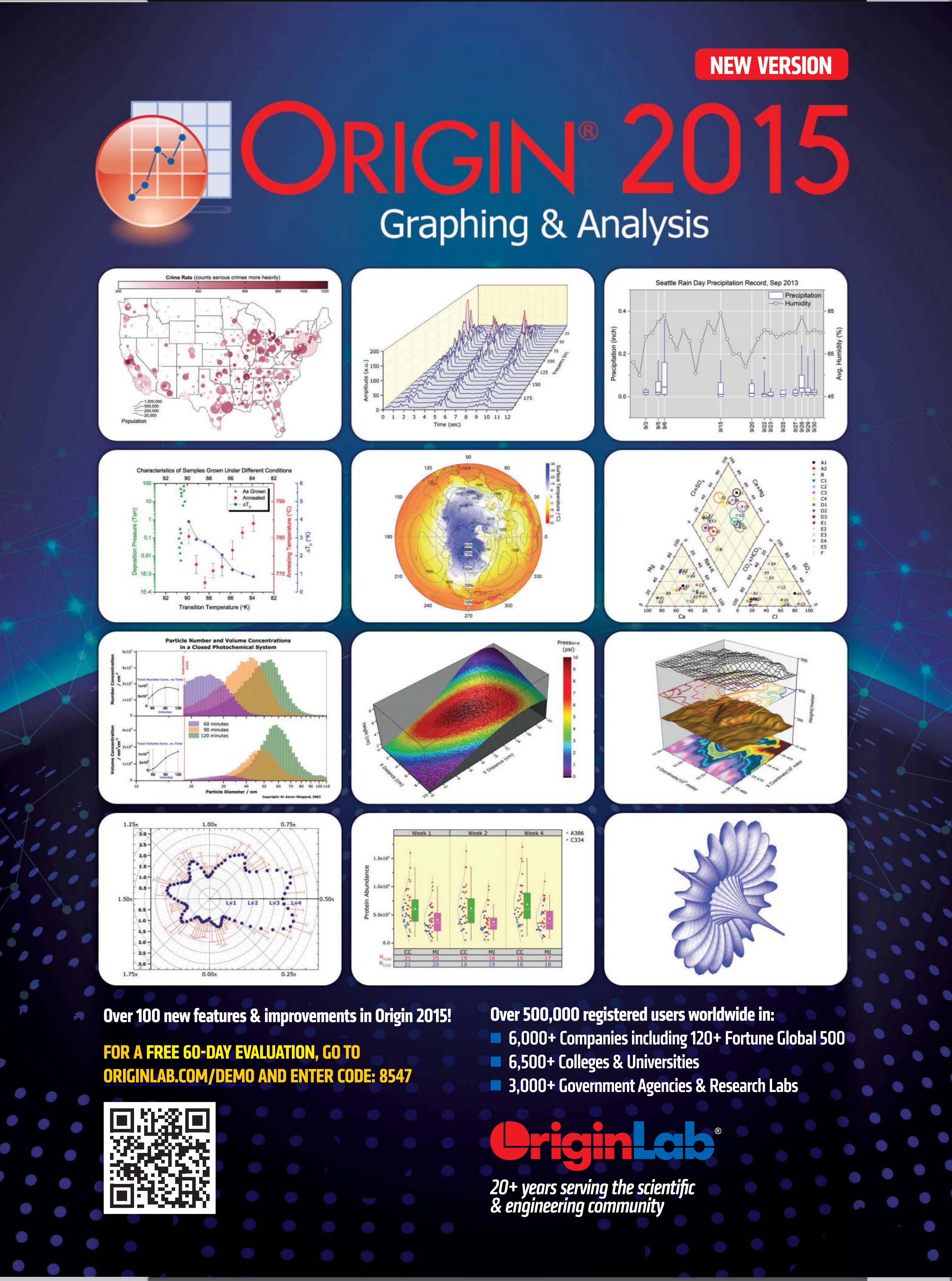
The number of levels of resistance is flexible, and the device could achieve 10. "The ultimate limit is the resolution between each level," says O'Kelly.

Such a system makes O'Kelly imagine base-10 memories that can retain 10 different states per memory cell. Whether memory like that would be worthwhile in a universe of binary computing is questionable, of course. On the one hand, base-10 memory might be much more dense. For example, the largest unsigned binary 64-bit integer—18,446,744,073,709,551,615—could be held in 20 bits instead of 64. But interfacing base-10 memory with binary logic might defeat any gains. Electronics engineers would have to come up "with new infrastructure to deal with this new type of memory," says O'Kelly.

Long before anyone contemplates redesigning computers around the Trinity memristor, that device will have to make some big gains. James Scott, a physicist at the University of Cambridge, compares the low speed of the device with that of "a hand-operated eighth-century abacus."

Making the device smaller should help fix that problem, suggests Harika Manem, an electrical engineer at the State University of New York, Albany. Manem isn't a believer in a future of base-10 computing, but she thinks that these multistate memristors could be very useful in one of her research interests—unconventional bioinspired logic systems based on neural networks. "What is nice is that their device has controllable states that are very repeatable and consistent, and if they scale it down, it should be more applicable," she says.
—ALEXANDER HELLEMANS

TRINITY COLLEGE


NEW VERSION
ORIGIN® 2015
Graphing & Analysis
Over 100 new features & improvements in Origin 2015!
FOR A FREE 60-DAY EVALUATION, GO TO
ORIGINLAB.COM/DEMO AND ENTER CODE: 8547
Over 500,000 registered users worldwide in:
6,000+ Companies including 120+ Fortune Global 500
6,500+ Colleges & Universities
3,000+ Government Agencies & Research Labs
OriginLab®
20+ years serving the scientific
& engineering community

PHOTOGRAPH BY Valery Hache/AFP/Getty Images

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

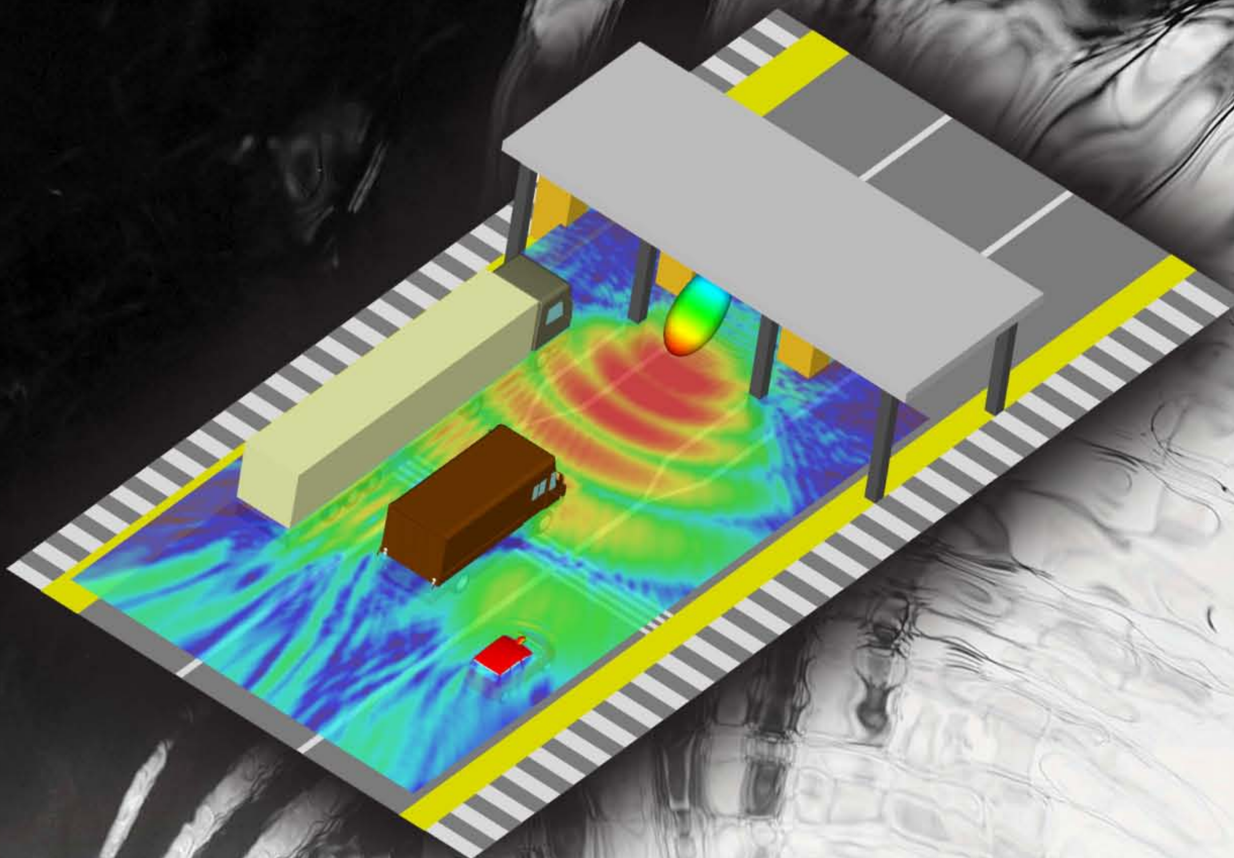
ABOARD THE SKY YACHT

IS IT A SMALL BOAT using a lighter-than-air vehicle as its sail, or is it an airship that uses a boat to better maintain control? However you slice it, the Aerosail is certainly a conversation starter. (The stabilizing keel, connected by cables, isn't visible in this photo.) French adventurer and researcher Stephane Rousson's aim is to sail—or pilot—this hybrid vessel from Nice, France, to Calvi, on the island of Corsica. This wind-powered trip in his latest oddball means of transportation follows Rousson's failed attempt, in 2008, to cross the English Channel in a pedal-powered airship—a plan inspired by the climactic flying bicycle scene in the movie *E.T.*

THE BIG PICTURE

NEWS

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page



RESOURCES

HOLIDAY GIFT GUIDE 2014

IEEE Spectrum's annual selection of gadgets for techies

DIGITAL BOLEX

RESOURCES_TOOLS & TOYS

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

ROLLING SPIDER

This miniature drone by Parrot takes many of the automatic stabilization features found on Parrot's larger flying machines, such as the AR Drone, and squeezes them into a tiny package. Four rotors, a ground-speed monitoring camera, an ultrasonic range finder, and a barometric altimeter all allow the $130 Rolling Spider to zoom around and hover while you control it via a smartphone app. **—s.c.**

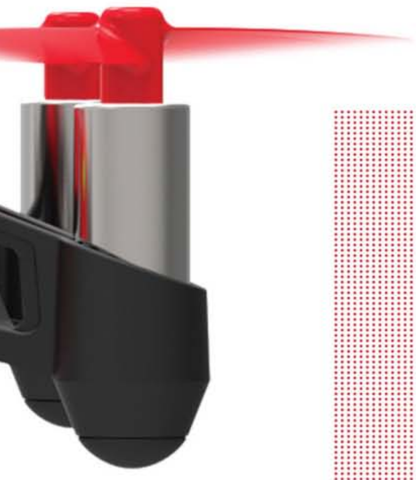
DIGITAL BOLEX D16

Many filmmakers and documentarians of the last century relied on Bolex film cameras—relatively rugged, lightweight, and powered by a hand-wound spring, they were ideal for shooting in the field. Now, 21st-century cinematographers can shoot with a digital version of the Bolex, the D16, which goes for US $3,300 or $3,600 (depending on the size of its internal solid-state drive). The camera is designed to be compatible with vintage Super 16 and 16-mm lenses, and instead of a more typical CMOS image sensor, it uses a charge-coupled-device (CCD) sensor, which the makers claim gives videos a more filmlike feel.

—STEPHEN CASS

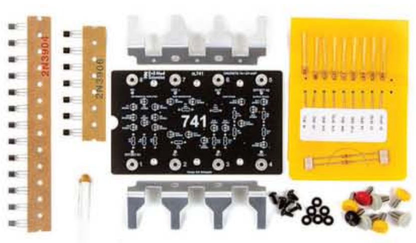
CLOCKWISE FROM TOP: PARROT; DIGITAL BOLEX (2)

RESOURCES_TOOLS & TOYS



XL741

A follow-on to the Three Fives kit that *IEEE Spectrum* featured in February 2014, this is a giant version of the ubiquitous and influential Fairchild Semiconductor µA741 operational amplifier. Made from discrete components, the $35 XL741 is based directly on the design for the original µA741. For many circuits, the XL741 should work as a drop-in replacement—allowing you to turn that noninverting amplifier or voltage follower into a fun conversation piece! **–s.c.**



V.360 HD CAMERA

Have you ever taken a vacation video only to miss something exciting that happened out of the frame? Or ended up turning around several times on the spot in the name of capturing a perfect panorama? These are no longer problems with the V.360 HD camera, which captures a continuous 360-degree view of the world around it at a resolution of 6480 by 1080. The camera is also waterproof, and it comes with software that allows it to detect motion or stream video remotely. The price was still to be determined at press time, but it's likely to be under $500 –s.c.

SEEK THERMAL SMARTPHONE CAMERA

This $200 plug-in for iPhone or Android smartphones is a true thermal infrared video camera. Unlike many camcorders that feature infrared night vision, the Seek Thermal camera works in bright light as well as in the dark, and it can tell users the temperature of any object seen on screen within about a degree Celsius. In addition to security uses, this can be handy for a cook checking to see if a barbecue is cooking evenly, a plumber searching for a pipe, or an electrical engineer hunting for hot spots on a motherboard. An "unboxed" version of the sensor is expected to be released next year for makers wishing to incorporate thermal vision into their designs. **–s.c.**

CLOCKWISE FROM BOTTOM RIGHT: VSN MOBIL; SEEK THERMAL (2); EVIL MAD SCIENTIST LABORATORIES (2)

PONOPLAYER

Pocketable high-definition music systems aren't for everybody, but a few companies are trying to make them at least affordable to everybody. The highest-profile among these is by Pono, a company started by rocker Neil Young. The result is the $400 PonoPlayer, which can play music files at sampling rates of up to 192 kilohertz and with samples up to 24 bits long. (For comparison, the popular AAC media format used by Apple devices, among others, samples at a maximum rate of 96 kHz.) Unfortunately, Pono won't start shipping units until January 2015, but you can get someone a preorder now.

—GLENN ZORPETTE

SCANSNAP iX100

I've been a fan of Fujitsu's line of document scanners since the company introduced its first desktop scanner in 2009: Being able to easily turn paper into searchable PDFs on my laptop has dramatically reduced my office storage requirements. Now, with the iX100, a lightweight $200 battery-powered wireless version that can work with a smartphone, you can take a lot of that desktop functionality on the road. Convert and toss conference fliers in your hotel room, or scan expense receipts on the plane home. —S.C.

MUSE

Feeling stressed? InteraXon's $300 Muse might help. The headband contains seven EEG sensors that detect the user's brain waves—quite a step up from products released a few years ago that made a virtue of using a single electrode to keep costs down. A paired smartphone app tracks the production of alpha waves, which are associated with relaxation, and guides the user through short meditative exercises. InteraXon says the app's feedback will let users cultivate calm in a hectic world.

—ELIZA STRICKLAND

CLOCKWISE FROM TOP LEFT: KRANZ KRACHTUS/PONOPLAYER/AP PHOTO; FUJITSU; INTERAXON (2)

RESOURCES_TOOLS & TOYS

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page
Qmags THE WORLD'S NEWSSTAND®

DIY EXOPLANET DETECTOR

FIND THE SIGNATURE OF AN ALIEN WORLD WITH A TRACKING MOUNT AND A DIGITAL CAMERA

STAR TRACK: The rotation of the Earth causes stars to continuously shift position in the sky. Detecting the subtle signs of the existence of an orbiting exoplanet requires compensating for this shift. To do that, I built my own hinged "barn door" tracker.

DAVID SCHNEIDER

SINCE 1995, WHEN ASTRONOMERS ANNOUNCED the discovery of a planet orbiting the star 51 Pegasi, exoplanets—which orbit stars other than the sun—have been a hot topic. I knew that dedicated amateurs could detect some of these exoplanets, but I thought it required expensive telescopes. Then I stumbled on the website of the KELT-North project at Ohio State University, in Columbus. The project's astronomers find exoplanets not with a giant telescope but by combining a charge-coupled-device (CCD) detector with a Mamiya-Sekor lens originally designed for high-end cameras. That got me wondering: Might I be able to detect an exoplanet without a telescope or a research-grade CCD detector? ● I discovered that one amateur astronomer had already posted online about how he had detected a known exoplanet using a digital single-lens reflex (DSLR) camera outfitted with a telephoto lens. He was able to discern the dip in the brightness of a star as an orbiting planet passed in front of it—a technique known as transit detection. ● The exoplanet he chose to go after was a gas giant that belongs to a binary star system variously named HD 189733, HIP 98505, or V452 Vulpeculae, depending on the star catalog. It was the obvious choice because its parent star is relatively bright (although still invisible to the naked eye), and the star drops in apparent brightness during a transit

by 2.6 percent, which is a lot as these things go. (Astronomers, who use a logarithmic scale to describe the magnitude of a star's brightness, would call that a 28-millimagnitude difference.)

So I decided to follow this lead and went shopping for a telephoto lens for my Canon EOS Rebel XS DSLR. With old manual-focus lenses now useless to most photographers, I was able to acquire a 300-millimeter Nikon telephoto lens on eBay for a song (US $92, shipped), along with a Nikon-to-Canon adapter ($17 from Amazon).

The next task was to figure out how to make the camera track a star during long exposures. I could have bought a commercial star tracker, but that would have put me back several hundred dollars. Instead I built a "barn door" tracker—essentially two pieces of plywood hinged together. Aligning the hinge to your hemisphere's celestial pole allows you to track a star as the plywood "doors" separate at a constant rate.

To drive the tracker, I pulled some gears out of a defunct inkjet printer, attaching one gear to a stepper motor and the other to a nut screwed onto a gently curved length of threaded rod. Rotating the nut pushes the doors of the tracker apart. The stepper motor is controlled, via a driver board, by an Arduino microprocessor that lets me set the rate at which the doors separate.

Initially, I mounted my tracker on a camera tripod. But I soon abandoned that as being too precarious and built a sturdy wooden platform. The final component of the tracker is a ball head ($18 on Amazon) bolted to the top, which allows me to orient the camera in any direction.

The trickiest step in the operation is getting the camera pointed at the target star. I aim my camera by first eyeballing things and then walking the field of view from star to star. A right-angle viewfinder attachment ($20, used) makes that easier, but it's still a challenge. Some nights it has taken me 15 minutes or more to get the target star framed.

THE LONG SHOT: Sixty-three light-years away, HD 189733 is too dim to be seen with the naked eye. Finding it required the use of such waypoints as the Dumbbell Nebula [top]. Once the star system is targeted, the Earth's rotation causes the sky's image to blur [middle left] during long exposures. An Arduino-controlled star tracker [bottom right] compensated for this motion [bottom left].

DAVID SCHNEIDER (4)

To take images, I used software that came with my Canon camera. It allows you to adjust the camera settings, take shots, record images directly to your computer, and program a sequence of timed exposures. I also purchased a $14 AC power adapter so that I could run my camera for hours without its battery giving out.

I took test sequences of images of HD 189733 for a few nights, settling on a routine of taking one 50-second exposure per minute. I figured that duration would minimize variations in brightness that come from scintillation—twinkling—and that it would also average over small periodic errors in tracking. With such long-duration exposures, I used a low ISO setting to avoid saturating the camera's CMOS imaging sensor.

The hardest part of the whole project proved to be waiting for an opportunity to observe the transit of HD 189733's exoplanet, which takes place once every 2.2 days. That sounds frequent, but transits that occur during daytime or are too close to the horizon are impossible to observe. (The Czech Astronomical Society provides a handy online resource for determining opportunities to observe this and other exoplanet transits.) And of course, I needed clear skies.

Finally, after weeks of waiting, an opportunity came in mid-October. I recorded images for almost 3 hours, beginning about a half-hour before the start of the 108-minute transit. That, I figured, would capture the transition from normal brightness to ever-so-slightly dimmed and back to normal again.

Of course, you can't just look at the images to see the subtle effects of a transit: There are too many confounding influences, such as changes in the transparency of the atmosphere. And the response of a camera's imaging sensor is seldom uniform: If the position of the target shifts in the field of view (which is hard to avoid over the course of an evening), the amount of light registered will also change, even if there is no actual change in brightness. To compensate, I used free software called Iris, which allowed me to perform the corrections needed to calculate the brightness of HD 189733, as well as four reference stars.

I loaded the results from Iris into Microsoft Excel to make differential-photometry calculations—that is, comparing HD 189733 with one of the four reference stars to compensate for changes in atmospheric conditions. The scatter in the final results was about the same size as the signal I was attempting to measure, but the general dip in brightness was easy enough to discern nevertheless. The average magnitude of the target star diminished and recovered just as the exoplanet's transit began and ended.

And the shift in magnitude was very close to, if not precisely, the 28 mmag expected. So it seems my home-brew observatory *did* detect an exoplanet—using little more than run-of-the-mill DSLR and a $92 eBay camera lens! —**DAVID SCHNEIDER**

AMBIENT IS EVERYWHERE

Ambient Reality is the ultimate disruption, as it alters the actual fabric of the universe. We begin living in the prenow. Things happen before they happen. —*Nicholas Carr*

THE WORD *AMBIENT* BEGAN ITS ENGLISH CAREER innocently enough, as a form of the Latin verb *ambire*, "to go around," and writers used it to describe something that was lying around or encircling something else. By the end of the 17th century, the meaning of *ambient* had expanded, so to speak, to describe anything that completely surrounded or circumfused an area or volume, as in the *ambient air* or *ambient light*. By the middle of the 20th century, audio engineers spoke of *ambient sound* (the atmospheric sounds in a particular area, particularly background noise picked up by a microphone), and by the late 1970s audio listeners spoke of *ambient music* (music that aimed to invoke a particular mood or atmosphere). ● That might have been it for a solid but unremarkable word. But modern technologists and futurists have continued to give *ambient* new duties in a world where information and interfaces are everywhere. ● Remember back around the turn of the century, when the resolution of a dinner party disagreement had to wait until everyone could return to their computers in order to Google the answer? Now, of course, people just pull out their smartphones and look up the answer on the spot. This is the first stage of an ideal called **ambient findability**: being able to find anything from anywhere at any time. For this to work requires **ambient connectivity**, the ability to get online no matter where you are. ● For now, this connectivity comes via our smartphones and wearables such as Google Glass, but in the future (so say the futurists) we'll connect using voice-activated **ambient interfaces** that are seemingly everywhere and nowhere, **glanceable ambient displays**, and **ambient devices** that offer **touch-everywhere** surfaces.

The point of all this is to achieve two ideals. The first is **ambient informatics**, where information is always readily available. The second is **ambient intelligence**, a surrounding electronic infrastructure that responds to its environment, particularly the presence of people.

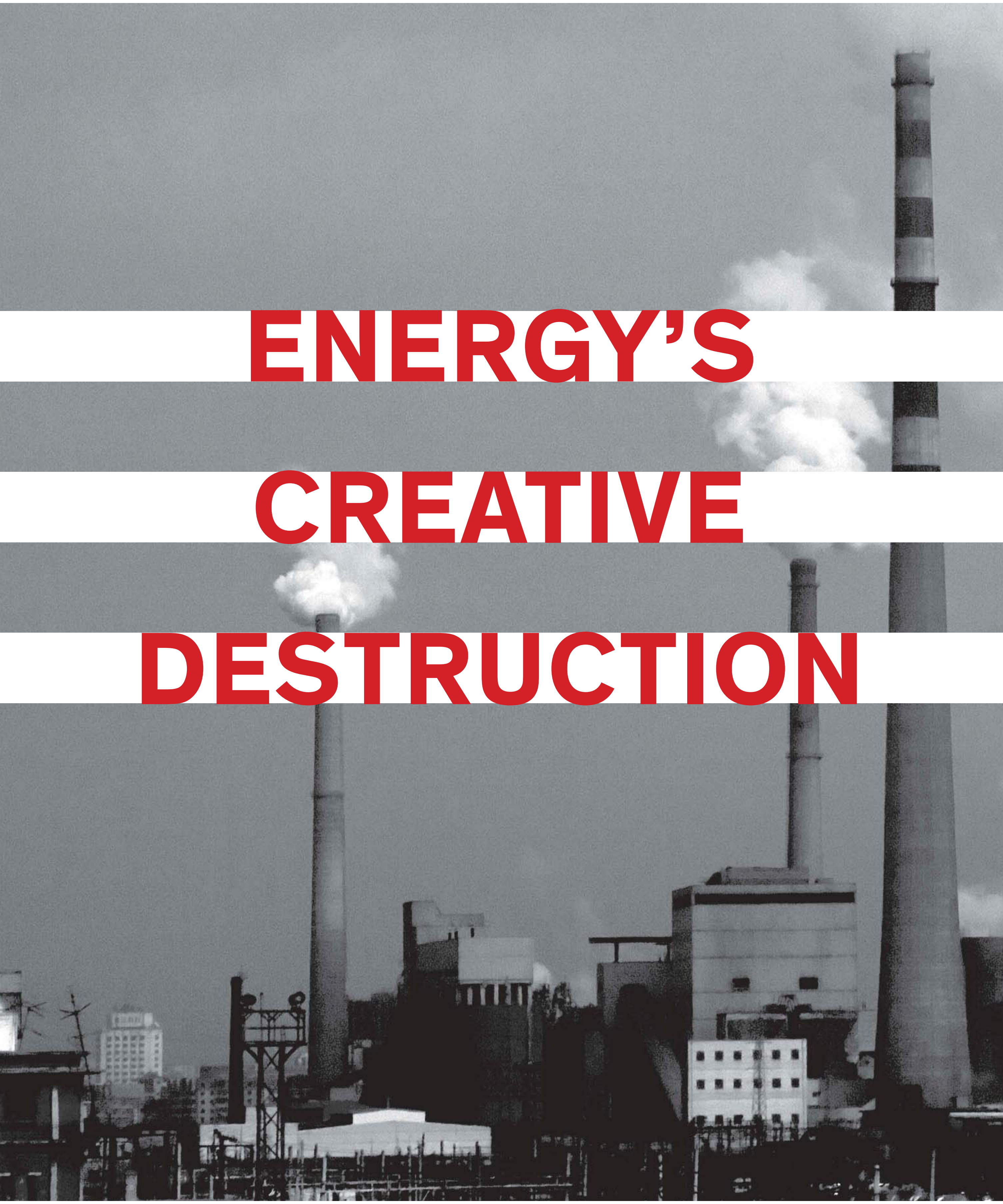
Some see these ideals as strictly positive goals that will enable life-enhancing developments such as being able to see or hear art wherever and whenever you want (**ambient art**) or the ability to stay in touch with family and friends instantly and constantly (**ambient intimacy**). On a more mundane level, business types seek the ability of consumers to purchase anything, anywhere, anytime–the inevitable **ambient commerce**.

But is being surrounded by information and data connections always a good thing? Constant connectivity can lead to constant work, as many a modern employee has found. Writing in *The New Republic*, Stephen Poole laments that "our world has become an **ambient factory** from which there is no visible exit." When Google's engineering director envisions a world in which embedded microphones constantly listen to our conversations so that the company can swiftly answer our queries, technology critic Nicholas Carr rightly lampoons the idea by calling it the **Ambient Nag**. In the here and now, we have the **inline tweet**, a selected snippet of an article or blog post formatted as a special link that enables readers to easily post it as a tweet. Some see this as a convenience, but others have derided it as **ambient tweetability**.

Perhaps we should forget *information* overload and instead worry about ***ambient* overload**, where interfaces, connections, and sensors are all but inescapable. The academic Malcolm McCullough (in his terrific book *Ambient Commons*) counsels that these **ambient information practices** mean we must now take a different approach to technology: "Henceforth, may you seek, inhabit, and maintain surroundings that are less thoughtlessly layered in media, and more discriminately curated for use." Call it *ambient curation*, the necessary survival skill in the Age of the Ambient. ■

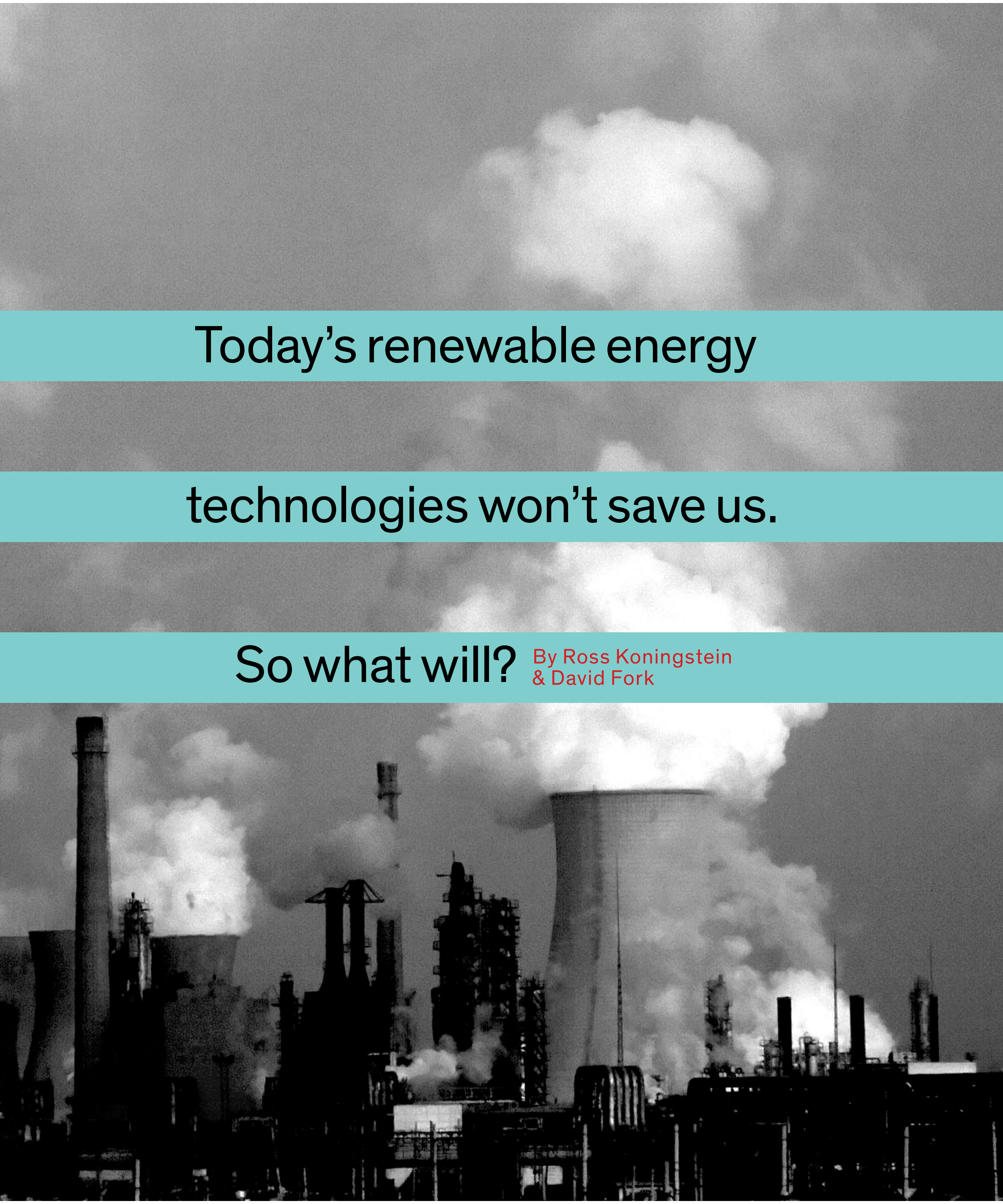
ILLUSTRATION BY Greg Mably

ENERGY'S CREATIVE DESTRUCTION



Today's renewable energy technologies won't save us. So what will?

By Ross Koningstein & David Fork



IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

GOOGLE COFOUNDER LARRY PAGE is fond of saying that if you choose a harder problem to tackle, you'll have less competition. This business philosophy has clearly worked out well for the company and led to some remarkably successful "moon shot" projects: a translation engine that knows 80 languages, self-driving cars, and the wearable computer system Google Glass, to name just a few.

Starting in 2007, Google committed significant resources to tackle the world's climate and energy problems. A few of these efforts proved very successful: Google deployed some of the most energy-efficient data centers in the world, purchased large amounts of renewable energy, and offset what remained of its carbon footprint.

Google's boldest energy move was an effort known as RE<C, which aimed to develop renewable energy sources that would generate electricity more cheaply than coal-fired power plants do. The company announced that Google would help promising technologies mature by investing in start-ups and conducting its own internal R&D. Its aspirational goal: to produce a gigawatt of renewable power more cheaply than a coal-fired plant could, and to achieve this in years, not decades.

Unfortunately, not every Google moon shot leaves Earth orbit. In 2011, the company decided that RE<C was not on track to meet its target and shut down the initiative. The two of us, who worked as engineers on the internal RE<C projects, were then forced to reexamine our assumptions.

At the start of RE<C, we had shared the attitude of many stalwart environmentalists: We felt that with steady improvements to today's renewable energy technologies, our society could stave off catastrophic climate change. We now know that to be a false hope—but that doesn't mean the planet is doomed.

As we reflected on the project, we came to the conclusion that even if Google and others had led the way toward a wholesale adoption of renewable energy, that switch would not have resulted in significant reductions of carbon dioxide emissions. Trying to combat climate change exclusively with today's renewable energy technologies simply won't work; we need a fundamentally different approach. So we're issuing a call to action. There's hope to avert disaster if our society takes a hard look at the true scale of the problem and uses that reckoning to shape its priorities.

What's needed are **zero-carbon energy sources** so cheap that the operators of power plants and industrial facilities alike have an economic rationale for switching over within the next 40 years

CLIMATE SCIENTISTS have definitively shown that the buildup of carbon dioxide in the atmosphere poses a looming danger. Whether measured in dollars or human suffering, climate change threatens to take a terrible toll on civilization over the next century. To radically cut the emission of greenhouse gases, the obvious first target is the energy sector, the largest single source of global emissions.

RE<C invested in large-scale renewable energy projects and investigated a wide range of innovative technologies, such as self-assembling wind turbine towers, drilling systems for geothermal energy, and solar thermal power systems, which capture the sun's energy as heat. For us, designing and building novel energy systems was hard but rewarding work. By 2011, however, it was clear that RE<C would not be able to deliver a technology that could compete economically with coal, and Google officially ended the initiative and shut down the related internal R&D projects. Ultimately, the two of us were given a new challenge. Alfred Spector, Google's vice president of research, asked us to reflect on the project, examine its underlying assumptions, and learn from its failures.

We had some useful data at our disposal. That same year, Google had completed a study on the impact of clean energy innovation, using the consulting firm McKinsey & Co.'s low-carbon economics tool. Our study's best-case scenario modeled our most optimistic assumptions about cost reductions in solar power, wind power, energy storage, and electric vehicles. In this scenario, the United States would cut greenhouse gas emissions dramatically: Emissions could be 55 percent below the business-as-usual projection for 2050.

While a large emissions cut sure sounded good, this scenario still showed substantial use of natural gas in the electricity sector. That's because today's renewable energy sources are limited by suitable geography and their own intermittent power production. Wind farms, for example, make economic sense only in parts of the country with strong and steady winds. The study also showed continued fossil fuel use in transportation, agriculture, and construction. Even if our best-case scenario were achievable, we wondered: Would it really be a climate victory?

A 2008 paper by James Hansen, former director of NASA's Goddard Institute for Space Studies and one of the world's foremost experts on climate change, showed the true gravity of the situation. In it, Hansen set out to determine what

PREVIOUS PAGES: JON BOWER/LOOP IMAGES/CORBIS level of atmospheric CO_2 society should aim for "if humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted." His climate models showed that exceeding 350 parts per million CO_2 in the atmosphere would likely have catastrophic effects. We've already blown past that limit. Right now, environmental monitoring shows concentrations around 400 ppm. That's particularly problematic because CO_2 remains in the atmosphere for more than a century; even if we shut down every fossil-fueled power plant today, existing CO_2 will continue to warm the planet.

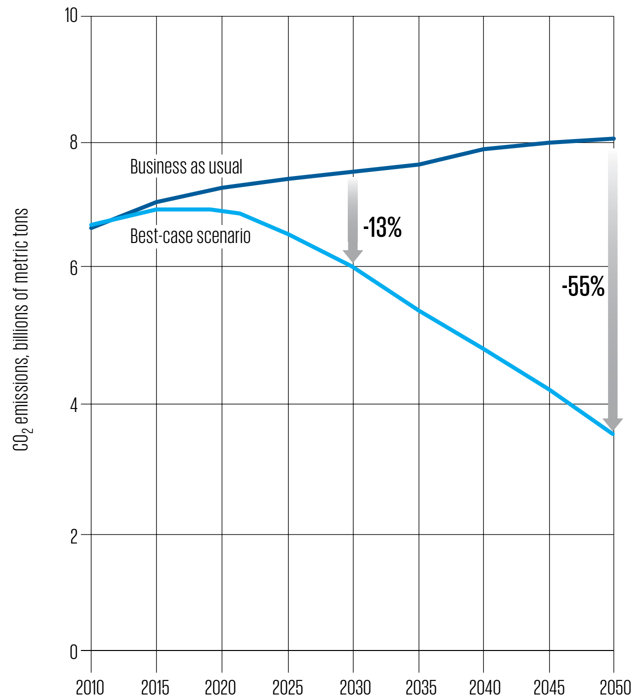
We decided to combine our energy innovation study's best-case scenario results with Hansen's climate model to see whether a 55 percent emission cut by 2050 would bring the world back below that 350-ppm threshold. Our calculations revealed otherwise. Even if every renewable energy technology advanced as quickly as imagined and they were all applied globally, atmospheric CO_2 levels wouldn't just remain above 350 ppm; they would continue to rise exponentially due to continued fossil fuel use. So our best-case scenario, which was based on our most optimistic forecasts for renewable energy, would still result in severe climate change, with all its dire consequences: shifting climatic zones, freshwater shortages, eroding coasts, and ocean acidification, among others. Our reckoning showed that reversing the trend would require both radical technological advances in cheap zero-carbon energy, as well as a method of extracting CO_2 from the atmosphere and sequestering the carbon.

Those calculations cast our work at Google's RE<C program in a sobering new light. Suppose for a moment that it had achieved the most extraordinary success possible, and that we had found cheap renewable energy technologies that could gradually replace all the world's coal plants—a situation roughly equivalent to the energy innovation study's best-case scenario. Even if that dream had come to pass, it *still* wouldn't have solved climate change. This realization was frankly shocking: Not only had RE<C failed to reach its goal of creating energy cheaper than coal, but that goal had not been ambitious enough to reverse climate change.

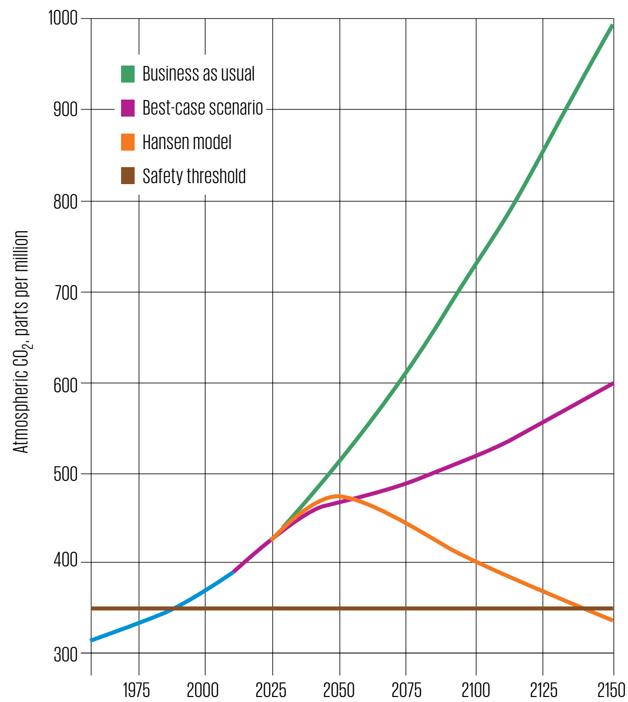
THAT REALIZATION prompted us to reconsider the economics of energy. What's needed, we concluded, are reliable zero-carbon energy sources so cheap that the operators of power plants and industrial facilities alike have an economic rationale for switching over soon—say, within the next 40 years. Let's face it, businesses won't make sacrifices and pay more for clean energy based on altruism alone. Instead, we need solutions that appeal to their profit motives. RE<C's stated goal was to make renewable energy cheaper than coal, but clearly that wouldn't have been sufficient to spur a complete infrastructure changeover. So what price should we be aiming for?

Consider an average U.S. coal or natural gas plant that has been in service for decades; its cost of electricity genera-

The Climate Conundrum



IN THE ENERGY INNOVATION study's best-case scenario, rapid advances in renewable energy technology bring down carbon dioxide emissions significantly.

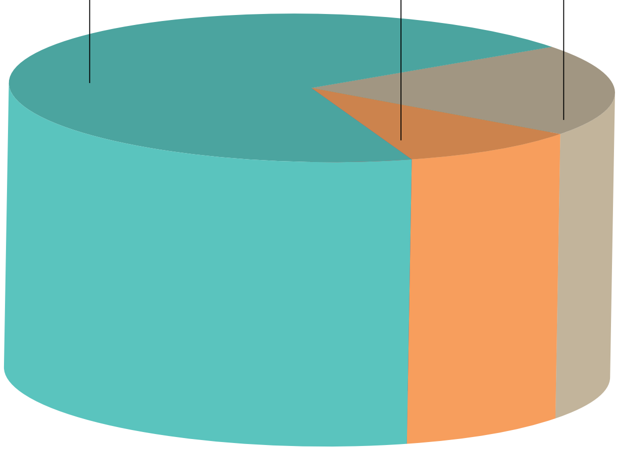


YET BECAUSE CO_2 lingers in the atmosphere for more than a century, reducing emissions means only that less gas is being added to the existing problem. Research by James Hansen shows that reducing global CO_2 levels requires both a drastic cut in emissions and some way of pulling CO_2 from the atmosphere and storing it.

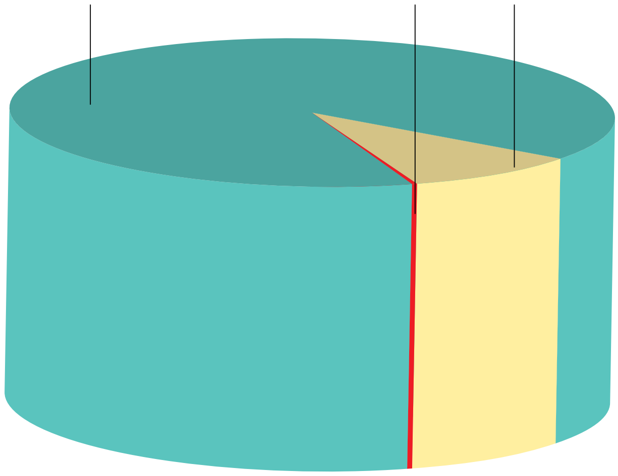
DATA SOURCES: "THE IMPACT OF CLEAN ENERGY INNOVATION," GOOGLE-MCKINSEY, 2011; "TARGET ATMOSPHERIC CO_2: WHERE SHOULD HUMANITY AIM?," JAMES HANSEN ET AL., 2008

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

How to Revolutionize R&D



A BALANCED ENERGY R&D PORTFOLIO proposed by the authors would allocate the bulk of resources to proven technologies like hydro, wind, solar photovoltaics, and nuclear; devote 20 percent of funds to related technologies like thin-film solar PV and next-generation nuclear fission reactors; and keep a pot of money for "crazy" ideas like cheap fusion.



TODAY IN THE UNITED STATES, the vast bulk of funding for energy R&D goes to established technologies. Essentially no money is allocated to related and potentially disruptive technologies, and about 10 percent is spent on projects that don't seek to produce economically competitive energy.

tion is about 4 to 6 U.S. cents per kilowatt-hour. Now imagine what it would take for the utility company that owns that plant to decide to shutter it and build a replacement plant using a zero-carbon energy source. The owner would have to factor in the capital investment for construction and continued costs of operation and maintenance–and still make a profit while generating electricity for less than $0.04/kWh to $0.06/kWh.

That's a tough target to meet. But that's not the whole story. Although the electricity from a giant coal plant is physically indistinguishable from the electricity from a rooftop solar panel, the *value* of generated electricity varies. In the marketplace, utility companies pay different prices for electricity, depending on how easily it can be supplied to reliably meet local demand.

"Dispatchable" power, which can be ramped up and down quickly, fetches the highest market price. Distributed power, generated close to the electricity meter, can also be worth more, as it avoids the costs and losses associated with transmission and distribution. Residential customers in the contiguous United States pay from $0.09/kWh to $0.20/kWh, a significant portion of which pays for transmission and distribution costs. And here we see an opportunity for change. A distributed, dispatchable power source could prompt a switchover if it could undercut those end-user prices, selling electricity for less than $0.09/kWh to $0.20/kWh in local marketplaces. At such prices, the zero-carbon system would simply be the thrifty choice.

Unfortunately, most of today's clean generation sources can't provide power that is both distributed and dispatchable. Solar panels, for example, can be put on every rooftop but can't provide power if the sun isn't shining. Yet if we invented a distributed, dispatchable power technology, it could transform the energy marketplace and the roles played by utilities and their customers. Smaller players could generate not only electricity but also profit, buying and selling energy locally from one another at real-time prices. Small operators, with far less infrastructure than a utility company and far more derring-do, might experiment more freely and come up with valuable innovations more quickly.

Similarly, we need competitive energy sources to power industrial facilities, such as fertilizer plants and cement manufacturers. A cement company simply won't try some new technology to heat its kilns unless it's going to save money and boost profits. Across the board, we need solutions that don't require subsidies or government regulations that penalize fossil fuel usage. Of course, anything that makes fossil fuels more expensive, whether it's pollution limits or an outright tax on carbon emissions, helps competing energy technologies locally. But industry can simply move manufacturing (and emissions) somewhere else. So rather than depend on politicians' high ideals to drive change, it's a safer bet to rely on businesses' self interest: in other words, the bottom line.

In the electricity sector, that bottom line comes down to the difference between the cost of generating electricity and its price. In the United States alone, we're aiming to replace about 1 terawatt of generation infrastructure over the next 40 years. This won't happen without a breakthrough energy technology that has a high profit margin. Subsidies may help at first, but only private sector involvement, with eager money-making investors, will lead to rapid adoption of a new technology. Each year's profits must be sufficient to keep investors happy while also financing the next year's capital investments. With exponential growth in deployment, businesses could be replacing 30 gigawatts of installed capacity annually by 2040.

While this energy revolution is taking place, another field needs to progress as well. As Hansen has shown, if all power plants and industrial facilities switch over to zero-carbon energy sources right now, we'll still be left with a ruinous amount of CO_2 in the atmosphere. It would take centuries for atmospheric levels to return to normal, which means centuries of warming and instability. To bring levels down below the safety threshold, Hansen's models show that we must not only cease emitting CO_2 as soon as possible but also actively remove the gas from the air and store the carbon in a stable form. Hansen suggests reforestation as a carbon sink. We're all for more trees, and we also exhort scientists and engineers to seek disruptive technologies in carbon storage.

Perhaps technology would change the **economic rules of the game** by producing not just electricity but also fertilizer, fuel, or desalinated water

INCREMENTAL IMPROVEMENTS to existing technologies aren't enough; we need something truly disruptive to reverse climate change. What, then, is the energy technology that can meet the challenging cost targets? How will we remove CO_2 from the air? We don't have the answers. Those technologies haven't been invented yet. However, we have a suggestion for how to foster innovation in the energy sector and allow for those breakthrough inventions.

Consider Google's approach to innovation, which is summed up in the 70-20-10 rule espoused by executive chairman Eric Schmidt. The approach suggests that 70 percent of employee time be spent working on core business tasks, 20 percent on side projects related to core business, and the final 10 percent on strange new ideas that have the potential to be truly disruptive.

Wouldn't it be great if governments and energy companies adopted a similar approach in their technology R&D investments? The result could be energy innovation at Google speed. Adopting the 70-20-10 rubric could lead to a portfolio of projects. The bulk of R&D resources could go to existing energy technologies that industry knows how to build and profitably deploy. These technologies probably won't save us, but they can reduce the scale of the problem that needs fixing. The next 20 percent could be dedicated to cutting-edge technologies that are on the path to economic viability. Most crucially, the final 10 percent could be dedicated to ideas that may seem crazy but might have huge impact. Our society needs to fund scientists and engineers to propose and test new ideas, fail quickly, and share what they learn. Today, the energy innovation cycle is measured in decades, in large part because so little money is spent on critical types of R&D.

We're not trying to predict the winning technology here, but its cost needs to be vastly lower than that of fossil energy systems. For one thing, a disruptive electricity generation system probably wouldn't boil water to spin a conventional steam turbine. These processes add capital and operating expenses, and it's hard to imagine how a new energy technology could perform them a lot more cheaply than an existing coal-fired power plant already does.

A disruptive fusion technology, for example, might skip the steam and produce high-energy charged particles that can be converted directly into electricity. For industrial facilities, maybe a cheaply synthesized form of methane could replace conventional natural gas. Or perhaps a technology would change the economic rules of the game by producing not just electricity but also fertilizer, fuel, or desalinated water. In carbon storage, bioengineers might create special-purpose crops to pull CO_2 out of the air and stash the carbon in the soil. There are, no doubt, all manner of unpredictable inventions that are possible, and many ways to bring our CO_2 levels down to Hansen's safety threshold if imagination, science, and engineering run wild.

We're glad that Google tried something ambitious with the RE<C initiative, and we're proud to have been part of the project. But with 20/20 hindsight, we see that it didn't go far enough, and that truly disruptive technologies are what our planet needs. To reverse climate change, our society requires something beyond today's renewable energy technologies. Fortunately, new discoveries are changing the way we think about physics, nanotechnology, and biology all the time. While humanity is currently on a trajectory to severe climate change, this disaster can be averted if researchers aim for goals that seem nearly impossible.

We're hopeful, because sometimes engineers and scientists do achieve the impossible. Consider the Apollo space program, which required outlandish inventions for the rockets that brought astronauts to the moon. MIT engineers constructed the lightweight and compact Apollo Guidance Computer, for example, using some of the first integrated circuits, and did this in the vacuum-tube era when computers filled rooms. Their achievements pushed computer science forward and helped create today's wonderful wired world. Now, R&D dollars must go to inventors who are tackling the daunting energy challenge so they can boldly try out their crazy ideas. We can't yet imagine which of these technologies will ultimately work and usher in a new era of prosperity—but the people of this prosperous future won't be able to imagine how we lived without them. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/renewable1214

The Long Road to Maxwell's Equations

HOW FOUR ENTHUSIASTS HELPED BRING THE THEORY OF ELECTROMAGNETISM TO LIGHT

ILLUSTRATION BY LORENZO PETRANTONI

BY JAMES C. RAUTIO

SHOULD YOU WISH TO PAY homage to the great physicist James Clerk Maxwell, you wouldn't lack for locales in which to do it. There's a memorial marker in London's Westminster Abbey, not far from Isaac Newton's grave. A magnificent statue was recently installed in Edinburgh, near his birthplace. Or you can pay your respects at his final resting place near Castle Douglas, in southwestern Scotland, a short distance from his beloved ancestral estate. They're fitting monuments to the person who developed the first unified theory of physics, who showed that electricity and magnetism are intimately connected.

But what these landmarks don't reflect is the fact that, at the time of Maxwell's death in 1879, his electromagnetic theory—which underpins so much of our modern technological world—was not yet on solid ground.

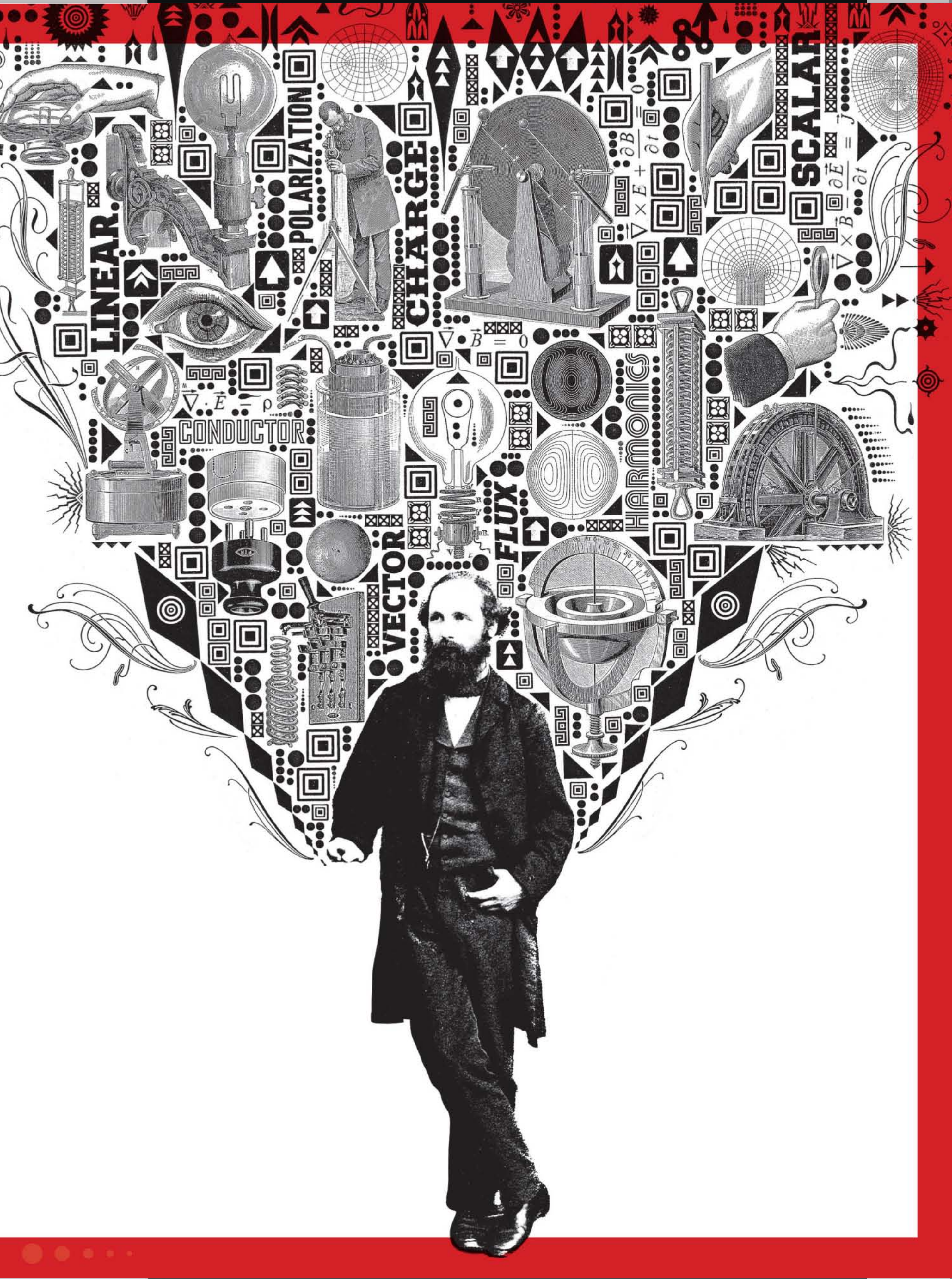
An extraordinary amount of information about the world—the basic rules by which light behaves, current flows, and magnetism functions—can be boiled down to four elegant equations. Today, these are known collectively as Maxwell's equations, and they can be found in just about every introductory engineering and physics textbook.

It could be argued that these equations got their start 150 years ago this month, when Maxwell presented his theory uniting electricity and magnetism before the Royal Society of London, publishing a full report the next year, in 1865. It was this work that set the stage for all the great accomplishments in physics, telecommunications, and electrical engineering that were to follow.

But there was a long gap between the presentation and the utilization. The mathematical and conceptual underpinnings of Maxwell's theory were so complicated and counterintuitive that his theory was largely neglected after it was first introduced.

It took nearly 25 years for a small group of physicists, themselves obsessed with the mysteries of electricity and magnetism, to put Maxwell's theory

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page


LINEAR
POLARIZATION
CHARGE
SCALAR
CONDUCTOR
HARMONICS
FLUX
VECTOR

on solid footing. They were the ones who gathered the experimental evidence needed to confirm that light is made up of electromagnetic waves. And they were the ones who gave his equations their present form. Without the Herculean efforts of this group of "Maxwellians," so named by historian Bruce J. Hunt, of the University of Texas at Austin, it might have taken decades more before our modern conception of electricity and magnetism was widely adopted. And that would have delayed all the incredible science and technology that was to follow.

TODAY, WE LEARN early on that visible light is just one chunk of the wide electromagnetic spectrum, whose radiation is made up of oscillating electric and magnetic fields. And we learn that electricity and magnetism are inextricably linked; a changing magnetic field creates an electric field, and current and changing electric fields give rise to magnetic fields.

We have Maxwell to thank for these basic insights. But they didn't occur to him suddenly and out of nowhere. The evidence he needed arrived in bits and pieces, over the course of more than 50 years.

You could start the clock in 1800, when physicist Alessandro Volta reported the invention of a battery, which allowed experimenters to begin working with continuous direct current. Some 20 years later, Hans Christian Ørsted obtained the first evidence of a link between electricity and magnetism, by demonstrating that the needle of a compass would move when brought close to a current-carrying wire. Soon after, André-Marie Ampère showed that two parallel current-carrying wires could be made to exhibit a mutual attraction or repulsion depending on the relative direction of the currents. And by the early 1830s, Michael Faraday had shown that just as electricity could influence the behavior of a magnet, a magnet could affect electricity, when he showed that drawing a magnet through a loop of wire could generate current.

These observations were piecemeal evidence of behavior that no one really understood in a systematic or comprehensive way. What was electric current really? How did a current-carrying wire reach out and twist a magnet? And how did a moving magnet create current?

A major seed was planted by Faraday, who envisioned a mysterious, invisible "electrotonic state" surrounding the magnet–what we would today call a field. He posited that changes in this electrotonic state are what cause electromagnetic phenomena. And Faraday hypothesized that light itself was an electromagnetic wave. But shaping these ideas into a complete theory was beyond his mathematical abilities. That was the state of affairs when Maxwell came on the scene.

In the 1850s, after graduating from the University of Cambridge, in England, Maxwell set about trying to make mathematical sense of Faraday's observations and theories. In his initial attempt, an 1855 paper called "On Faraday's Lines of Force," Maxwell devised a model by analogy, showing that equations that describe incompressible fluid flow could also be used to solve problems with unchanging electric or magnetic fields.

His work was interrupted by a flurry of distractions. He took a job in 1856 at Marischal College, in Aberdeen, Scotland; devoted several years to a mathematical study of the stability of the rings of Saturn; was laid off in a college merger in 1860; and contracted smallpox and nearly died before finally taking a new job, as a professor at King's College London.

Somehow, in all of this, Maxwell found the time to flesh out Faraday's field theory. Although not yet a complete theory of electromagnetism, a paper he published in several parts in 1861 and 1862 proved to be an important stepping-stone.

Building on previous ideas, Maxwell envisioned a kind of molecular medium in which magnetic fields are arrays of spinning vortices. Each of these vortices is surrounded by small particles of some form that help carry spin from one vortex to another. Although he later laid it aside, Maxwell found that this mechanical vision helped describe a range of electromagnetic phenomena. Perhaps most crucially, it laid the groundwork for a new physical concept: the displacement current.

Displacement current isn't really current. It's a way of describing how the change in electric field passing through a particular area can give rise to a magnetic field, just as a current does. In Maxwell's model, the displacement current arises when a change in electric field causes a momentary change in the position of the particles in the vortex medium. The movement of these particles generates a current.

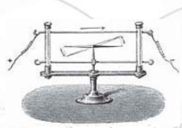
One of the most dramatic manifestations of displacement current is in the capacitor, where in some circuits the energy stored between two plates in a capacitor oscillates between high and

FROM LEFT: WIKIPEDIA (2); UNIVERSAL HISTORY ARCHIVE/GETTY IMAGES

Maxwellian

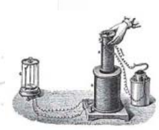
1785 CHARLES-AUGUSTIN DE COULOMB reports that the force between two charges varies with the inverse square of the distance.

1800 ALESSANDRO VOLTA invents the first battery, which allowed experimenters to begin working with continuous direct current.



1820 HANS CHRISTIAN ØRSTED shows that the needle of a compass can move when brought close to a current-carrying wire, the first evidence of a link between electricity and magnetism.

1820 ANDRÉ-MARIE AMPÈRE shows that two parallel current-carrying wires can attract or repel each other, depending on the relative direction of their currents.



1831 MICHAEL FARADAY, who conceived of electrical and magnetic fields, discovers electromagnetic induction.

1831 JAMES CLERK MAXWELL is born in Edinburgh.

1855 MAXWELL'S first paper on Faraday's observations and theories debuts.

1800 1810 1820 1830 1840

FOUR GOLDEN RULES

$$\nabla \cdot \mathrm{D} = \rho$$

$$\nabla \cdot \mathrm{B} = 0$$

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial t}$$

$$\nabla \times \mathrm{H} = \frac{\partial \mathrm{D}}{\partial t} + \mathrm{J}$$

Today, the relationship between electricity and magnetism, along with the wave nature of light and electromagnetic radiation in general, is encoded in the four "Maxwell's equations" shown at left. The equations can be written in different ways. Here, *J* is the current density. *E* and *B* are the electric and magnetic fields, respectively. And there are two other fields, the displacement field *D* and the magnetic field *H*. These fields are related to *E* and *B* by constants that reflect the nature of the medium that the fields pass through (the values of these constants in vacuum can be combined to give the speed of light). The displacement field *D* was one of Maxwell's key contributions, and the last equation describes how both current and changing electric fields can give rise to magnetic fields. The symbols at the beginning of each equation are differential operators. These compactly encode calculus that involves vectors, quantities that have a directionality and thus *x*, *y*, and *z* components. Maxwell's original formulation of his electromagnetic theory contained 20 equations.

low values. In this system, it's fairly easy to visualize how Maxwell's mechanical model would work. If the capacitor contains an insulating, dielectric material, you can think of the displacement current as arising from the movement of electrons that are bound to the nuclei of atoms. These swing back and forth from one side to another, as if attached to stretched rubber bands. But Maxwell's displacement current is more fundamental than that. It can arise in any medium, including the vacuum of space, where there are no electrons available to create a current. And just like a real current, it gives rise to a magnetic field.

With the addition of this concept, Maxwell had the basic elements he needed to link measurable circuit properties to two, now out-of-use, constants that express how readily electric and magnetic fields form in response to a voltage or a current. (Nowadays, we formulate these fundamental constants differently, as the permittivity and permeability of free space.)

Much as a spring constant determines how quickly a spring rebounds after it's stretched or compressed, these constants can be combined to determine how fast an electromagnetic wave travels in free space. After others had determined their values using experiments on capacitors and inductors, Maxwell was able to estimate the speed of an electromagnetic wave in vacuum. When he compared the value to existing estimates of the speed of light, he concluded from their near equality that light must be an electromagnetic wave.

MAXWELL COMPLETED the last key pieces of his electromagnetic theory in 1864, when he was 33 (although he made some simplifications in later work). In his 1864 talk and the paper that followed, he left the mechanical model behind but kept the concept of displacement current. Focusing on the mathematics, he described how electricity and magnetism are linked and how, once properly generated, they move in concert to make an electromagnetic wave.

This work is the foundation of our modern understanding of electromagnetism, and it provides physicists and engineers with all the tools they need to calculate the relationships among charges, electric fields, currents, and magnetic fields.

But what should have been a coup was actually met with extreme skepticism, even from Maxwell's closest colleagues. One of the most vocal skeptics was Sir William Thomson (later Lord Kelvin). A leader of the British scientific community at the time, Thomson simply didn't believe that such a thing as displacement current could exist.

His objection was a natural one. It was one thing to think of a displacement current in a dielectric filled with atoms. It was quite another to imagine it forming in the nothingness of a vacuum. Without a mechanical model to describe this environment and without actual moving electric charges, it wasn't clear what displacement current was or how it might arise. This lack of a physical mechanism was distasteful to many physicists in the Victorian era. Today, of course, we're willing to accept physical theories, such as quantum mechanics, that defy our everyday physical intuition, so long as they are mathematically rigorous and have great predictive power.

Maxwell's contemporaries perceived other big shortcomings in his theory. For example, Maxwell postulated that oscillating electric and magnetic fields together form waves, but he didn't

LEFT: POPPERFOTO/GETTY IMAGES; RIGHT: SSPL/GETTY IMAGES

Milestones

1864 MAXWELL presents new work before the Royal Society of London, published the next year. It suggests that electric and magnetic fields can move through space in waves and that light itself is such a wave.

1861 & 1862 MAXWELL publishes a four-part paper, "On Physical Lines of Force." It introduces the core idea that a change in electric flux through a surface can create a magnetic field.

1879 HEINRICH HERTZ'S interest in Maxwell's work is piqued by a Prussian Academy of Sciences competition to obtain experimental evidence for or against electromagnetic waves.

1873 MAXWELL publishes his magnum opus, *A Treatise on Electricity and Magnetism*, which contains further mathematical and interpretive work.

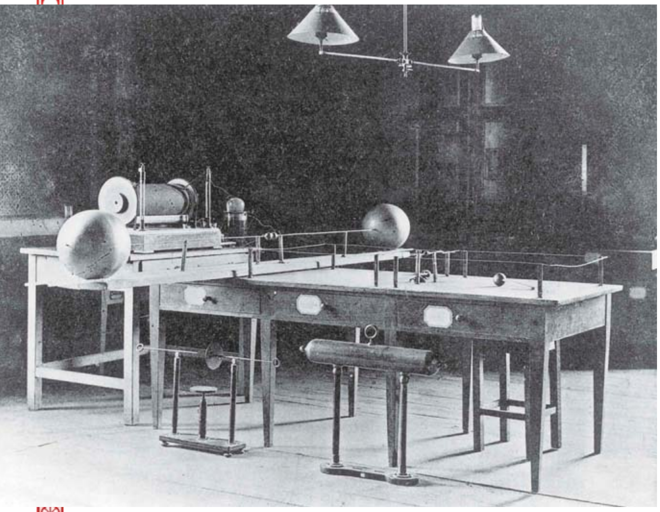
1879 MAXWELL dies of stomach cancer at age 48.

1885 OLIVER HEAVISIDE publishes a condensed version of Maxwell's equations, reducing the equation count from 20 to four.

1940 ALBERT EINSTEIN gives the term "Maxwell's equations" a boost with his monograph "Considerations Concerning the Fundaments of Theoretical Physics."

1888 HERTZ, several years after moving to a well-equipped laboratory in Karlsruhe, reports confirmation of the existence of the electromagnetic waves predicted by Maxwell.

1860 1870 1880 1890 1900



RADIO MAGIC: Heinrich Hertz used the coil [left] and the antennas [right] to produce and detect electromagnetic radiation outside the visible range.

describe how they move through space. All waves known at this time required a medium in which to travel. Sound waves travel in air and water. So if electromagnetic waves existed, physicists of the time reasoned, there must be a medium to carry them, even if that medium couldn't be seen, tasted, or touched.

Maxwell, too, believed in such a medium, or ether. He expected that it filled all of space and that electromagnetic behavior was the result of stresses, strains, and movements in this ether. But in 1865, and in his later two-volume *Treatise on Electricity and Magnetism*, Maxwell presented his equations without any mechanical model to justify how or why these mystical electromagnetic waves could possibly propagate. For many of his contemporaries, this lack of a model made Maxwell's theory seem grievously incomplete.

Perhaps most crucially, Maxwell's own description of his theory was stunningly complicated. College students may greet the four Maxwell's equations with terror, but Maxwell's formulation was far messier. To write the equations economically, we need mathematics that wasn't fully mature when Maxwell was conducting his work. Specifically, we need vector calculus, a way of compactly codifying the differential equations of vectors in three dimensions.

Maxwell's theory today can be summed up by four equations. But his formulation took the form of 20 simultaneous equations, with 20 variables. The dimensional components of his equations (the *x*, *y*, and *z* directions) had to be spelled out separately. And he employed some counterintuitive variables. Today, we are accustomed to thinking of and working with electric and magnetic fields. But Maxwell worked primarily with another kind of field, a quantity he called electromagnetic momentum, from which he would then calculate the electric and magnetic fields that Faraday first envisioned. Maxwell may have selected that name for the field—today known as magnetic vector potential—because its derivative with respect to time yields an electric force. But the potential does us no favors when it comes to calculating a lot of simple electromagnetic behavior at boundaries, such as how electromagnetic waves reflect off a conductive surface.

The net result of all of this complexity is that when Maxwell's theory made its debut, almost nobody was paying attention.

BUT A FEW PEOPLE WERE. And one of them was Oliver Heaviside. Once described by a friend as a "first rate oddity," Heaviside, who was raised in extreme poverty and was partially deaf, never attended university. Instead, he taught himself advanced science and mathematics.

Heaviside was in his early 20s and working as a telegrapher in Newcastle, in northeast England, when he obtained Maxwell's 1873 *Treatise*. "I saw that it was great, greater and greatest," he later wrote. "I was determined to master the book and set to work." The next year, he left his job and moved in with his parents to learn Maxwell.

It was Heaviside, working largely in seclusion, who put Maxwell's equations in their present form. In the summer of 1884, Heaviside was investigating how energy moved from place to place in an electrical circuit. Is that energy, he wondered, carried by the current in a wire or in the electromagnetic field surrounding it?

Heaviside ended up reproducing a result that had already been published by another British physicist, John Henry Poynting. But he kept pushing further, and in the process of working through the complicated vector calculus, he happened upon a way to reformulate Maxwell's score of equations into the four we use today.

The key was eliminating Maxwell's strange magnetic vector potential. "I never made any progress until I threw all the potentials overboard," Heaviside later said. The new formulation instead placed the electric and magnetic fields front and center.

One of the consequences of the work was that it exposed the beautiful symmetry in Maxwell's equations. One of the four equations describes how a changing magnetic field creates an electric field (Faraday's discovery), and another describes how a changing electric field creates a magnetic field (the famous displacement current, added by Maxwell).

This formulation also exposed a mystery. Electric charges, such as electrons and ions, have lines of electric field around them that radiate from the charge. But there is no source of magnetic field lines: In our known universe, magnetic field lines are always continuous loops, with no start or end.

This asymmetry troubled Heaviside, so he added a term representing a magnetic "charge," assuming that it had just not yet been discovered. And indeed it still hasn't. Physicists have since conducted extensive searches for such magnetic charges, also called magnetic monopoles. But they have never been found.

Still, magnetic current is a useful artifice for solving electromagnetic problems with some kinds of geometries, such as the behavior of radiation moving through a slit in a conductive sheet.

If Heaviside modified Maxwell's equations to this degree, why don't we call them Heaviside's equations? Heaviside answered this question himself in 1893

KARLSRUHE INSTITUTE OF TECHNOLOGY ARCHIVES

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

in the preface to the first volume of his three-volume publication, *Electromagnetic Theory*. He wrote that if we have good reason "to believe that he [Maxwell] would have admitted the necessity of change when pointed out to him, then I think the resulting modified theory may well be called Maxwell's."

MATHEMATICAL elegance was one thing. But finding experimental evidence for Maxwell's theory was something else. When Maxwell passed away in 1879, at age 48, his theory was still considered incomplete. There was no empirical evidence that light is composed of electromagnetic waves, aside from the fact that the speed of visible light and that of electromagnetic radiation seemed to match up. In addition, Maxwell did not specifically address many of the qualities electromagnetic radiation should have if it makes up light, namely behaviors like reflection and refraction.

Physicists George Francis FitzGerald and Oliver Lodge worked to strengthen the link to light. Proponents of Maxwell's 1873 *Treatise*, the pair met the year before Maxwell's death at a meeting of the British Association for the Advancement of Science in Dublin, and they began collaborating, largely through the exchange of letters. Their correspondence with each other and with Heaviside helped to advance the theoretical understanding of Maxwell's theory.

As historian Hunt outlines in his book, *The Maxwellians*, Lodge and FitzGerald also hoped to find experimental evidence to support the idea that light is an electromagnetic wave. But here they didn't have much success. In the late 1870s, Lodge developed some circuitry that he hoped would be capable of converting lower-frequency electricity into higher-frequency light, but the effort fizzled when Lodge and FitzGerald realized their schemes would create radiation of too low a frequency to be detected by eye.

Nearly a decade later, Lodge was performing experiments on lightning protection when he noticed that discharging capacitors along wires produced arcs. Curious, he changed the wire lengths and found that he could realize spectacular sparks. He correctly deduced that this was the action of an electromagnetic wave in resonance. He found that with enough power, he actually could see the air becoming ionized around the wires, a dramatic illustration of a standing wave.

Now confident that he was generating and detecting electromagnetic waves, Lodge planned to report his astounding results at a meeting of the British Association, right after he returned from a vacation in the Alps. But while reading a journal on the train out of Liverpool, he discovered he'd been scooped. In the July 1888 issue of *Annalen der Physik*, he found an article entitled "Über elektrodynamische Wellen im Luftraum und deren Reflexion" ("On electrodynamic waves in air and their reflection") written by a little-known German researcher, Heinrich Hertz.

POST YOUR COMMENTS at http://spectrum.ieee.org/maxwell1214

Hertz's experimental work on the subject began at the Technische Hochschule (now the Karlsruhe Institute of Technology) in Karlsruhe, Germany, in 1886. He noticed that something curious happened when he discharged a capacitor through a loop of wire. An identical loop a short distance away developed arcs across its unconnected terminals. Hertz recognized that the sparks in the unconnected loop were caused by the reception of electromagnetic waves that had been generated by the loop with the discharging capacitor.

Inspired, Hertz used sparks in such loops to detect unseen radio-frequency waves. He went on to conduct experiments to verify that electromagnetic waves exhibit lightlike behaviors of reflection, refraction, diffraction, and polarization. He performed a host of experiments both in free space and along wires. He molded a meter-long prism made of asphalt that was transparent to radio waves and used it to observe relatively large-scale examples of reflection and refraction. He launched radio waves toward a grid of parallel wires and showed that they would reflect or pass through the grid depending on the grid's orientation. This demonstrated that electromagnetic waves were transverse: They oscillate, just as light does, in a direction perpendicular to the direction of their propagation. Hertz also reflected radio waves off a large sheet of zinc, measuring the distance between canceled-out nulls in the resulting standing waves in order to determine their wavelengths.

With this data—along with the frequency of the radiation, which he calculated by measuring the capacitance and inductance of his circuitlike transmitting antenna—Hertz was able to calculate the speed of his invisible waves, which was quite close to that known for visible light.

Maxwell had postulated that light was an electromagnetic wave. Hertz showed that there was likely an entire universe of invisible electromagnetic waves that behave just as visible light does and that move through space at the same speed. This revelation was enough, by inference, for many to accept that light itself is an electromagnetic wave.

Lodge's disappointment at being scooped was more than compensated by the beauty and completeness of Hertz's work. Lodge and FitzGerald worked to popularize Hertz's findings, presenting them before the British Association. Almost immediately, Hertz's work went on to inform the development of wireless telegraphy. The earliest incarnations of the technology employed transmitters much like the broadband spark-gap devices Hertz used.

Eventually scientists accepted that waves could travel through nothing at all. And the concept of a field, at first distasteful because it lacked any mechanical parts to make it work, became central to much of modern physics.

There was much more to come. But even before the close of the 19th century, thanks to the dogged efforts of a few dedicated enthusiasts, Maxwell's legacy was secure. ■

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

A METAL MANICURE: The iHY hand picks up a ball bearing from a tabletop, using its "fingernails." These thin metal plates let it scoop small items off flat surfaces and form a cage to hold them.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

STARTING FROM SCRATCH: To develop a robotic gripper that can handle objects large and small, researchers at Harvard, Yale, and iRobot abandoned the familiar human hand, aiming to re-create its functions with a simpler design.

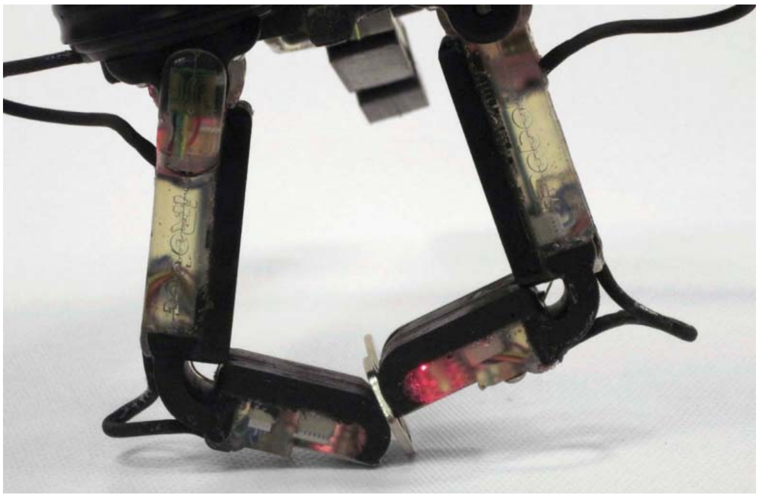
Robots Get a Grip

This inexpensive, rubber-jointed hand can pick up a telephone and use a drill

BY ROBERT HOWE, AARON DOLLAR & MARK CLAFFEE

ALL PHOTOGRAPHS BY iRobot

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®



THE HUMAN HAND is one of nature's marvels—and a stupendous challenge to engineers who would replicate it. It's an intricate assemblage with 29 flexible joints and thousands of specialized nerve endings, overseen by a control system so sensitive that it can instantly indicate how hot an object is, how smooth its surface is, and even how firmly it should be grasped.

No wonder, then, that creating robot hands with even a fraction of human capabilities has proved an elusive goal. But increasingly, researchers are concluding that copying nature is not the right approach in this case. The better idea is to decide which of the hand's critical functions are to be emulated and how this can best be accomplished with the technologies now available.

Industrial robots have, of course, been manipulating objects for decades. But these generally employ simple parallel-jaw grippers that open and close on command to grasp, hold, or move a single type of object that they've been specifically programmed to handle. That inflexibility isn't a problem on the assembly line, but it won't suffice for future robots designed to interact with people in a much less structured environment.

Like many robotics researchers, we envision a new generation of robots roaming around residences, nursing homes, factories, and the like. These machines will be called on to brew coffee, deliver medications, and shuttle components around a shop floor. These functions will in turn demand many smaller capabilities. For example, opening a jar will require a robot to identify the size and shape of the object, grasp it effectively on the first try, and then apply enough pressure and torque to open it—but not enough pressure to break it. To meet those needs, robot hands will need the flexibility to adapt to a huge variety of situations on the fly, as well as a gentler touch.

The quest for a versatile robot hand has produced designs that precisely mimic the human hand and others that look more like metal clamps. Two of us—Dollar at Yale and Howe at Harvard—have been working for almost a decade on a compromise between these two methods: hands that have some of the dexterity of human appendages but without their great complexity. The hands we've developed don't look human, but they have proved adept at gripping and manipulating a wide variety of objects in many different settings and tasks.

We got a chance to find out just how adept at a competition sponsored by the Defense Advanced Research Projects Agency (DARPA) not long ago—the Autonomous Robotic Manipulation program. Inspired by the success of the agency's Grand Challenge, which helped to spur innovation in the field of self-driving cars, DARPA asked teams to develop multifingered robotic hands that could complete a variety of tasks, like picking up a telephone handset or operating a power drill. After years of work, it was a chance for us, along with our colleagues at iRobot, to see how our design approach stacked up against those of other researchers.

SINCE THE 1980s, researchers have been able to produce robotic hands with three or four fingers and an opposable thumb, replicating the structure of the human hand. These hands had a futuristic, sci-fi look, and they attracted lots of attention, but most of them weren't very effective. Re-creating the many joints of the human hand increased the complexity and cost of anthropomorphic hands. It also introduced more chances for something to go wrong. Some examples had more than 30 motors, each of which powered a single joint and each of which could potentially fail. And having tactile sensors with limited sensitivity on every finger made it harder to coordinate a response between all the points of contact.

Underactuated hands are an alternative approach to robotic manipulation. They're called underactuated because they have fewer motors than joints. They use springs or mechanical linkages to connect rigid parts—such as the sections of a finger—and couple their motions. Careful design of these connections can allow the hand to automatically adapt to object shapes. This means the fingers can, for example, wrap themselves around an object without the need for active sensing and control.

We were pleased with our previous underactuated hand designs, but we knew we had plenty of work to do before our design could meet DARPA's specifications. And we had just 18 months to do it. The newly formed team took a fresh look at underactuated hand design with the specific challenges posed by DARPA in mind. How would we lift a thin object like a key off a tabletop? What would we need to do to turn on a flashlight? We reconsidered such fundamental aspects as the number of fingers, their placement around the base of the hand, and the grip the fingertips could provide.

We settled on a design that used two fingers and an opposable thumb. Those three digits were driven by a set of five motors, so the overall number of moving parts in the hand was relatively low. We dubbed our entry the iHY (pronounced "eye-high") hand, representing the three organizations involved in developing it: iRobot, based in Bedford, Mass., which oversaw the project as a whole, and Harvard and Yale universities, whose students and professors brought additional years of expertise in underactuated hand design.

Each digit of the iHY hand consisted of two links—a proximal link that connected the finger to the base of the hand and a distal link that extended to the fingertip. Those links were connected by a heavy-duty elastic joint that made the finger unit flexible, letting it bend on contact to match the shape of an object and form a grip around it, a technique known as passive adaptation.

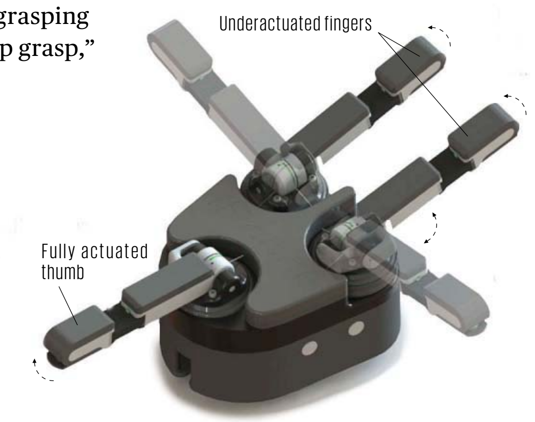
To give that grip power, we used cable "tendons" that ran from the tip of each finger to a motor in the base of the hand. When that motor pulled the tendons tight, the fingers went from being wrapped around an object to clutching it firmly. And because the initial grip was passive, nothing had to run in reverse to loosen it—letting the tendons go slack released our hand's grasp as its rubbery joints moved back into place on their own.

Because passive adaptation let the fingers of the iHY hand conform to the shape of the object it was grasping, we didn't need to control how they bent in the middle. One of the hand's three digits, though, not only had to grip objects but also manipulate them—to push the button on a flashlight, for example. To accomplish that, we needed to be able to control that digit at both joints.

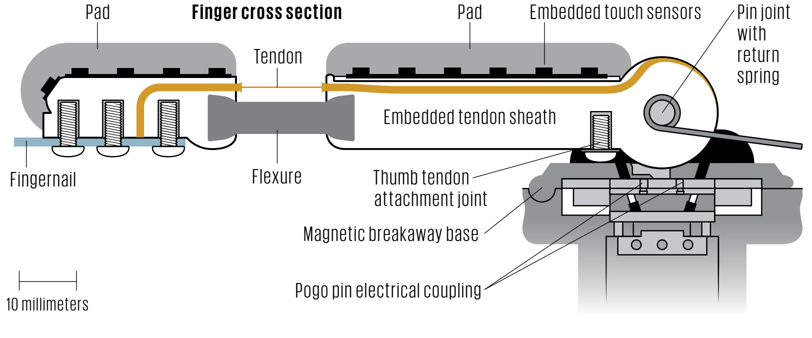
We decided to give the thumb two independently controllable joints. We did that by connecting both the upper and lower parts of the thumb to individual tendons, each driven by a separate motor. That way, we could manipulate the bottom part of the finger to place it above a button and then control the fingertip to make it push the button. That was a level of control not available in the two other fingers, where a single tendon was connected to a single motor, allowing the digit to apply pressure and form a tight grip around objects.

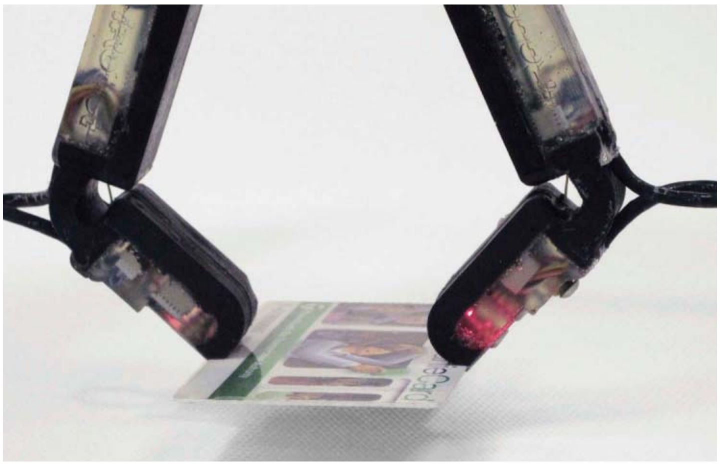
While four motors drove the three digits, a final motor allowed the fingers to move quickly between two configurations for different kinds of grasping motions. For a powerful "wrap grasp," the two fingers were set in parallel on one side of the hand with the thumb opposite them, interlacing to close the grip. This grasp, in effect, arranged all three digits into a cage around target objects before pulling tight around them. We could also perform "power grasps" by using all three fingers in a triangular formation to grip an object. This configuration enabled the iHY hand to grip large objects, like a basketball, firmly in its palm. Facing one another on either side of the hand, the two fingers closed in a "pinch grasp," which could pick up small items.

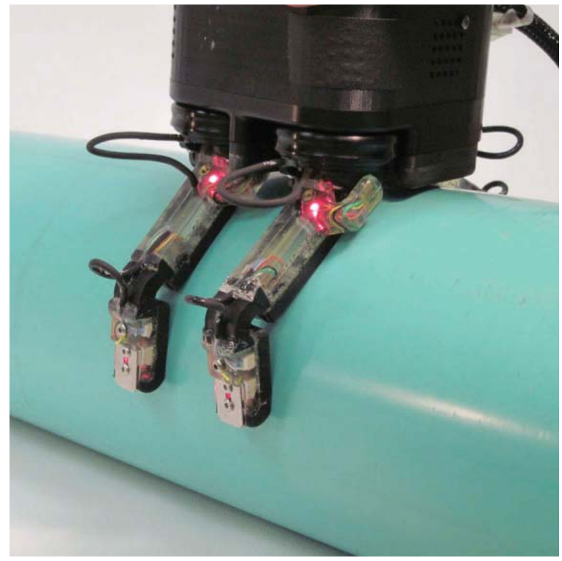
These different grasping motions helped us meet all the requirements of the DARPA competition. In its pinching configuration, the iHY hand could lift a key off a tabletop during the DARPA challenge. One of our Yale team members, Lael Odhner, developed a technique that let the hand squeeze objects into its grasp. For example, the hand put one finger behind the key, while the opposite finger moved toward it, flipping the object into its grip. To facilitate this pinch



FLEXING TO FIT: The rubber-jointed fingers of the iHY hand bend to match the shape of objects, gripping them without software controls. They also move into different configurations, depending on the size and shape of the object being held.







HOW MANY FINGERS? To pick up a small item like an ID card, the iHY hand uses a two-fingered "pinch grasp." For bigger jobs, like lifting a length of pipe, all three fingers of the hand wrap around the target object to form a more powerful grip.

grip, we added thin metal "fingernails" to each finger, which helped the hand keep its hold on small items.

The pinch grasp would have been useless for some of the challenges posed by DARPA, like using a hammer. To complete tasks like that, we used the wrap grasp, which let us lift and swing a hammer five times during the competition, taking an average of less than 15 seconds per swing.

Although team members Nicholas Corson and Mark Claffee operated the hand during the DARPA challenges, it would eventually need to be controlled by an autonomous robot. That meant developing sensors that could give the robot a sense of the shape, weight, and pliability of the object it was handling. These sensors give software designers the information they need to program robots that will one day control the hand independently. We used two kinds of sensors on the iHY hand—one that detected where an object made contact with the hand and another that monitored how the fingers moved around that object.

To track the motion of the fingers around their target, our Harvard colleague Leif Jentoft developed a set of fiber-optic sensors. These consisted of a loop of fiber-optic cable embedded in the rubber middle joint and a pair of photodiode receptors housed in each of the finger links. The fiber-optic cables emitted light that hit the receptors differently depending on how the joint was bent—for instance, when the joint was bent at a 60 degree angle, the fiber-optic light hit the receptors in a different place and with a different intensity than at a 75 degree angle. That data could eventually be used to map where each finger rested during a passive grasp.

To complement that information, we also installed arrays of pressure detectors. Harvard's Yaroslav Tenzer adapted these off-the-shelf sensors, originally designed for weather and GPS applications in smartphones, to act like the nerves in human skin. The sensors could tell if the hand was touching an object at the fingertip, the palm, or somewhere in between. Patterns in that information provided data about the shape of the object being grasped to the computer controlling the hand. For instance, the handle of a screwdriver would make contact with different sensors than a telephone handset would.

The pressure sensors also supplied data on an object's weight and the pliability of its surface, telling robots how tightly to grip an object. Heavy objects typically exert a lot of pressure and need a firm grasp, while those that offer less resistance require a lighter touch. Each of the fingers on the iHY hand housed 22 of these sensors, connected to printed-circuit boards and embedded in the rubber finger pads of the hand. Another 48 lined the palm of the hand.

Our iRobot colleagues developed the hardware and software that let us control the hand and relay information from it to a connected computer. Microcontrollers embedded in each digit collected data from the joint and touch sensors in the fingers and thumb and sent it to a controller in the palm. This controller acted as a sort of traffic cop for the whole hand, sending readings from the hand to the control computer via Ethernet and relaying commands from that computer to individual fingers. While this information wasn't used to control the hand during the competition, we provided visualizations of the information to demonstrate its sensing capabilities.

A HAND IS NOTHING without its fingers, and the iHY hand is no exception. To build the digits, we took inspiration from our Yale and Harvard colleagues, who had built robotic parts with electronic components already embedded in them for previous robotic hands. We created the individual parts using several different molds, first crafting the rubber finger joint with its embedded fiber-optic sensors. Then we placed the printed-circuit boards and pressure sensors of the fingers in a pair of molds and poured rubber over these components, creating soft pads for the fingers that housed the more fragile electronics. To strengthen the finger design, we molded rigid backing pieces that would act as the bones of the iHY fingers. We affixed these pieces to the rubber finger pads and placed them in a final mold, where the upper and lower pieces that would make up the finger were chemically bonded to the rubber joint. That result was a single, unified finger unit that housed all the electronics it needed to function.

The manufacturing method let us simplify our design. From an initial finger prototype composed of 60 different parts, we ended up with one made from just 12 parts. And by connecting the parts in a mold, we eliminated the need for small screws and other fasteners that can be points of failure in a robotic hand. Crafting the fingers from rubber and polyurethane also made for fingers that were sensitive to touch but could survive severe impacts, bending on impact rather than breaking.

We also used magnets to connect the finger units to the hand. This caused the fingers to separate entirely from the hand if they were in danger of becoming overloaded, instead of breaking in the middle. That way we could simply reattach the finger rather than having to replace a part. To test its durability, we brought the iHY prototype to a park and knocked a baseball out of its grip with a bat. The hand continued working after multiple strikes, demonstrating its durability and confirming its standing as the world's most advanced baseball tee.

Using common plastics and rubber to make our fingers and the molds to build them not only made them durable, it also kept costs down. That helped us stay close to DARPA's expectation that competitors produce a versatile robotic hand for around US $5,000—a fraction of the cost of models with comparable capabilities currently on the market.

ON THE DAY of the competition, in June 2012, the iHY hand outperformed all our expectations. The challenge, which took place in Arlington, Va., consisted of 19 tests—nine different objects the hand would have to grasp, nine it would have to grasp and then manipulate, and one test of the hand's pure strength—each performed five times to demonstrate that no performance was a fluke. Grasping such items as a ball, a canteen, and a telephone handset took us just seconds. Even manipulation tasks like drilling a hole in a wood block and activating a handheld radio were accomplished with ease. Perhaps most surprising was the strength test, where the iHY hand lifted and held a 22-kilogram weight—6 kg more than it had held in previous lab tests.

Though the challenges were scheduled to take all day, we finished with a couple of hours to spare. That let us show off some of the other capabilities of the hand, including ones we didn't know it had. In one impromptu test, an iRobot staffer placed a pair of tweezers and a thin straw on the test table, challenging us to pick up the tweezers with the iHY hand—and then pick up the straw using the tweezers. This was uncharted territory for the hand and its operators, but we did it in just one try.

While we were happy with our performance, DARPA had invited only one team at a time to compete, so we didn't know how we measured up against teams from SRI International (formerly known as the Stanford Research Institute) and Sandia National Laboratories. But a few weeks later, DARPA contacted us to let us know we had won the competition. Our victory meant that DARPA would continue using the iHY hand in future robotics competitions. Several teams of competitors in the DARPA Robotics Challenge, in which entrants design humanoid robots to respond to emergency situations, have used a version of the iHY hand. Attached to humanoid robot bodies like that of Boston Dynamics' Atlas, the iHY hand has been used in that competition to open doors and handle fire hoses, suggesting crisis response as one possible application for the iHY hand and its descendants.

Eventually, we hope to develop versions of the iHY hand for a variety of commercial purposes. But first, we hope that the low cost and high durability of the iHY hand will help to make hands like it a fixture in robotics research labs around the world. While there are many fine robot hands available, the expense of procuring one—and of repairing one if it is damaged during an experiment—can make researchers timid about how they use it, slowing the pace of research.

The iHY hand, however, is hard to break and inexpensive to replace if you do. That should make it less frightening for researchers to push its limits in the lab. And with a strong, capable hand easily accessible, other teams can concentrate their efforts on writing new control software or making iterative improvements to the hardware, rather than building new hands from scratch. Our research has already spun off into a company, RightHand Robotics, based in Cambridge, Mass. The company has just begun to ship the beta version of the ReFlex Hand, a direct descendant of the iHY hand designed for lab research.

As we develop the technology further, it's likely that the company will offer several different models of the hand to research teams, from basic, stripped-down versions to more complex models with full sensor suites. While we learned a lot about underactuated design during the competition, the design has plenty of room for improvement. By making the technology easily accessible to other teams of researchers and engineers, we think those improvements will come more quickly, not just to the hands we've worked on but to the field of robotic manipulation as a whole.

Considering the complexity of grasping, it's likely this design won't be the final word on robot hands. Just as the DARPA Robotics Challenge competitors have used hands we designed for some tasks as well as other hands—including those developed by Sandia—there is likely space for a number of hand designs, each with different capabilities and specifications. But as the field moves forward, we feel that offering our fellow researchers a simple, durable, and effective hand and inviting them to improve on it is a good place to start. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/robothand1214

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

THE WAX ROCKET

Paraffin-based fuels could allow safer, hybrid designs to rival the best liquid-fueled rockets

By **BRIAN J. CANTWELL** • Photo by **DAN SAELINGER**

SINCE SPACEFLIGHT BEGAN, there have been fewer than 5,500 launches into orbit, and only about 300 of those have carried astronauts. These endeavors have always been risky. Indeed, the failure rate for space launches over the past five decades has hovered around 8 percent. • Early aircraft were also subject to frequent accidents, but private industry invested billions in development, and these machines grew steadily safer over time. Without a mass market to drive a similar evolution, space travel has remained exceedingly dangerous. No wonder it still takes a good dollop of "the right stuff" to be an astronaut. • Soon, though, the advent of suborbital space tourism may finally do what decades of government-sponsored R&D could not. Companies such as Airbus Defence & Space, Armadillo Aerospace, Blue Origin, Virgin Galactic, and Xcor Aerospace are planning to offer suborbital flights for prices that ordinary people—or at least ordinary wealthy people—can afford.

PROP STYLIST: BIRTE VON KAMPEN

THE LOSS OF VIRGIN'S *SPACE-SHIPTWO*

and the death of one of its pilots during a test flight on 31 October are, however, sobering reminders of the challenges that remain. If space tourism nevertheless blossoms, the technology to reach space should become increasingly safe and reliable. This would benefit a variety of space-based applications, including communications, remote sensing, and scientific research.

But that's a big *if*. The well-known dangers of rocket propulsion arise simply because heaving thousands of kilograms into orbit is an extremely difficult job. Rockets must rapidly mix and react huge quantities of a fuel and an oxidizer in a combustion chamber to release enough energy each second to send prodigious amounts of hot gas flying out of the nozzle at high speed. The rocket's various components must endure extreme low and high temperatures as well as punishing levels of vibration and stress.

In liquid-fueled rockets, a malfunction that brings fuel and oxidizer together in an uncontrolled way or causes a loss of thrust after launch can create a massive explosion, destroying the vehicle and damaging the launchpad. Orbital Sciences Corp.'s Antares launch vehicle recently experienced just such a calamity.

Solid-propellant rockets have the fuel and oxidizer already mixed and held together in a polymer binder. That reduces complexity, but it doesn't eliminate the dangers: Cracks or imperfections in the solid fuel or its packaging can cause uncontrolled combustion and explosion, as tragically happened to the solid rocket boosters of the space shuttle *Challenger* in 1986 when an O-ring seal in the motor case failed.

Are there no safer alternatives? One under study is the hybrid rocket. Hybrid rocket motors store the oxidizer as a liquid and the fuel as a solid, a configuration that is mechanically simple and reduces the opportunity for chemical explosion, both in flight and during ground operations. That makes hybrids safer than solid-fueled rockets. Hybrids are also more flexible because the flow of oxidizer can be controlled, meaning that the thrust can be adjusted or even shut down and restarted during flight.

These advantages prompted the designers at Scaled Composites to select a hybrid rocket motor for *SpaceShipOne*, the vehicle that won the Ansari XPrize in 2004 when it traveled into space twice within the span of two weeks. This was the first hybrid rocket ever used in a crewed flight. The company's larger suborbital vehicle, *SpaceShipTwo*, also employs a hybrid rocket, which at the time of this writing did not appear to have caused October's tragic accident.

Although they might seem cutting edge, hybrid rockets have in fact been around since the 1930s, when the first examples were developed in the Soviet Union. While the basic concept has always been attractive from a safety standpoint, such rockets have never really caught on in the space industry. It's easy enough to understand why: Traditional hybrid rockets produce relatively meager thrust.

I and two colleagues, Arif Karabeyoglu and David Altman, are trying to eliminate that disadvantage through our research at Stanford University and at a small rocket-design company we founded in 1999.

JOSE STEVENS/SPG

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

TRIAL BY FIRE: A paraffin-fueled hybrid rocket motor undergoes testing in Butte, Mont. The oxidizer employed was liquid oxygen, although the author and his colleagues have also been testing a design that uses nitrous oxide in this role.

These efforts may one day allow hybrid rockets to become the design of choice for many different kinds of space vehicles, including those that require the best possible performance.

The fundamental innovation that could make this possible is a change in the composition of the solid fuel that's used. Instead of the usual rubbery polymer, we use ordinary paraffin wax. Yes, wax. So when some cocky space tourist of the future tries to imitate Mercury astronaut Alan Shepard by yelling "Light this candle!" at launch, it could turn out to be a very apt description.

THE OVERALL DESIGN of a hybrid rocket is quite simple. The solid fuel is built into the combustion chamber in the form of a cylinder with one or more channels hollowed out along its axis. Once the liquid oxidizer is released from its storage tank, it becomes a gas and flows through these openings. After ignition, combustion takes place between the oxidizing gas and material evaporating from the surface of the fuel that is exposed inside the channels. The hot, high-pressure gases that result flow out of a suitably designed nozzle, generating thrust.

The problem is that fuel. The heat inside the combustion chamber causes some fuel to vaporize, at which point it readily burns with the oxidizer. But despite the intense heat in the chamber, the polymeric fuels normally used in hybrid rockets vaporize slowly, making it very difficult to produce the large amount of thrust needed for a launch into space.

To compensate, designers often try to expand the surface area of the fuel that's exposed to combustion. That's easy enough—just increase the number of channels. This strategy works to some extent, but if taken too far it can make the mass of fuel look like a block of Swiss cheese and may cause the fuel to fracture as it burns away.

The synthetic-rubber fuel used in the motor for *SpaceShipOne* required four channels for combustion to produce the needed thrust, and that caused some difficulties. As the fuel was burned, these openings became larger and larger, and the walls of solid fuel between them shrank. Toward the end of a burn, the expanding holes made the solid fuel prone to breakage. Indeed, on at least one flight of *SpaceShipOne*, large chunks of solid fuel went flying out of the nozzle, causing intense shaking and reducing the rocket's performance—and making the pilot think at one point that the tail of his craft had blown off.

At Stanford, we have focused our research on ways to increase the thrust of hybrid rockets without adding these problematic extra channels. We first became interested in this challenge in the late 1990s, when the U.S. Air Force was studying some exotic cryogenic designs for hybrid rockets. One scheme would have swapped the roles of the fuel and oxidizer—its fuel was liquid hydrogen, which would flow over and burn with solid oxygen. While investigating this odd configuration, the Air Force also studied a different combination of cryogenic propellants: liquid oxygen and pentane, a hydrocarbon that's liquid at room temperature but in this application was frozen solid, using a bath of liquid nitrogen.

The Air Force researchers found to their amazement that solid pentane burns three or four times as fast as normal fuels. These researchers graciously shared their measurements with us, and after a careful analysis, we figured out why the pentane was burning so fast. It turns out that the fuel wasn't burning in the usual way. Rather, the heat of the combustion chamber caused a layer of liquid to form on the surface of the solid pentane. As oxidizer flowed over it, tiny droplets of liquid pentane would become entrained in the stream of gas, and the multitude of droplets offered an enormous amount of surface area for evaporation and burning.

Normal polymeric fuels also melt when they are exposed to hot combustion. But the resulting liquid is too viscous for droplets to form, so the amount of surface area over which evaporation and burning can occur is limited—hence the usual lack of oomph.

Our discovery that pentane produced tiny droplets and that they multiplied the burn rate a few times over was completely serendipitous—and very welcome. But frozen pentane itself didn't make for a promising fuel. After all, it wouldn't be practical to have to dip your rocket in a vat of liquid nitrogen before launch. So we started searching for something to replace frozen pentane.

We began by considering some other common hydrocarbons. Familiar examples include methane (one carbon atom per molecule), ethane (two carbons), and propane (three carbons). As the number of carbon atoms in each molecule increases, these substances become room-temperature liquids, such as pentane (five carbons), and eventually solids such as waxes and polyethylene, the material used to make milk jugs.

What we needed was something that would be solid at room temperature and produce a low-viscosity liquid when it melted. It would also have to be strong enough to withstand the high-temperature, high-pressure, high-vibration environment of a rocket motor's combustion chamber.

The trick was to pick a hydrocarbon molecule with the right molecular weight. At high molecular weights, the liquid form of the hydrocarbon would be too viscous for droplets to form readily. At low molecular weights, these hydrocarbons are either gases, liquids, or soft solids, much too weak to withstand the rigors of the rocket's combustion chamber. In between, though, are some Goldilocks substances with anywhere from 25 to 50 carbon atoms per molecule, which are robust enough structurally and, as anyone who has ever watched the top of a candle knows, produce low-viscosity liquids when they melt: paraffin waxes.

The kind of paraffin wax we use is sometimes called sculptor's wax or hurricane wax. It's surprisingly strong—something I can attest to firsthand, having had to use a sledgehammer on a few occasions to break it up and extract it from spent fuel cartridges.

Fabricating, handling, and transporting traditional solid-rocket propellants is usually very costly, but a paraffin-based fuel would be easy to deal with in all those regards. It would be nontoxic, and indeed, it wouldn't be hazardous at all. What's more, the complete combustion of this fuel with oxygen produces no pollutants. The by-products are simply carbon dioxide and water. A more benign, easier-to-use rocket fuel could hardly be imagined.

HOT AEROSOL SPRAY: Paraffin-based fuels give hybrid rockets more oomph, because the fuel that is exposed to combustion melts, atomizes, and becomes entrained in the flowing oxidizer [inset]. This enlarges the surface area over which the fuel can vaporize and react.

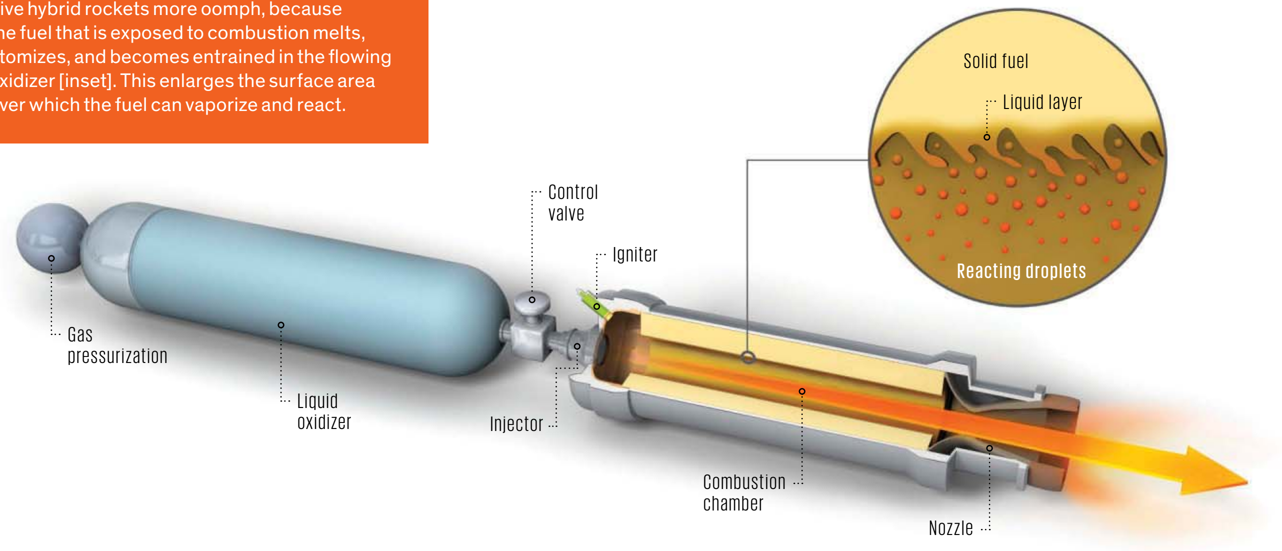


ILLUSTRATION BY Emily Cooper

WITH MOUNTING ENTHUSIASM for this novel fuel, we built a laboratory-scale hybrid rocket motor that could run off gaseous oxygen and several fuels, including paraffin wax. To our delight, we found that paraffin's operational characteristics matched our theoretical predictions: It burned significantly faster than conventional fuels (measured by how fast the surface of the fuel burns away), giving greater thrust.

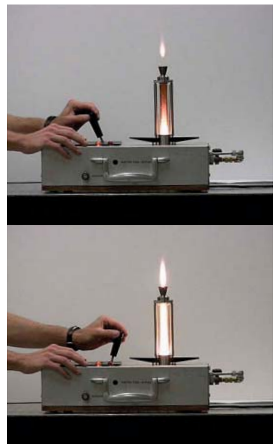
How well did it do? To appreciate the answer, you need to understand how rocket engineers measure performance. You can't use just thrust as your metric: A big rocket with poor performance could produce more thrust than a small one that performs very well. Instead, you need to evaluate thrust in a way that takes into account the amount of propellant used each second. Rocket designers do that with a quantity called specific impulse, which is directly proportional to the speed of the gas exiting the rocket nozzle. (The higher the speed, the better.)

An equally important parameter is the sheer mass of fuel that can be stored on board a motor of a given size. A high-density fuel helps, but that's not the only consideration. In particular, the extra combustion channels required to generate adequate thrust in traditional hybrid motors reduce the volume of fuel that can be stored. And not all that fuel can be burned anyway, because that would cause the walls of fuel separating the combustion channels to break up. Together, these constraints lead to a substantial loss of performance in traditional hybrids.

Our very first laboratory prototype, a tiny motor just 5 centimeters in diameter, burned fuel three to four times as fast as typical hybrid rocket motors. Having demonstrated that, we were convinced that a wax-based hybrid rocket requiring just a single channel for combustion could compete favorably with conventional solid or liquid systems.

To further test the feasibility of a wax rocket, we and our colleagues at NASA's Ames Research Center, in nearby Mountain View, Calif., soon built a motor five times as large, which operated with combustion-chamber pressures and fuel-consumption rates that were similar to those of rockets in commercial use. It, too, burned its fuel three to four times as fast as conventional hybrids.

To develop this technology for commercial use, we then formed a company called Space Propulsion Group, based in Palo Alto, Calif. Over the past eight years, our company has successfully conducted more than 40 test firings of a liquid-oxygen, paraffin-fueled hybrid motor that is 28 centimeters in diameter and produces 25,000 newtons of thrust. More recently, Space Propulsion Group has been testing a motor that is 56 cm in diameter, one capable of 100,000 newtons of thrust–enough to lift more than 10 metric tons. The result of all our trials–which at one point included a motor exploding–is that our designs are now very reliable and produce very high specific impulse.



LIGHT THIS CANDLE! The tabletop unit shown here is designed to demonstrate the basic concept of a hybrid rocket. It burns a transparent fuel, allowing the interior of the combustion chamber to be viewed.

BRIAN CANTWELL/SPG (2)

Over the same period, we have been working with Greg Zilliac at NASA Ames to develop a large, wax-based hybrid that uses nitrous oxide in place of liquid oxygen, an effort known as the Peregrine project. It has taken several years and a major motor failure to finally come up with a design that performs well.

These tests aren't just meant to show how big a motor we can make. We need them to achieve certain design goals whose success is hard to predict from theory. You see, hybrid rocket motors, while simple in principle, have some subtle complications in practice. In particular, they are subject to certain low-frequency instabilities, along with high-frequency instabilities common to all kinds of rockets.

Thanks to years of fine-tuning, the latest motor tests of Space Propulsion Group and NASA Ames have shown excellent stability. Despite this progress, the detailed physics of what goes on inside a hybrid rocket–combustion that is just as intense as that of any other kind of rocket–remain something of a mystery, which is why we continue to perform lots of experiments.

How good could such hybrid rockets get? Russia's kerosene-fueled RD-180, which powers the Atlas V launch vehicle, is the gold standard for heavy lifting today. With enough investment, hybrid motors could be developed that would approach that engine's impressive specific impulse at a fraction of the cost.

THE HYBRID-ROCKET CONCEPT is now more than 80 years old. For most of that time the idea has languished, but in the last decade there have been important technical advances and growing interest around the world. Research into hybrid rockets is now going on in Brazil, France, Germany, Israel, Italy, Japan, Norway, and South Korea. In the United States, such work is taking place at the Aerospace Corp., in El Segundo, Calif., as well as at NASA, Penn State, Purdue, and of course, at Space Propulsion Group and Stanford, where my colleagues and I have been working.

So there's every reason to expect that hybrid-rocket technology will continue to improve in coming years. Perhaps paraffin-based fuels and other refinements to this old concept will eventually bring the long-sought improvements in safety, cost, and performance needed to support routine access to space. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/waxrocket1214

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

Faculty Positions in Electrical Engineering 2014–15

King Abdullah University of Science and Technology (KAUST) is an international graduate-level research university located on the shores of the Red Sea in Saudi Arabia. With a student body representing over 70 nations, the University attracts world-class faculty and top international scientists, engineers and students to conduct fundamental and goal-oriented research to address the world's pressing scientific and technological challenges. The University's facilities and state-of-the-art technology offer an ideal setting in which to study and conduct high-impact research. KAUST offers generous assured research funding and internationally attractive salaries. For further information, please visit: www.kaust.edu.sa.

The Electrical Engineering (EE) program at KAUST currently has 17 full-time faculty and is recognized for its vibrant research programs and collaborative environment. EE research is strongly supported by KAUST's international research collaboration networks and the University's advanced research facilities, including the Nanofabrication, Imaging and Characterization, and Supercomputing Core Facilities. More information about the EE academic program and research activities is available at ee.kaust.edu.sa.

The EE Program invites applications for faculty positions at all ranks (Assistant, Associate, and Full Professor) beginning in the fall of 2015. Candidates at the rank of Assistant Professor should have an excellent potential for high impact research. Candidates at the ranks of Associate and Full Professor should have distinguished records in research and a strong commitment to service and teaching at the graduate level. Priority will be given to candidates with research interests in areas that may enhance and complement the existing research capabilities, including, but not limited to:

Power/Energy Systems: Specific expertise in the areas of smart grids, integration of renewable energy, monitoring and protection of power systems, energy storage and generation, power economics, and efficient power transmission, distribution, and management.

Power Electronics: Applicable for harsh environments (high temperatures and pressures), high voltage, power converters, power switches, RF power amplifiers, power inverters for electric vehicles, solar panels and wind, convertors for power grids, building applications, such as computer servers/data centers using conventional wide band gap semiconductors, and innovative usage of two dimensional atomic crystal structure materials.

Photonics/Electromagnetics: Experimental and/or computational photonics/electromagnetics, including the design, fabrication, and/or characterization of photonic and terahertz devices/systems for solid-state lighting, environmental sensing and monitoring, subsurface imaging for oil/gas reservoir monitoring and characterization, energy harvesting, and communication.

Cyber-Physical Systems: General background in control systems, real-time computing, and/or embedded systems with application to energy systems, smart grids, internet of things, transportation systems, environmental monitoring, and smart agriculture and food systems.

Digital Signal, Data, and Information Processing: Development of novel algorithms for large-scale information processing, big/high dimensional data analytics, statistical machine learning, internet of things, sensor systems, compressive sensing, distributed storage, secure transactions, and/or image processing.

Prospective candidates are advised to apply as soon as possible. Applications received by January 5, 2015 will receive full consideration and positions will remain open until filled. The application cycle will close on April 15, 2015. To apply, visit **http://apptrkr.com/528485**. All applications must be submitted through this site for consideration.

THE CHINESE UNIVERSITY OF HONG KONG

Applications are invited for:-

Department of Mechanical and Automation Engineering

(1) Professor
(Ref. 1415/103(370)/2)
Applications are invited for a Professorship in the undergraduate energy engineering programme launched in fall 2012, which is targeted to become full-fledged in four years' time. Further information about the Department is available at http://www.mae.cuhk.edu.hk. Applicants should have (i) a doctoral degree in a relevant engineering or scientific discipline related to energy technologies in the areas of renewable, environmental, power grid, and building automation and control; and (ii) recognized leadership in the academic discipline. The appointee will (a) teach and conduct research in his/her expert areas; (b) concurrently serve as the Programme Director; and (c) lead the development and promotion of the programme, staff recruitment and fostering of partnership with industries. Appointment will normally be made on contract basis for two to three years initially commencing August 2015 or earlier, which, subject to mutual agreement, may lead to longer-term appointment or substantiation later. Outstanding candidates with substantial experience for Professor rank may be considered for substantive appointment forthwith. Applications will be accepted until the post is filled.

(2) Professors / Associate Professors / Assistant Professors
(Ref. 1415/104(370)/2)
The Department is seeking excellent candidates to fill the above faculty positions in the following areas:

- Energy technologies, including energy management, smart metering and smart grid;
- Environmental engineering, including building automation and control, smart/green building; and
- Robotics and manufacturing, including 3D printing and CAD.

Applicants should have (i) a PhD degree; and (ii) a proven track record or demonstrating potential for teaching and research excellence. The appointees will (a) teach undergraduate and postgraduate courses; (b) develop an externally funded research programme; and (c) supervise postgraduate students. Appointments will normally be made on contract basis for up to three years initially commencing August 2015, which, subject to mutual agreement, may lead to longer-term appointment or substantiation later. Outstanding candidates with substantial experience for Professor rank may be considered for substantive appointment forthwith. Applications will be accepted until the posts are filled. Further information about the Department is available at http://www.mae.cuhk.edu.hk.

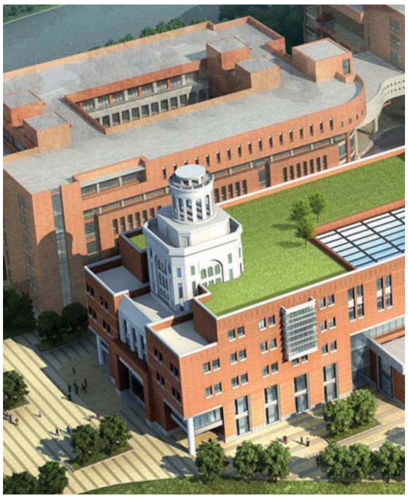
Salary and Fringe Benefits
Salary will be highly competitive, commensurate with qualifications and experience. The University offers a comprehensive fringe benefit package, including medical care, plus a contract-end gratuity for appointments of two years or longer, and housing benefits for eligible appointees. Further information about the University and the general terms of service for appointments is available at http://www.per.cuhk.edu.hk. The terms mentioned herein are for reference only and are subject to revision by the University.

Application Procedure
For post (1): Please send full resume, a cover letter describing how the applicant can bring significant value to the programme, and contact information of three professional referees, to the Dean, Faculty of Engineering by e-mail to energy-pd@erg.cuhk.edu.hk. The University reserves the right to fill the post by invitation. Review of applications begins immediately and will continue until the post is filled.

For post (2): Please send full resume, copies of academic credentials, publication list with abstracts of selected published papers, details of courses taught and evaluation results (if available), a research plan, a teaching statement, together with names, addresses and fax numbers/e-mail addresses of three to five referees to whom the applicants' consent has been given for their providing references (unless otherwise specified), to the Dean, Faculty of Engineering by e-mail to recruit@erg.cuhk.edu.hk.

The Personal Information Collection Statement will be provided upon request. Please quote the reference number and mark 'Application – Confidential' on cover.

Joint Institute of Engineering



FACULTY POSITIONS AVAILABLE IN ELECTRICAL/COMPUTER ENGINEERING

Sun Yat-sen University & Carnegie Mellon University are partnering to establish the **SYSU-CMU Joint Institute of Engineering (JIE)** to innovate engineering education in China and the world. The mission of the JIE is to nurture a passionate and collaborative global community and network of students, faculty and professionals working toward pushing the field of engineering forward through education and research in China and in the world.

JIE is seeking **full-time faculty** in all areas of electrical and computer engineering (ECE). Candidates should possess a doctoral degree in ECE or related disciplines, with a demonstrated record and potential for research, teaching and leadership. The position includes an initial year on the Pittsburgh campus of Carnegie Mellon University to establish educational and research collaborations before locating to Guangzhou, China.

This is a worldwide search open to qualified candidates of all nationalities, with an internationally competitive compensation package for all qualified candidates.

PLEASE VISIT: **jie.cmu.edu** for details

SHUNDE INTERNATIONAL

Joint Research Institute

RESEARCH STAFF POSITIONS AVAILABLE IN ELECTRICAL/COMPUTER ENGINEERING

SYSU-CMU Shunde International Joint Research Institute (JRI) is located in Shunde, Guangdong. Supported by the provincial government and industry, the JRI aims to bring in and form high-level teams of innovation, research and development, transfer research outcomes into products, develop advanced technology, promote industrial development and facilitate China's transition from labor intensive industries to technology intensive and creative industries.

The JRI is seeking **full-time research faculty** and **research staff** that have an interest in the industrialization of science research, which targets electrical and computer engineering or related areas.

Candidates with industrial experiences are preferred.

Applications should include a full CV, three to five professional references, a statement of research and teaching interests, and copies of up to five research papers.

Please submit the letters of reference and all above materials to the address below.

Application review will continue until the position is filled.

EMAIL APPLICATIONS OR QUESTIONS TO: **sdjri@mail.sysu.edu.cn**

SUN YAT-SEN UNIVERSITY Carnegie Mellon University

School of Electrical & Computer Engineering

College of Engineering

The University of Oklahoma
Assistant Professor of Electrical and Computer Engineering
in Phased Array Radar

As part of our Strategic Radar Initiative, the University of Oklahoma (OU) announces the search for a tenure-track Assistant Professor in the School of Electrical and Computer Engineering. Successful candidates must be visionary, collegial and energetic leaders in the design and development of high-performance phased array antennas and associated RF circuits, including transmit/receive modules, antenna elements, and control circuits/systems. Experience with overall system design, integration, test, and fielding of advanced phased array radars is highly desirable. A Ph.D. in Electrical Engineering or closely related field is required. Exceptional candidates with a record of professional achievement sufficient for tenured or tenure-track appointment at the rank of Associate Professor will also be given serious consideration. Successful candidates will be expected to rapidly establish a vibrant/vigorous externally funded research program and to have a strong commitment to graduate and undergraduate research and education.

The Radar Program. Through an alliance that spans several decades, the University and its Federal partners in the National Oceanic and Atmospheric Administration lead the world in the development, testing, operational deployment, and support of advanced weather radar systems. Principal capabilities range from design/prototyping of a variety of mobile radar systems, phased array technology, antenna design/applied electromagnetics, digital signal/array processing, automated algorithms, decision support tools, data assimilation, and end user training. New and continuing relationships with private companies worldwide and an aggressive expansion into defense-related radar fields are greatly enhancing this portfolio, with substantial increases in both Department of Defense and private sector sponsored research and development. Plans are currently underway for the development of an advanced, multi-function, digital polarimetric phased array radar which will push the limits of technology for weather, air surveillance and security applications. In the context of OU's Strategic Radar Initiative, OU President David L. Boren has built an interdisciplinary foundation of over a dozen new radar faculty members, state-of-the-art laboratory facilities, advanced radar testbeds, and the recently opened 35,000-sqft Radar Innovations Laboratory. The RIL supports the efforts of the Advanced Radar Research Center (ARRC **http://arrc.ou.edu**), which is one of the largest academic centers in the world focused on innovations in radar science and engineering.

Application Process. Confidential review of nominations, indications of interest, and applications will begin 1 December 2014 and continue until the position is filled. Candidates are invited to submit a letter of interest along with a statement of research goals and teaching philosophy, a detailed curriculum vitae, and the contact information of four professional references. Minorities and women are encouraged to apply. Electronic submission in PDF format is preferred, and all application information and inquiries should be directed to the search committee chair:

Dr. Robert D. Palmer, Associate Vice President for Research
University of Oklahoma
110 W Boyd St, Room 150
Norman, OK 73019
Voice: 405.325.6319
Email: radarsearch@ou.edu

The University of Oklahoma is an Affirmative Action/Equal Opportunity Employer and encourages diversity in the workplace. Protected veterans and individuals with disabilities are encouraged to apply.

NANYANG TECHNOLOGICAL UNIVERSITY

School of Electrical and Electronic Engineering

DISTINCTIVE LEADERSHIP AND RESEARCH OPPORTUNITY

with NTU Singapore

Tenured & Tenure-track Faculty Positions

Young and research-intensive, Nanyang Technological University (NTU Singapore) is the fastest-rising university in the world's Top 50 and ranked 39th globally. NTU is also placed 1st amongst the world's best young universities. The School of Electrical and Electronic Engineering (EEE) at NTU Singapore is one of the largest EEE schools in the world and ranks 10th in the field of Electrical & Electronic Engineering in the 2014 QS World University Rankings.

The School offers several tenured and tenure-track faculty positions. Join the School as a faculty member and embark on a challenging and exciting career in research innovations and discoveries and teaching excellence. Applicants should possess a PhD degree in Electrical Engineering or in a relevant discipline, with an outstanding scholarship record and a strong commitment to excellence in research and teaching.

Position 1: Tenured Full Professor in Power Electronics
Position 2: Tenured Full Professor in Satellite Engineering
Position 3: Tenure-track Associate Professor/Assistant Professor in Satellite Engineering
Position 4: Tenure-track Associate Professor/Assistant Professor in High Voltage Power Electronic Systems
Position 5: Tenure-track Assistant Professor in Power Systems
Position 6: Tenure-track Assistant Professor with Specialisation in Solar Energy
Position 7: Tenure-track Assistant Professor in Electrical Machines Analysis, Design and Applications

For job requirements, please visit: **http://www.eee.ntu.edu.sg/aboutus/CareerOpportunities/Faculty/Pages/Home.aspx**

Emoluments and General Terms & Conditions of Service
The commencing salary will depend on the candidate's qualifications, experience and the level of appointment offered. Information on emoluments and general terms and conditions of service is available in the section on Terms and Conditions of Service for Faculty Appointments **(http://www.ntu.edu.sg/ohr/CareerOpportunities/TermsandConditions/Pages/FacultyPositions.aspx).**

Application Procedure
To apply, please access **http://www.ntu.edu.sg/ohr/CareerOpportunities/Pages/index.aspx** and refer to the Guidelines for Submitting an Application for Faculty Appointment **(http://www.ntu.edu.sg/ohr/CareerOpportunities/SubmitanApplication/Pages/FacultyPositions.aspx).** Email your application including Personal Particular Form **(http://www3.ntu.edu.sg/hr/forms/Personal Particulars Form.doc)**, cover letter and a full CV to:

Chair, School of Electrical & Electronic Engineering
NANYANG TECHNOLOGICAL UNIVERSITY
50 Nanyang Avenue, Singapore 639798
E-mail: eeehr@ntu.edu.sg
Fax: (65) 6791-2687
Website: http://www.eee.ntu.edu.sg/Pages/Home.aspx

Electronic submission of applications is encouraged. Only short-listed candidates will be notified.
Application Deadline: Position is open until filled.

www.ntu.edu.sg

ShanghaiTech Faculty Search

ShanghaiTech University invites *highly qualified* candidates to fill multiple tenure-track/tenured faculty positions as its core team in the School of Information Science and Technology (SIST). Candidates should have exceptional academic records by international standards or demonstrate strong potential in cutting-edge research areas of information science and technology. English fluency is required and overseas academic experience is highly desired. ShanghaiTech aims to become a world-class research university for training future scientists, entrepreneurs, and technological leaders. Located in Zhangjiang High-Tech Park in the cosmopolitan Shanghai, we shall trail-blaze a new education system in China. Besides establishing and maintaining a world-class research profile, faculty candidates must also contribute substantially to graduate and undergraduate education.

Academic Disciplines:
We welcome candidates in all cutting edge areas of information science and technology. Our recruitment focus includes, but is not limited to: computer architecture and software, cloud and high performance computing, computational foundations, data mining and analysis, visualization, computer vision, machine learning, data sciences and statistics, IC designs, solid-state electronics, high speed and RF circuits, embedded systems, intelligent and signal processing systems, smart energy/power devices and systems, next-generation networking, control systems, robotics, sensor networks as well as inter-disciplinary areas involving information science and technology.

Compensation and Benefits:
Salary and startup funds are highly competitive, commensurate with experience and academic accomplishment. We also offer a comprehensive benefit package to employees and eligible dependents, including housing benefits. All regular faculty members will join our new tenure-track system commensurate with international practice for tenure evaluation and promotions.

Qualifications:
- A well articulated research plan and demonstrated record/potentials;
- Ph.D. (Electrical Engineering, Computer Engineering, Computer Science, Statistics, or related field);
- A minimum relevant research experience of 4 years.

Applications:
Submit (in English, PDF) *a cover letter, a 2-page research plan, a CV plus copies of 3 most significant publications, and names of three referees* to: ***sist@shanghaitech.edu.cn*** by December 31st, 2014 (or until positions are filled). *More information is at **http://www.shanghaitech.edu.cn**.*

THE CHINESE UNIVERSITY OF HONG KONG

Applications are invited for:-

Department of Computer Science and Engineering
Professors / Associate Professors / Assistant Professors
(Ref. 1415/078(370)/2)

The Department invites applications for Professorships / Associate Professorships / Assistant Professorships in computer engineering to pursue new strategic research initiatives, to fill faculty openings within current strengths and to teach in the new curriculum. The Department is looking for a leader and a couple of young and aspiring professors for added momentum to its Computer Engineering Programme, and in particular, talents in the following areas:

- *advanced architectural and 3D chip design for energy efficient computing; and*
- *hardware security for cloud computing.*

Applicants should have (i) a PhD degree; and (ii) a good scholarly record demonstrating potential for teaching and research excellence. The appointees will (a) teach both undergraduate and postgraduate courses; (b) develop a significant independent research programme with external funding; and (c) supervise postgraduate students. Appointments will normally be made on contract basis for two to three years initially commencing August 2015, which, subject to performance and mutual agreement, may lead to longer-term appointment or substantiation later. Applications will be accepted until the posts are filled.

Salary and Fringe Benefits
Salary will be highly competitive, commensurate with qualifications and experience. The University offers a comprehensive fringe benefit package, including medical care, plus a contract-end gratuity for appointments of two years or longer, and housing benefits for eligible appointees. Further information about the University and the general terms of service for appointments is available at http://www.per.cuhk.edu.hk. The terms mentioned herein are for reference only and are subject to revision by the University.

Application Procedure
Please send full resume, copies of academic credentials, publication list with abstracts of selected published papers, details of courses taught and evaluation results (if any), a research plan and a teaching statement, together with names of three to five referees to the Dean of Engineering by e-mail to recruit@erg.cuhk.edu.hk. Applicants should mark clearly the area(s) of their interests. The Personal Information Collection Statement will be provided upon request. Please quote the reference number and mark 'Application – Confidential' on cover.

BAYLOR UNIVERSITY

Faculty Positions

The Electrical and Computer Engineering Department of Baylor University seeks faculty applicants for three tenured/tenure-track Faculty Positions at all levels. Any area of expertise will be considered but applicants in computer engineering will be given special consideration. Applicants for assistant professor must demonstrate potential for sustained, funded scholarship and excellent teaching; applicants for associate or full professor must present evidence of achievement in research and teaching commensurate with the desired rank. The ECE department offers B.S., M.S., M.E. and Ph.D. degrees and is rapidly expanding its faculty size. Facilities include the Baylor Research and Innovation Collaborative (BRIC), a newly-established research park minutes from the main campus.

Chartered in 1845 by the Republic of Texas, Baylor University is the oldest university in Texas. Baylor has an enrollment of over 15,000 students and is a member of the Big XII Conference. Baylor's mission is to educate men and women for worldwide leadership and service by integrating academic excellence and Christian commitment within a caring community. The department seeks to hire faculty with an active Christian faith; applicants are encouraged to read about Baylor's vision for the integration of faith and learning at **www.baylor.edu/profuturis/**.

Applications received by **January 1, 2015** will be assured full consideration. Applications must include:

1) a letter of interest that identifies the applicant's anticipated rank,

2) a complete CV,

3) a concise statement of teaching and research interests,

4) the names and contact information for at least four professional references.

Additional information is available at www.ecs.baylor.edu. Send materials via email to Dr. Ian Gravagne at Ian_Gravagne@baylor.edu. Please combine all submitted material into a single pdf file.

Baylor University is affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Employment Opportunity employer, Baylor encourages candidates of the Christian faith who are minorities, women, veterans, and persons with disabilities to apply.

Faculty Positions in Computer Science

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

The Computer Science program at KAUST invites applications to faculty positions at all levels (Full, Associate and Assistant Professors) effective immediately. Areas of interest include:

- Big data and data analytics.
- Computer security.
- Data mining and machine learning.
- High performance computing.
- Operating systems and distributed systems.
- Scientific visualization.

A successful candidate must have a doctoral degree in Computer Science or related area. A strong record of publications in top conferences or journals is a must. Candidates applying for senior levels must have demonstrated strong leadership in the field and visibility as evidenced by top publications and active participation in research governance of top conferences and journals. Women are strongly encouraged to apply. Also of particular interest are interdisciplinary candidates who can open new areas of investigation.

KAUST is an international, graduate-only research university dedicated to the advancement of science and technology. Located on the shores of the red sea, it features world-class infrastructure and an attractive research funding model.

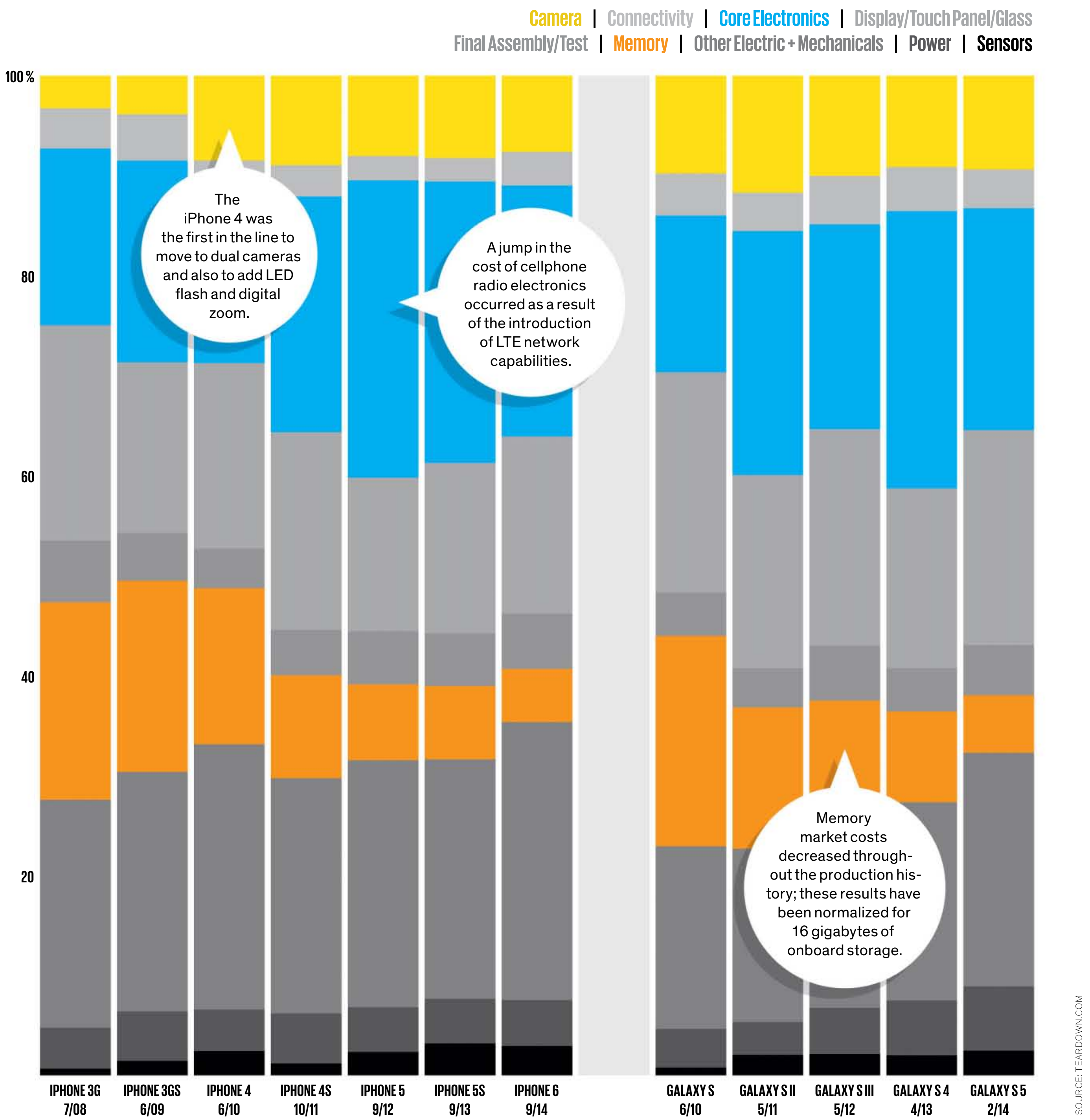
Please apply via **http://apptrkr.com/527428** employment site. Please include the names of three references for Assistant Professor positions and at least six for senior positions. Applications will be considered until the positions are filled but not later than April 15, 2015. Prospective candidates are advised to apply as soon as possible.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

DATAFLOW_

THE SMARTPHONE RECIPE
TEARDOWNS REVEAL MANUFACTURERS' PRIORITIES

Smartphones are complex devices. Their flexibility means that for every generation, manufacturers must make trade-offs that represent how they think they can best meet users' changing priorities at the lowest production cost. The charts below provide a breakdown of the portions of the total cost due to different components for Apple's iPhone and Samsung's Galaxy series of phones, provided by analysis company Teardown.com. These reveal both changes in the costs of underlying technologies and where manufacturers are investing in boosting the capabilities of their phones. For more details, including absolute costs, visit the interactive version of this article online. —SARAH LEWIN



INFOGRAPHIC BY Brandon Palacio