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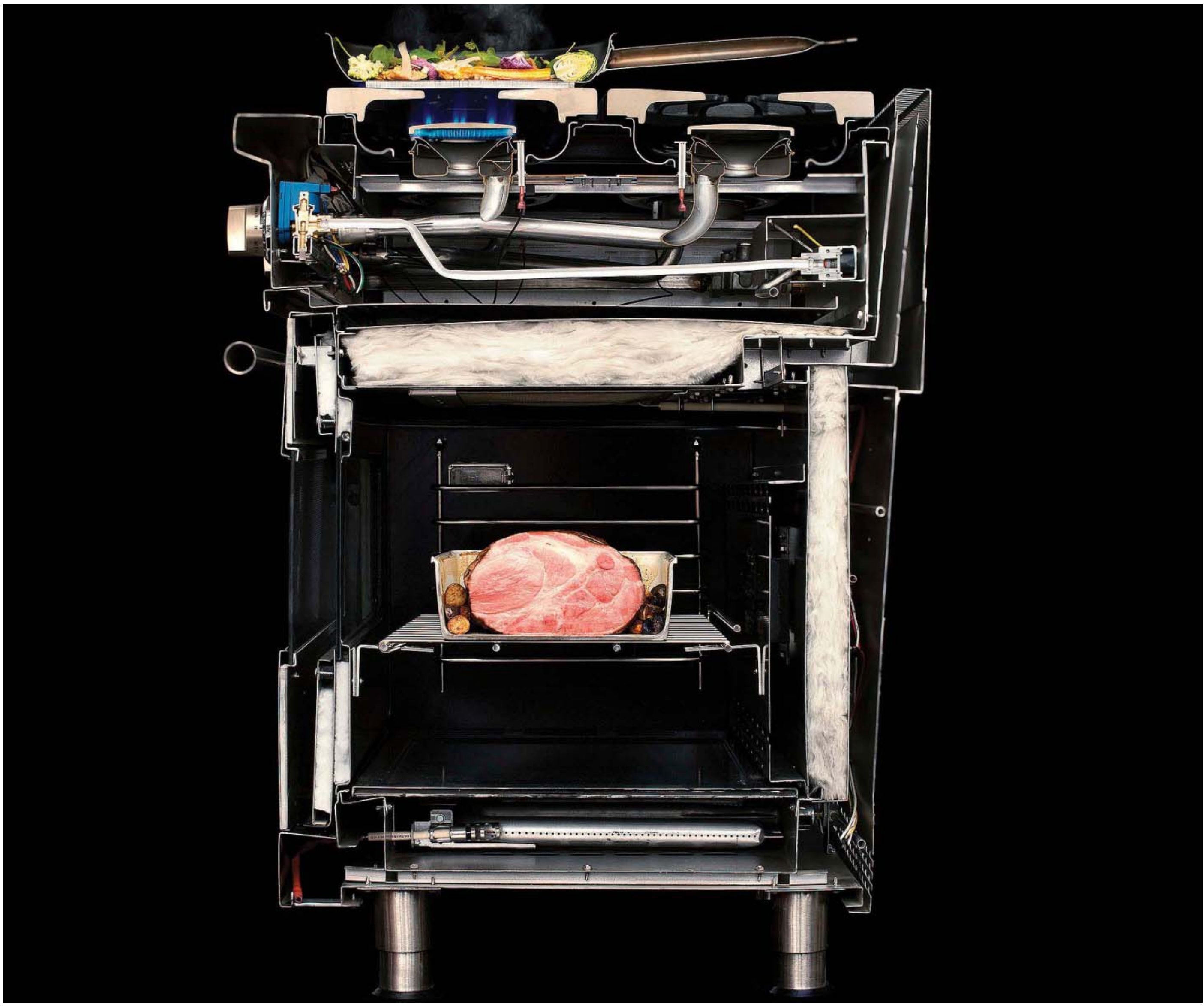

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RECIPE FOR A BETTER OVEN

The typical kitchen oven has a host of problems. But today we have the technology to solve all of them–if manufacturers would only use it.

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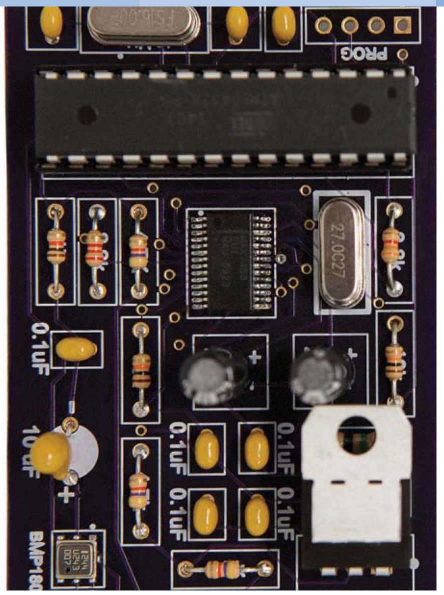

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Customize *IEEE Spectrum*'s list of the top programming languages with an interactive version. Filter results for different sectors, use presets to see what employers are looking for or what's generating buzz, or take complete control by adjusting the weight of every data source used to create the rankings.

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NEXT-GENERATION WIRELESS Today's wireless networks will be hard-pressed to accommodate the millions of machines that will be connected by the Internet of Things. That's why the IEEE Communications Society is helping to educate the industry and others about 5G. The fifth-generation network is expected to offer seamless communications between anybody, anywhere, at any time, by just about any wireless device.

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FROM LEFT: OXFORD UNIVERSITY; RANDI KLETT; IEEE SPECTRUM

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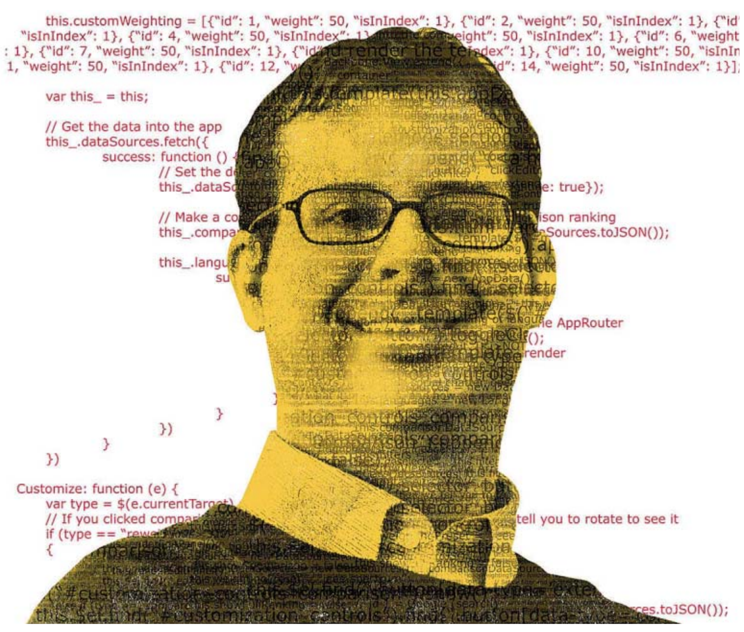
BACK STORY_



Building a Better Ranking

WHEN *IEEE SPECTRUM* wanted to update its 2011 list of the top 10 programming languages, Nick Diakopoulos was a natural choice for the project. Diakopoulos is a leader among the new breed of computational journalists. He couples a reporter's story sense with programming expertise in big data, visualization, and interactive technologies, and he is a fellow at the Columbia University Journalism School, in New York City.

Diakopoulos says the initial hurdle was just figuring out which programming-related data sources had useful information that could be extracted via an application programming interface, or API. "*Spectrum*'s editors and I came up with 10 to 15 sources; then I had to go through and figure out which ones were realistic," he says. The sources included Topsy's database of tweets, open-source repository GitHub, and the IEEE's own Xplore archive of technical papers.

Once the sources had been identified, Diakopoulos began working out how to combine the data from them and formulate rankings. "We let the notion of transparency guide the design, so that users could play with the weighting of the data sources to come up with their own rankings," he says. After about three iterations of the design, the result is the general-purpose ranking you see in Dataflow ("The Top 10 Programming Languages," in this issue). For the interactive application, go to the online version of the article. It lets you customize the ranking for your own particular interest, whether it's finding out what language skills are hot in the job market or which languages are dominant in the mobile sector. ■

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PHOTO-ILLUSTRATION BY **Gluekit**

07.14

CONTRIBUTORS_

Jonathan Schaeffer, Martin Müller & Akihiro Kishimoto

Schaeffer [left], a computer science professor at the University of Alberta, in Canada, had been creating game-playing artificial intelligence programs for 15 years when Müller [center] and Kishimoto [right] came to the university in 1999 as a professor and graduate student, respectively. Together they tried to crack the game of Go using methods discussed in their article "Go-bot, Go" [p. 42]. Kishimoto has since left for IBM Research–Ireland, but the work goes on—and Schaeffer now finds it plausible that a computer will beat Go's grand masters soon. "Ten years ago, I thought that wouldn't happen in my lifetime," he says.

Steven A. Johnson

Johnson, a performance scientist at Oracle/Sun Microsystems in Bloomfield, Colo., chronicles the ups and downs of owning a plug-in hybrid vehicle [p. 20], which he bought to use up the net-metering credits from his rooftop solar panels. "I looked into just about every form of electric vehicle: electric motorcycles, electric bicycles, even battery-laden skateboards," he says. "Given Colorado's winters, though, I concluded that something enclosed—a car, in other words—was the most practical."

Jin-Woo Han & Meyya Meyyappan

Han [left] and Meyyappan work at NASA Ames Research Center in Moffett Field, Calif., where Han is a research scientist and Meyyappan is chief scientist for exploration technology. The vacuum-channel transistors they describe in this issue ["The Device Made of Nothing," p. 24] grew out of an unrelated attempt to oxidize a single thin nanowire. "It ended up as two separate electrodes," says Han, who then realized that the botched experiment could be turned into a new kind of transistor.

Nathan Myhrvold & W. Wayt Gibbs

Myhrvold [left], founder of Intellectual Ventures and the Cooking Lab and former chief technology officer of Microsoft, cooked his family's Thanksgiving dinner at age 9. Myhrvold and freelance writer Gibbs have collaborated on two noteworthy culinary works: the six-volume *Modernist Cuisine: The Art and Science of Cooking* (2011) and *Modernist Cuisine at Home* (2012). In "Recipe for a Better Oven," in this issue [p. 30], they look at designing the perfect high-tech oven.

G. Pascal Zachary

Zachary is a former reporter for *The Wall Street Journal* and a professor at Arizona State University's Walter Cronkite School of Journalism and Mass Communication. In this issue, he explores the vexing question of why engineering has so few heroes [p. 36]. Zachary has the good fortune of living with one of his own heroes: his wife, Chizo Okon. "She's overcome adversity, she's courageous, and she accepts that people are imperfect," he says.

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PHOTO-ILLUSTRATIONS BY **Gluekit**

MOON SHOT: Buzz Aldrin, second man on the moon. There are few photographs of the first man, Neil Armstrong, because Armstrong held the camera for most of the Apollo 11 moonwalk.

The Fires of Apollo

IEEE SPECTRUM 1964 / 2014

FORTY-FIVE YEARS AGO THIS MONTH, Neil Armstrong became the first human being to walk on the moon. This was the crowning achievement of the Apollo program, the greatest technological adventure in history. From the launch of Sputnik in 1957 to the Apollo 11 mission in 1969, the world watched, enthralled, as the United States and the Soviet Union raced to be the first to land men on the moon.

And that space fever burned brightly at *IEEE Spectrum*. In the mid-'60s, we averaged about three space-related editorial items in each issue, along with countless references to space exploration in other articles. Items ranged from a short news brief about the difficulties of radio communication on the lunar surface to a long feature dissecting the telemetry and command system of the Mariner Mars probe. Wernher von Braun contributed an essay to our December 1965 issue that explained why it was "The Time for Space Exploration."

Spectrum had good reason for its enthusiasm: Many of its readers were at the forefront of answering President John F. Kennedy's challenge to land a man on the moon before 1970. *Spectrum* issues in those days bulged with recruitment ads for aerospace outfits like the Jet Propulsion Laboratory, Goodyear Aerospace, and the systems engineering division of Bellcom.

Those were heady times. A glorious spacefaring destiny seemed to await, and ideas that would have been considered outrageous science fiction a few years previously were given serious consideration in *Spectrum*, as in March 1966 with an 11-page article titled "Communication With Extraterrestrial Intelligence." An analysis of what form signals from an alien civilization might take and how we might decode them, this article wasn't the product of some fringe element. Rather, it was a condensation of presentations and a panel discussion organized by Harold Wooster, a director in the U.S. Air Force Office of Scientific Research, at the 1965 IEEE Military Electronics Conference. Participants included Lambros D. Callimahos of the National Security Agency and Father Francis J. Heyden, head of Georgetown

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, Senior Editor Stephen Cass recounts our coverage of the Apollo program.*

NASA

SPECTRAL LINES_

University's astronomy department. "We are not alone in the universe," declared Callimahos.

We also documented the birth of a slew of space technologies that would prove to be decades ahead of their time. For example, the May 1965 issue described a test model of an inflatable module intended for large space stations; not until 2006 would an actual inflatable space station module prototype reach orbit. Similarly, a January 1967 feature laid out the case for laser-based deep-space communications, but it wasn't until January 2013 that the first such transmission was successfully received.

> While the dazzle and spirit of the Apollo program are gone, the space business is fizzing again with technological ferment

All good things come to an end. After the United States won the moon race, interest waned and funding dwindled. Two months after the moon landing, Vice President Spiro Agnew's Space Task Group recommended the immediate development of a nuclear rocket engine; a series of space stations of increasing size; a reusable space shuttle; and an ambitious unmanned exploration program beyond the moon and Mars. But *Spectrum*'s editors sensed that the good times were over. "The electronics industry and others with a stake in space should be kept plenty busy...if President Nixon applies the necessary follow-through and Congress is agreeable," wrote *Spectrum* (and that skeptical ellipsis is in the original text).

By December 1970, slashed budgets had translated into an unemployment crisis; an article noted how the U.S. Department of Labor was trying to find aerospace engineers jobs in other fields. *Spectrum*'s space coverage shifted from preparations for permanent lunar outposts and Mars missions to communications satellites.

Though it ended in 1972, the Apollo lunar program will never be forgotten. Here at *Spectrum*, in 1994, we marked the 25th anniversary of the first moon landing with a comprehensive chronicle by contributing editor Dave Dooling. The supplement featured interviews with a who's who of the engineers who made it happen. In 2005, for the 35th anniversary of the Apollo 13 crisis, I interviewed many of the mission controllers who helped bring the crew home alive, and unearthed a few new details in a special report.

And while the dazzle and spirit of the Apollo program are gone, the space business is at last fizzing again with technological ferment. *Spectrum* associate editor Rachel Courtland and I find ourselves covering the advent of a new era in spaceflight. It's led by scrappy commercial newcomers like SpaceX, Virgin Galactic, and Skybox Imaging, and it's spurred on by competitions such as the Google Lunar X Prize. These ventures and contests are forging a new paradigm for space exploration. If it succeeds, we may get those moon bases and missions to Mars one day after all. —STEPHEN CASS

NEWS

387 TERAWATT-HOURS: ELECTRICITY EXCHANGED AMONG EUROPEAN COUNTRIES IN 2013

PLANET OBSERVER/UNIVERSAL IMAGES GROUP/GETTY IMAGES

AN ALGORITHM UNITES EUROPE'S ELECTRICAL FIEFDOMS

But a better alignment of markets and physics will be needed to expand the new electrical empire

Some six decades since Europe began to trade certain goods freely across its borders, electricity is finally joining the common market. In May, 16 countries, accounting for three-quarters of Europe's power consumption, completed the adoption of a common system for cross-border trading that is now setting wholesale electricity prices from Spain to Finland and from the United Kingdom to Austria.

Integrating the world's largest synchronized power grid is possible because of a sophisticated optimization algorithm for Europe's day-ahead power markets—the Pan-European Hybrid Electricity Market Integration Algorithm, or Euphemia. This algorithm crunches every buy and sell bid submitted to the participating national and regional power markets. It simultaneously allocates rights to transborder transmission and sets the power prices for each market, outputting a selection of trades for the following day.

Euphemia's goal is to maximize what economists call the "social welfare" of the region by maximizing the use of its most efficient power supplies and thus minimizing overall costs to consumers. »

NO BORDERS: Images from Landsat 5 and Landsat 7 show Europe's unified electrical landscape.

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"Where there are price differentials in neighboring markets, the process is designed to make sure there's full use of the transmission paths between them," says Mark Bartholomew, an energy market specialist with the Birmingham, England-based law firm SGH Martineau, which helped bring U.K. transmission operator National Grid into the scheme.

A consortium of power exchanges and transmission operators began building Euphemia in 2011. The optimization scheme is based on one implemented in 2010 to link the markets of Belgium, France, Germany, Luxembourg, and the Netherlands. Features were added to meet the unique requirements of new markets such as Spain, the U.K., and the Nordic countries. For example, Euphemia can enforce limits on how quickly power levels change on Scandinavian grids, in order to moderate frequency variation there.

Euphemia was built to meet the European Commission's goal of unifying all of Europe's power markets by 2015, and that unified market has huge growth potential. Just 11.5 percent of the 3,355 terawatt-hours of energy consumed in Europe last year crossed borders.

Euphemia should help boost trading volume. Under the old system, parties wishing to trade internationally had to seek out exchanges. And executing trades required separate transactions for energy and for transmission, so traders had to bid for power before securing the means to move it (or vice versa). Euphemia cuts through the complexity by pairing bids with international counterparts as its software sees fit. "The traders just buy and sell on their national exchanges in the regular way, and all of the cross-border things happen automatically," says Bartholomew.

The EC's vision is for this common system to absorb more markets until it covers all of Europe's cross-border trading. However, some countries concerned about the efficiency and safety of the system are holding out for upgrades that take better account of the physics of the transmission grid.

The problem is that real power flows pay no heed to markets and national borders. Consider Poland's dilemma. North-south flows within Germany and between Germany and Austria loop out across the Polish border and overload Poland's lines. The problem can extend onto other grids such as the Czech Republic's, and it's especially severe when Germany's northern wind farms are running full tilt.

Germany is planning internal high-voltage direct current (HVDC) lines whose controllability will help keep its flows on course [see "Germany Jump-starts the Supergrid," *IEEE Spectrum*, May 2013]. Regional transmission operators have also collaborated to use existing HVDC lines to combat the flows. Danish and Swedish operators help by using a pair of HVDC lines to push power clockwise around the Baltic Sea, an electrical twist that has the effect of pulling German power away from the Polish frontier.

Robert Poprocki, deputy director at the Warsaw-based PSE Operator, says this Baltic HVDC redispatching scheme pushed more than 120 gigawatt-hours of electricity around the Baltic last year, but it has not completely solved the problem. Still, the trick consumes no power and the benefits are cost-effective, says Poprocki.

PSE postponed the linking of its market with Germany and Austria over concerns that this would exacerbate the flows. But in April, the eastern European countries relented after gaining assurances from Germany and Austria that commercial power exchanges would be limited in some way to safeguard PSE's grid.

Transmission experts say a more radical reengineering of power markets will ultimately be needed, one that pays less heed to national borders. "Today the borders are drawn at the wrong places," says Alexander Wirth, a transmission expert with Swissgrid and operational manager of the Transmission System Operator Security Cooperation initiative.

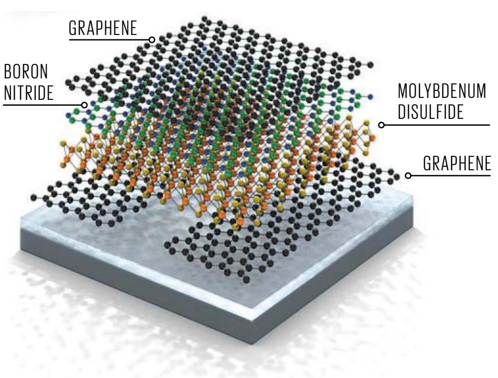
Rather than trading between countries, Wirth and other experts say, optimization schemes such as Euphemia should manage trading across the system's real transmission constraints. "Only 2 percent of congestion is located at borders," says Wirth.

Such a system implemented today would likely cut Germany in half and merge its halves with neighboring countries. It is also beyond what European states are ready to consider, Wirth says. That could take another decade. In the meantime, grid operators can look forward to same-day trades. Those will likely start testing by October.

—PETER FAIRLEY

THE FIRST 2-D TRANSISTORS

Researchers have built the first field-effect transistor (FET) made completely from 2-D materials. The work, published in the journal *ACS Nano*, could lead to transparent electronics and bright, ultrathin high-resolution displays.



Ali Javey and his colleagues at the University of California, Berkeley, used molybdenum disulfide, a semiconductor, for the transistor's channel region; hexagonal boron nitride for the insulating dielectric; and graphene to make the source, drain, and gate.

The device is an *n*-type FET, meaning that electrons flow through the channel. It's just a few atoms thick and has electron mobility as much as 30 times as high as that of the amorphous-silicon devices that drive displays. Mobility, a measure of how fast charges fly through the channel, dictates a transistor's switching speed and current. Faster transistors carrying more current could control smaller, brighter pixels.

But first, researchers will have to figure out how to make the 2-D materials on a large scale. Right now they must peel tiny flakes off of crystals by hand.

ILLUSTRATION BY Emily Cooper

MADS PERCH/GETTY IMAGES

SMARTPHONE APP KEEPS WATCH OVER SCHIZOPHRENIC PATIENTS

Monitoring behavioral patterns can predict a relapse

What if a schizophrenic patient could have the equivalent of a therapist in a pocket, watching for symptoms of a relapse? That's the promise of a smartphone-based system now being tested at a hospital in Glen Oaks, N.Y. The app, called CrossCheck, uses a suite of sensors to create a profile of a patient's healthy behavioral and social patterns and can then raise an alert when the patient deviates from the norm.

For a schizophrenic patient, a relapse is both damaging and demoralizing, says Dror Ben-Zeev, an assistant professor of psychiatry at Dartmouth College and the study's principal investigator. The patient can end up in jail or in the hospital, which disrupts therapies and normal routines.

The CrossCheck study will include 150 schizophrenic patients who have been discharged from Zucker Hillside Hospital, in Glen Oaks, within the past year. Half of those patients will receive smartphones with the app, while the other half, the control group, will receive the standard clinical services that the hospital provides after a patient is discharged. To see if the app leads to better outcomes, "we'll be looking at the time lag between when they're recruited and their first relapse, and also at the number of relapses they have over a year," Ben-Zeev explains.

Mobile health apps have the potential to change the management of chronic illnesses in general and may be particularly valuable for mental illnesses, says John Kane, chairman of psychiatry at the hospital. Kane says his patients come to the clinic about once a month, and in between those visits he has no way of knowing if they're sliding back into psychosis. "When they're having the relapse, they might not have the insight to call us and say, 'I think I'm becoming ill again,' " Kane says. "This technology lets us observe the patient's condition in real time."

CrossCheck ties together a number of data sets to create patient profiles. It uses GPS to create a map of patients' typical locations, and accelerometer data to determine when patients are walking, running, or sedentary. It uses the microphone to detect conversations that occur either over the phone or in person, and it records the duration and frequency of conversations (it doesn't record or analyze content). Finally, to discern sleep patterns, CrossCheck looks for times when the phone is stationary and not in use, and when light and sound sensors determine that the environment is dark and quiet. All this behavioral monitoring occurs in the background as patients go about their lives.

The patient's only active participation is filling out a brief questionnaire once a week, which asks about mood and symptoms. "When they indicate that things are going poorly, that they're feeling bad or not getting enough sleep, we mark that as a near-relapse event," explains Ben-Zeev. CrossCheck looks for behavioral markers

NEWS

associated with that event to create each patient's unique "relapse signature." Then, the next time CrossCheck detects that signature in the patient data, it sends out alerts: The patient is encouraged to get in touch with a doctor, and the study investigators at the hospital are notified that the patient may need help.

All this monitoring may seem intrusive and possibly alarming to patients who already have paranoid tendencies. "Part of the challenge with any kind of monitoring is making sure the patients understand why we're doing this," says Kane. He says the study will include an education component, in which investigators will present CrossCheck as a partnership between doctor and patient. "We're trying to work with them and help prevent them from going back into the hospital," he says.

Ben-Zeev has also developed an app called Focus, which gives schizophrenic patients a much more active role in managing the illness. That app's home screen lists categories such as "medication," "voices," and "social," and users can tap on whichever category they want help with. After they answer brief assessment questions, they receive either positive reinforcement or some friendly advice. For example, the social assessment might lead to the feedback "You can't control other people's behavior, only how you respond to it." That system is currently being tested in a multistate study that will conclude in 2016.

At Northwestern University's Center for Behavioral Intervention Technologies, assistant professor Stephen Schueller says he has evaluated a wide variety of apps intended to help patients cope with a mental illness. He's enthusiastic about apps like CrossCheck, which send smartphone data to health care providers. "When these things are embedded in the existing care relationship, then they hold a lot of potential," he says. In contrast, he says, those apps that are designed to let patients actively manage their own conditions aren't effective, because they're not downloaded often or used consistently. " 'If you build it, they will come' is not true at all," says Schueller.

—ELIZA STRICKLAND

OTHER MENTAL HEALTH APPS

A number of mental health researchers are experimenting with apps for psychological monitoring and intervention. Here are a few that are in the works.

PRIORI: Created by researchers at the University of Michigan, this smartphone app will attempt to spot the early signs of mood swings in people with bipolar disorder. So far researchers have trained the app to recognize manic and depressive moods by analyzing the user's voice, tracking pitch as well as patterns of speech and silence. The next iteration of Priori will use these subtle signals to prompt an intervention, such as a call from a therapist.

COMPANION: This app, created by the start-up Cogito, in Boston, analyzes both vocal characteristics and social behavior to detect symptoms of depression and post-traumatic stress disorder. The company was testing its app with Boston-area veterans at the time of the marathon bombing in 2013, and the researchers say the app did pick up signs of stress in the participants. Cogito is now working to commercialize the app and is preparing for a limited release in 2015, in cooperation with health care providers.

MOBILYZE: Northwestern University researchers are developing Mobilyze to help people with depression manage their illness. In a small pilot study, users "trained" the app by periodically rating their moods, which the app correlated with data based on GPS, accelerometer movement, and phone use. Mobilyze could then use that data to roughly predict users' moods. Researchers are now working on the next version of the app, which will use those predictions to trigger either statements of positive reinforcement or suggestions for mood-improving actions.

THE PEROVSKITE REVOLUTION

New crystal structures are energizing the photovoltaics world

Five years ago, a new photo-voltaic material made a rather low-key entrance on the solar power scene. Methylammonium lead tri-iodide belongs to a family of crystals known as perovskites, and a solar cell made from it converted light into electricity with an efficiency of just 3.8 percent—hardly likely to solve the world's energy troubles.

Fast forward to 2014 and perovskites are soaring higher than anyone could have hoped. At a Materials Research Society meeting in April, materials scientist Yang Yang at the University of California, Los Angeles, revealed that his lab had made a 19.3-percent-efficient perovskite cell—good enough to rival some commercial crystalline silicon solar cells, which typically notch up 17 to 23 percent efficiency.

"I don't know any group that works on photovoltaics that isn't looking at perovskites," says Henry Snaith, a physicist at the University of Oxford, in England, who is one of the leaders in the field.

The rapid rise of perovskites is unprecedented in solar photovoltaic research, where efficiencies usually inch upward over decades. And these new materials are poised to break out of the lab: Snaith's spin-off company, Oxford Photovoltaics, expects to have cells commercially available within four years.

Meanwhile, researchers are convinced that there is still plenty of room for improvement, predicting that perovskite cells will surpass 20 percent efficiency by the end of the year. "It's very hot, very competitive," says Mercouri Kanatzidis, a perovskite pioneer at Northwestern Univer-

PILES OF PEROVSKITES: The photovoltaic wunderkind's Achilles' heel is its lead content, but laboratories have found some success using tin instead.

sity, in Evanston, Ill. "The field has grown by leaps and bounds."

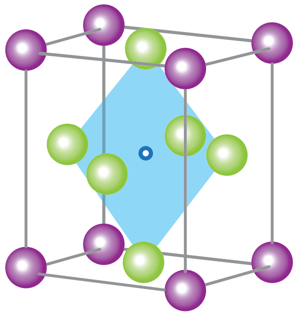
Solar cell manufacturers face a tricky trade-off between performance and cost. Most commercial solar cells rely on slabs of crystalline silicon that are more than 150 micrometers thick and take a lot of energy to produce. Thin-film solar cells–those containing just a few micrometers of such semiconductors as copper indium gallium selenide (CIGS)–have lower material costs, but they are also less efficient. Cells using crystalline gallium arsenide, on the other hand, can reach 30 percent, but the materials involved are too costly for utility-scale solar power.

Perovskites could resolve this quandary by matching the output of silicon cells at a lower price than that of thin-film CIGS: Their ingredients are cheap bulk chemicals, and the cells can be built using simple, low-cost processing techniques.

Perovskites made their debut in dye-sensitized solar cells. When light is absorbed by a dye in the cell, it injects excited electrons into a semiconductor such as titanium dioxide nanoparticles, which carry the charge away and ultimately generate current. Perovskites made attractive replacements for dyes because they absorb light efficiently over a broad spectrum, but researchers soon realized that they are also excellent charge carriers in their own right.

In 2013, Snaith unveiled a cell using a layer of perovskite without titanium dioxide nanoparticles, simplifying the cell's architecture and pushing its efficiency above 15 percent.

Since then, Sang Il Seok at the Korean Research Institute of Chemical Technology, in Daejeon, has refined the chemical reaction that forms the perovskite layer to smooth defects out of its structure, which pushed his cells' efficiency to 17.9 percent. And although Yang declined to discuss the technical details of his 19.3-percent cell, pending publication, other researchers say that removing defects was also crucial to his success. Further gains in performance could come from tweaking perovskites' chemical compositions to broaden the material's absorption spectrum. "Progress has been so fast," says Seok.



ABOUT FACE: Perovskites have a distinct structure, although their chemical compositions vary. In one photovoltaic crystal, lead [blue] lies at the center of the structure, with ammonia ions [purple] at the vertices and iodines at the center of each cubic face.

However, there are lingering concerns that a widespread use of lead-based cells could pose environmental problems, making investors somewhat wary of the technology. Snaith points out that annual lead emissions from coal combustion are 10 times as much as the amount of lead that would be needed for a 1-terawatt array of perovskite solar cells, but he acknowledges that "it would be better to have completely nontoxic materials."

In May, Snaith and Kanatzidis independently reported a possible solution: tin perovskites that managed 6 percent efficiencies. Although the tin perovskites are much less stable in air than their lead counterparts, both scientists are convinced that they have potential.

As competition in the lab grows ever more intense, a parallel commercial race is heating up. Oxford Photovoltaics is in the lead for now, but "a lot of other companies are starting to look at this," says Snaith.

Oxford is working with glass manufacturers to create photovoltaic glazing products. Windows coated with the company's perovskite have a gray tint and generate electricity with 6 to 8 percent efficiency. "That's more than adequate to meet builders' expectations," says Chris Case, Oxford's chief technical officer. It costs about 10 percent more than normal glass, and the electricity should pay back the cost of the windows within 10 years. The company expects the perovskite windows to be produced "in volume" by the end of 2017.

Oxford is also working on utility-scale products and investigating whether perovskites could be teamed with conventional silicon solar cells. The materials absorb different wavelengths of light, and perovskites generate a higher voltage than silicon, so using them in tandem would boost the power output of conventional cells.

The company has a development team of 24 people, backed by £7 million in financing. With perovskite efficiencies rising by the month, Oxford is now aiming to raise more money and expand. "It's not a cottage industry," says CEO Kevin Arthur. "We are going gangbusters on this." –MARK PEPLOW

TOP: UNIVERSITY OF OXFORD; BOTTOM: ERIK VRIELINK

NEWS

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NEWS

IN THE INTERCONNECTS: The demands of Moore's Law mean that copper wiring in advanced ICs is likely to form gaps when current flows through. Cobalt could keep that from happening.

COBALT COULD EASE CHIP-WIRING WOES

Adding another element to the chipmaking soup will keep superfine wiring from wandering

When it comes to talk of keeping Moore's Law on track, transistors seem to get all the attention. But the effort to boost the density of interconnect—the metal lines used to wire all those transistors together—is facing troubles of its own.

One of those is a simple matter of geometry: As the trenches used to make copper lines are made narrower, it becomes harder to lay down the metal without creating voids. Another problem is degradation. The smaller dimensions and higher densities of current that come with miniaturization speed up a process called electromigration: Current running down a line kicks copper atoms into the surrounding material, leaving what could become circuit-killing gaps.

Recently, Applied Materials, one of the leading manufacturers of tools for semiconductor fabs, came up with a new process that could address both problems. If adopted it would lead to the first big change in the materials used to make chip interconnects in 15 years, says Kavita Shah, global product manager of Applied's Metals Deposition Group.

The key, according to the company, is cobalt. A layer of the material a few nanometers thick could first be used to line the inner surfaces of trenches that are to be filled with copper, to help the material spread out more evenly. When a horizontal copper line is completed, cobalt can then be used to cap it to prevent electromigration. The company has already prepared chemical vapor deposition chambers to deposit the cobalt and has shipped them to customers to test.

Applied's process builds on the existing approach to making interconnects. First, trenches are carved into the chip-wiring layer's insulation. After they're lined with a layer of tantalum or tantalum nitride, the trenches are then filled with copper using an electrochemical process. This tantalum layer acts as a barrier to prevent the copper from diffusing its way out of the trenches.

Cobalt, along with other potential liner atoms such as ruthenium, might be good at getting copper to spread out, but it's not very effective at preventing diffusion, says Daniel Edelstein, an IBM Fellow at IBM's Thomas J. Watson Research Center, in Yorktown Heights, N.Y. This means that, at least for the moment, the tantalum has to stay, and the cobalt layer will take up some of the space in the trench that would otherwise have been used for copper. That may prove to be a hard trade for chipmakers to make. "We're at the point where every nanometer of barrier thickness raises the line resistance by 20 percent," says Edelstein.

Chipmakers will face another trade-off with the metal cap. A cobalt cap effectively shuts down copper migration, Edelstein says, but it adds extra risk to the manufacturing process, since a cap that spills over to a neighboring line can cause leakage or a short. Caps, albeit less effective ones, can currently be made in the same step as the copper lines, by filling trenches with a mix of copper and other metals such as aluminum and manganese. These other metals will eventually migrate up to form a cap at the top of the line.

Edelstein says that IBM, which collaborates with Applied on the cobalt technology, doesn't expect to need it for its 14-nanometer chips, the next generation down the line. But he adds that it will be important to have it when it's needed.

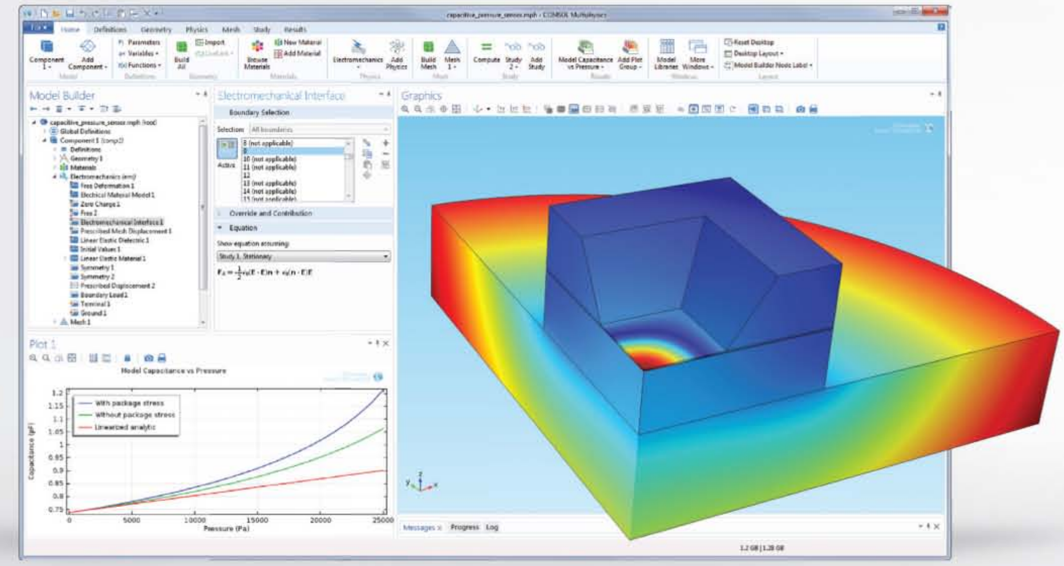
Should Applied's cobalt technology make it into mass production, it won't address another big problem: As interconnects shrink, their resistances shoot up and signal delays lengthen, sapping performance unless more energy is put toward driving signals. Little changes here and there, such as adding more metal layers with wider (and thus lower-resistance) lines, could help ease the problem, Edelstein says, although it will add to the cost of chips.

But for now, we're stuck on the copper path. No viable materials with resistivity below copper exist that could take its place, the International Technology Roadmap for Semiconductors determined last year. Exotic materials such as carbon nanotubes and graphene could offer some relief "in the next decade," the report says. In the meantime, we'll have to keep fighting for every small improvement we can. —RACHEL COURTLAND

A version of this article appeared online in May.

APPLIED MATERIALS

PRESSURE SENSOR: Model showing how the capacitance of a MEMS sensor changes due to temperature, pressure, and package stress.



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PHOTOGRAPH BY Imaginechina/AP Photo

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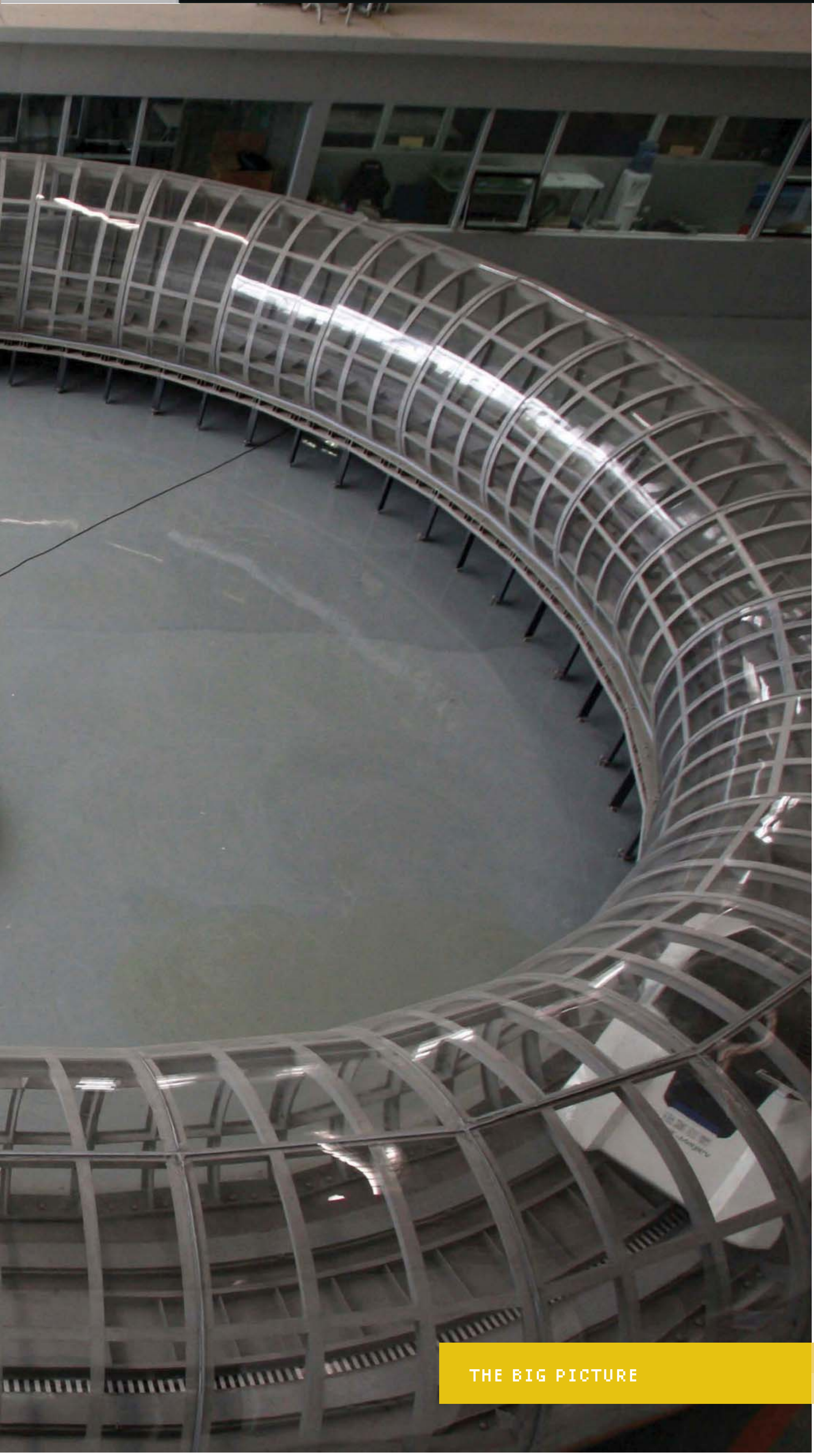


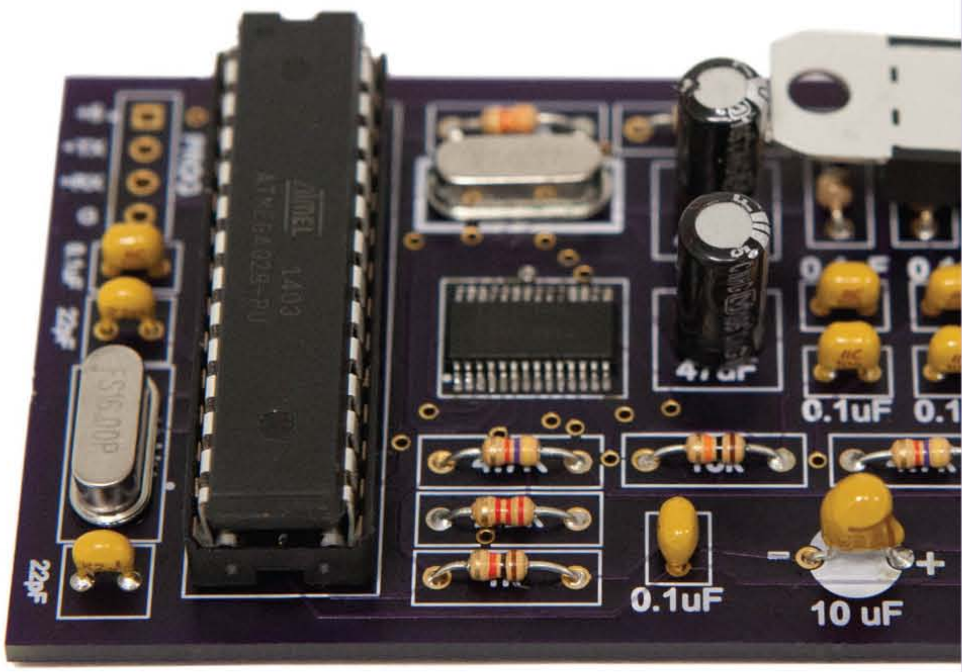
A SUPER CHUTE

THIS RING IS THE racetrack on which the future of ground transportation might be riding. Deng Zigang, a professor at Southwest Jiaotong University, in Chengdu, China, stands in the center of a prototype designed to test the latest turn in maglev (magnetic levitation) train technology. Right now, the best maglev trains reach speeds exceeding 400 kilometers (250 miles) per hour. Yeah, that's fast, but researchers like Deng are confident that the train cars, which are suspended above the tracks by powerful magnets, can go much faster. At these speeds, upwards of 80 percent of the energy meant to provide propulsive force is wasted battling air resistance. By placing a maglev train inside a vacuum tube, Deng says his team can virtually eliminate speed's enemy. At 10 percent of normal atmospheric pressure, such evacuated tube systems might allow maglev trains to rocket along guideways at 3,000 km (1,860 miles) per hour.

THE BIG PICTURE NEWS

RESOURCES

1936: PAUL EISLER INVENTS THE PRINTED-CIRCUIT BOARD. BY 2012, THE GLOBAL MARKET WAS ESTIMATED AT US $60 BILLION



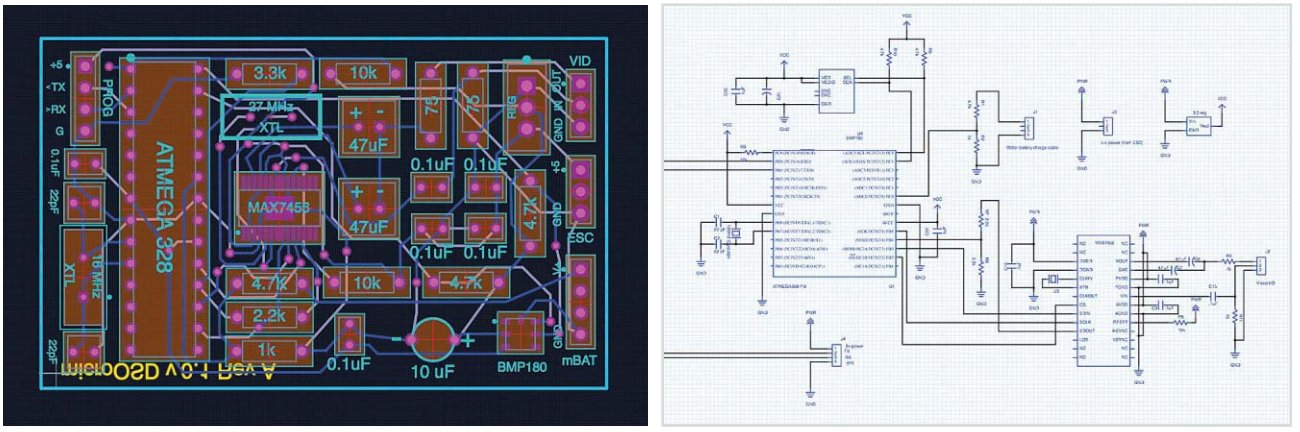
RANDI KLETT

CIRCUIT DESIGN COMES TO THE CLOUD

WEB-BASED ELECTRONIC-DESIGN TOOLS GAIN TRACTION

RESOURCES_HANDS ON

Suppose you want to create an electronic circuit and a corresponding printed-circuit board for it. What software will you use? Unless you already have a favorite, it might be hard to decide: There's a dizzying array of options, ranging from free software typically targeted at students and hobbyists to multithousand-dollar packages used by professionals. The possibilities have grown even wider recently with the addition of Web-based tools that allow you to edit schematic diagrams and lay out printed-circuit boards in a browser, without downloading and installing any software at all. ● If you weren't aware of these cloud-based electronic-design aids, your reaction might be similar to what mine was initially: incredulity. The disadvantages of using software that runs in the cloud are obvious enough. For one, you need to have a good Internet connection to get any work done. Of more concern, though, is the danger of being locked into a single software-as-a-service provider, especially if it experiences a prolonged outage, or worse, just ceases to exist. ● What then are the advantages? The main benefit is that these services promise to do for open-source hardware design what GitHub and the like have done for open-source software development: provide convenient central hubs for collaboration among strangers. And they offer the possibility of communal generation of Wikipedia-like electronic-component libraries, which would ease the burden of electronic design substantially. ● With such thoughts in mind, I examined four of these services: EasyEDA, PCBWeb, 123D Circuits, and Upverter. ● EasyEDA offers some pleasingly familiar part libraries—including ones from Sparkfun and Adafruit—which seemed attractive at first. But those libraries proved impossible to search. I couldn't even figure out how to specify that a resistor I was adding to my ▸



DEFT DESIGN: Upverter provides Web-based tools for editing schematic diagrams [right] and for laying out printed-circuit boards [left]—all at no cost for open-source projects.

DAVID SCHNEIDER (2)

circuit was a simple through-hole type. In desperation, I sought out a tutorial and found a few cryptic YouTube videos from EasyEDA with no narration at all. That was enough to steer me in other directions.

PCBWeb didn't offer much in the way of tutorials either, and its part library contained just a small number of generic components. Perhaps the service is just so intuitive, I thought in hopeful anticipation, that there's no real need for tutorials. Sad to say, that wasn't the case. And to the extent I could operate its schematic and PC-board editors, I found them to be really slow—an irritating reminder that the software was on some distant and rather pokey server.

123D Circuits (formerly Circuits.io, before it was purchased by Autodesk) works much better. Indeed, for my simple needs, its PC-board layout editor would probably do just fine. 123D Circuits' schematic editor was, however, a disappointment. After you specify a connection, the editor draws the corresponding line where it decides the line should go, and often its choices are just plain ugly. So I can't see how someone could create even a modestly pleasing schematic with it.

After such experiences, it came as a great relief to discover Toronto-based Upverter, a start-up that garnered support from the seed accelerator YCombinator in 2011. Upverter offers nice tutorials describing how to use its application, certainly enough to get somebody going. Its parts library is ample, if a little rough in terms of the quality of the information it contains at the moment. In any event, Upverter makes it very easy to jump to a given part's data sheet to figure out the ground truth—and it also allows you to quickly find vendors and to check the availability and prices of components.

Another pleasant discovery was that Upverter includes more than 500 open-source circuits from Sparkfun. There's no easy way yet to search this set for the particular circuit you're interested in. Still, this collection is a big plus for Upverter if you're a Sparkfun fan.

I especially liked Upverter's board-layout editor, which I found both intuitive and surprisingly responsive. Only rarely did I feel that I had to wait because of delays with Upverter's servers. That's not to say that the software is perfect by any means, but I suspect all layout editors have their quirks. And Upverter's price-value proposition is certainly good, the service being free for open-source circuits and boards, following the business model of places like GitHub, which charges only those who want to keep their work private. (The other Web-based electronic-design services generally do the same.)

Upverter also has integrated printed-circuit-board manufacturing, but I suspect this offering was slapped on as an experiment, because little information is provided to potential customers about the boards they'd be getting, and the prices aren't at all competitive. Upverter makes it easy enough, though, to export the needed files if you want to use another PC-board manufacturer, so this shortcoming isn't a significant drawback.

As a test, I designed a small board for an overlay display system for a first-person video project I'm working on. I exported the manufacturing files, and (after adjusting file names to accommodate the different naming conventions) had it fabricated through OSH Park. And I was delighted to see that the three boards I received 12 days later for US $7 each came out just fine.

Having said so many positive things about Upverter, I should also admit that I'm probably not ready to use it for more than an occasional experiment at this point. The worry that this start-up could suddenly disappear looms too large in my mind. But that concern would evaporate if there were an easy way to convert an Upverter project into a form that traditional electronic-design software like EAGLE or KiCad could import.

Upverter does provide open-source code that can translate schematic diagrams in this way, but translating board layouts so that they can be read and modified by other layout editors is not yet possible. Perhaps the programmers at Upverter—or other open-source developers—will tackle that job sometime soon. If so, I suspect many more people will start designing electronic circuitry using nothing more than a browser and a little help from their online friends.

—**DAVID SCHNEIDER**

TRANSATOMIC POWER
BUILDING A "WALK-AWAY SAFE" REACTOR

THE SALT SOLUTION: In Transatomic Power's reactor, molten salt containing radioactive material would circulate inside a reactor vessel [1]. The heat generated by the self-sustaining nuclear fission reaction would be transferred to circulating water [2], which would boil into steam [3] to power a turbine. Valves made of frozen salt [4] beneath the reactor vessel would be kept solid and closed by an electrical system. In the event of a power outage, the valves would melt, allowing the molten salt to drain into a wide tank [5], where the fission reaction would naturally come to a halt.

It's pretty straightforward to get some coders together in a spare room to create a software start-up. Should a nascent company have hardware inclinations, it might set out to make a consumer electronics gadget with an assist from Kickstarter. And then there's Transatomic Power Corp., of Cambridge, Mass., which is trying to build a nuclear reactor.

Cofounders Leslie Dewan and Mark Massie began dreaming up the idea in 2010, while working on their Ph.D.s in nuclear engineering at MIT. "We realized this is probably the smartest we will ever be in our lives," Dewan remembers. So the two decided to use their knowledge to design a better reactor, one that deals with what they see as the nuclear industry's biggest problems: waste and safety.

The design they came up with is a variant on the molten salt reactors first demonstrated in the 1950s. This type of reactor uses fuel dissolved in a liquid salt at a temperature of around 650 °C instead of the solid fuel rods found in today's conventional reactors. Improving on the 1950s design, Dewan and Massie's reactor could run on spent nuclear fuel, thus reducing the industry's nuclear waste problem. What's more, Dewan says, their reactor would be "walk-away safe," a key selling point in a post-Fukushima world. "If you don't have electric power, or if you don't have any operators on site, the reactor will just coast to a stop, and the salt will freeze solid in the course of a few hours," she says.

LESLIE DEWAN MARK MASSIE RUSS WILCOX

PHOTO-ILLUSTRATION: GLUEKIT

Dewan and Massie incorporated the company in April 2011, but they were still essentially just two grad students with a cool idea. Then, after their presentation at a TEDx meeting in November 2011, they met Russ Wilcox, the founder and former CEO of E Ink Corp. Having sold E Ink for US $215 million in 2009, Wilcox was looking for a new project, and he had reason to be receptive to Dewan and Massie's scheme for extrasafe nuclear power: He and his family had been at Tokyo Disneyland when the Fukushima disaster began, and he had gotten a dose of Japan's nuclear fear. Wilcox also thought it augured well for the technology when the TEDx attendees gave the talk a standing ovation, as nuclear projects often depend on public support. Soon the three decided to go into business together.

The team has raised about $1 million so far, much of that from friends, family, and angel investors who aren't expecting immediate returns; now they're looking for $15 million more to fund a series of lab experiments. Wilcox says this research will quickly reveal whether the reactor will work. "You want to start with the

ILLUSTRATION BY Emily Cooper

riskiest parts of your design and test those first," he says, adding that he learned that lesson while at E Ink. "Don't spend effort designing the box before you've built the product."

If those experiments reveal no showstoppers, Transatomic hopes to find industrial partners to help build a 5-megawatt demonstration plant at a U.S. national lab site. And if that demonstration is convincing, Dewan and Massie's reactor will be ready for full-scale commercialization. But Dewan says that's where the entrepreneurial ride will end. "We can't become the next Westinghouse," she says. "The goal is to demonstrate that this is a functional technology; then we would likely be subsumed by one of the industrial partners that funded us in the earlier phases."

According to Albert Machiels, an expert on advanced nuclear reactors at the Electric Power Research Institute, the industrial giants of the United States and the European nuclear industry are "not bullish" on advanced reactors. But the global market looks quite different, with countries such as China and India pursuing ambitious nuclear power policies. Machiels also notes that another interesting nuclear start-up, the Bill Gates–backed TerraPower, is cooperating with international organizations in China and elsewhere to develop its technology. If these start-ups can prove out their engineering and economics, they might find willing buyers for their intellectual property on other shores. **—ELIZA STRICKLAND**

Founded: April 2011 **Headquarters:** Cambridge, Mass. **Founders:** Leslie Dewan, Mark Massie, and Russ Wilcox **Funding:** US $1 million **Employees**: 3

RESOURCES_TOOLS

MY FIRST YEAR WITH A PLUG-IN HYBRID

THE FORD C-MAX ENERGI DOESN'T DISAPPOINT—BUT THAT RADIO!

STEVEN A. JOHNSON

IN AUGUST 2010, I WROTE FOR *IEEE SPECTRUM* ABOUT my first year with rooftop solar photovoltaics on my house in Boulder, Colo. After that article was published, I made a few energy-efficiency improvements, so my solar panels began producing 800 to 850 kilowatt-hours per year more than we needed. Selling that electricity back to the grid wasn't too lucrative, so in 2012 I decided to get some flavor of battery-powered car. ● I considered all-electric vehicles such as the Nissan Leaf, but I decided they would be impractical for long-distance road trips. The Chevy Volt plug-in hybrid, by contrast, seemed too pricey for a four-seater with a tiny trunk. I finally settled on the Ford C-Max Energi plug-in hybrid. The sales folks told me it would take about 7 kWh to fully charge the lithium-ion batteries—2 hours with a 240-volt charging station or 7 hours with the supplied 120-V charger. ● At Colorado electricity prices, it would cost US $0.77 per day to charge the car. Based on my driving habits, I created spreadsheets to calculate how much money I would save on fuel with the Energi compared with my 2005 Nissan Altima, which ran at 8.88 liters per 100 kilometers (26.5 miles per gallon). The estimated savings was $561 to $1,060 per year—only enough to cover a month or two of car loan payments, that is. Obviously, I couldn't justify the new car on fuel economy alone. Helping to tip the scales were some federal and state tax credits and a

FILL 'ER UP: During winters, the author [right] found that the Ford C-Max Energi's range suffered. During the day, he can top up the batteries at a charging station installed at his office [opposite page].

JOE WINGERD

discount purchasing plan that brought down the total cost of the car to $32,000. I also rationalized that just like my solar panels, the car would reduce my family's carbon footprint a little more.

Drivers can operate the Energi in one of three modes: EV Now (car uses batteries if possible), EV Later (car uses the gasoline engine), or Auto (car decides which mode to use).

I took delivery of the car a few weeks before Thanksgiving, just in time for a 2,900-km family trip. We left on a cold morning, and I was really hoping we would make it to Kansas City, Mo.—1,000 km away—on one tank. Early into the trip, it was clear that we didn't have a prayer. The batteries helped only for the first 30 km or so, and the engine wasn't as fuel efficient as I'd hoped. Our first tank returned 7.30 L/100 km (32.2 mpg). For the average car this is great efficiency, but for a plug-in it was well below expectations. Clearly, this hybrid did not like the interstate. Over our entire trip, we averaged 6.94 L/100 km (33.9 mpg). I was getting pretty depressed.

Back in Boulder, we started using the car for commuting to and from work. We plugged in every night and drove about 22 km each day. I dug out my Kill A Watt power meter to check how the car was charging. With the 120-V charger, the car took 8.18 kWh for a full overnight charge. After 21 days of commuting, our fuel efficiency hit 3.05 L/100 km (77 mpg)! However, as winter set in and we began to use the car's heater, the estimated battery power range would drop from 32 km to about 21. Owning a plug-in brings new meaning to the words "your mileage may vary."

By far the biggest disappointment has been the Sync entertainment system, a partnership between Ford and Microsoft. The result is dreadful. The simple act of playing the radio has been turned into a high-tech mess. The display on the screen is unreliable: Sometimes it shows buttons labeled with our preprogrammed stations; at other times the buttons are blank. The media input menu occasionally disappears. The clock randomly scrambles the hours and minutes. I could go on.

One thing Ford did get right is providing feedback to the driver. With my old Volkswagen Beetle, the only way to measure fuel consumption is with the odometer and a gas station receipt. The Energi measures just about everything: distance traveled, distance traveled in EV mode, fuel consumed per trip, kilowatt-hours consumed, range added from regenerative braking, and even my "brake score" (how well I did braking and getting the energy into the batteries). From this feedback I can see, for example, that routes with significant uphill sections result in worse fuel efficiency than flat routes.

Over the year, we did not achieve the fuel economies I had modeled with my spreadsheet. Two factors hurt my estimate: Highway fuel efficiency was 20 percent lower than the official U.S. Environmental Protection Agency figure, and cold weather with the heater active reduced the range by 35 percent [see the table, "A Year's Worth of Driving Data," for my overall results].

A Year's Worth of Driving Data

Total distance	26,131 km
EV-only distance	14,352 km
Regenerative braking distance	809 km
Average charge	6 kWh
Electricity used for charging	1,734 kWh
Electricity cost	US $191
Fuel used	1,132 L
Fuel cost	$1,041
Fuel efficiency	4.34 L/100 km (54.24 mpg)

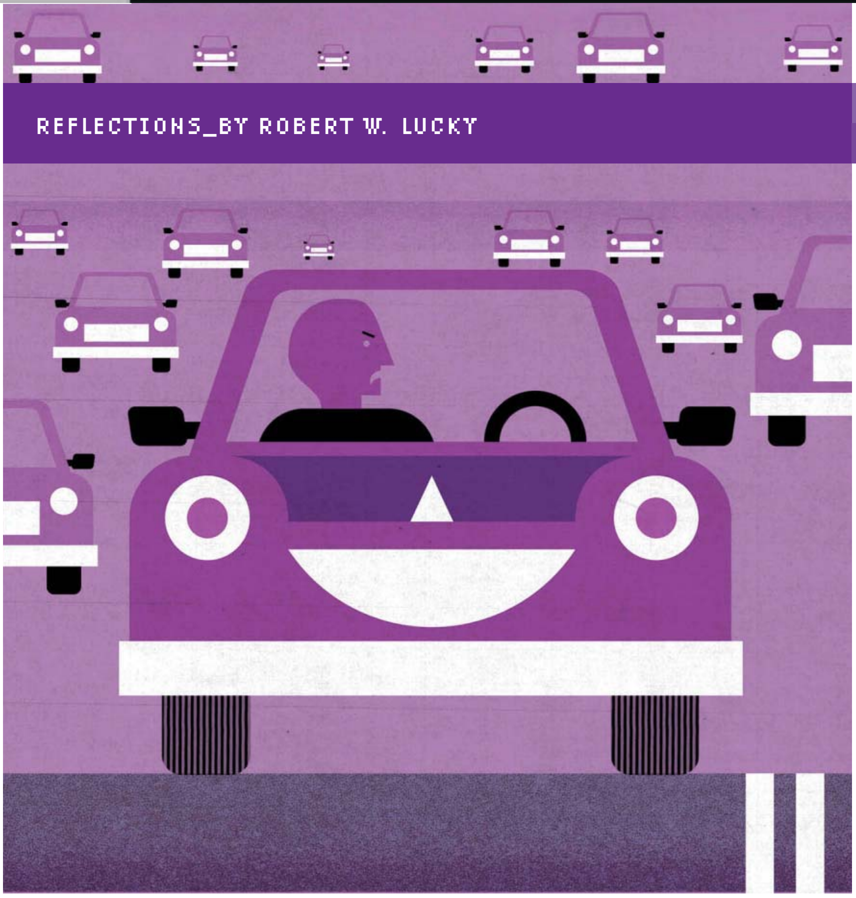
Thanks to my house's solar panels, my electricity was free, making the cost per kilometer around $0.040, compared with my Nissan Altima's $0.082/km. Not quite the savings I had estimated, but a good improvement. In addition, my office has put a charging station in the parking lot, which could potentially let me run a year on the same tank.

One interesting issue with driving an electric car is how quiet it is. It's nearly impossible to tell from noise or vibration when the engine starts and stops: Only if you accelerate hard and rev the engine can you hear it labor. Driving around a parking lot, for instance, I frequently find myself creeping along behind pedestrians who are oblivious to the car's presence. The U.S. government has been talking about requiring EV cars to produce a sound, which makes sense. But what kind of sound? I'd love to have the sound be programmable—I can just imagine my car mooing its way through the parking lot. And a traffic jam of EVs sounding like a herd of cattle would be really funny.

It makes little sense to use a plug-in to tow a boat or a heavy trailer. But plug-ins shine in short-distance commuting. In the C-Max Energi, I think Ford has built a practical family car with decent EV range.

—STEVEN A. JOHNSON

Read an extended version of this article online at http://spectrum.ieee.org/phev0714



THE DRIVE FOR DRIVERLESS CARS

Automated vehicles are coming, but will they be *fun*?

IN THE 1960s, THE TELEVISION SHOW "CANDID CAMERA" had several skits in which they faked driverless cars moving past unsuspecting people. It was funny because everyone knew that driverless cars were impossible. That was then, but now the great technical and social challenge of developing driverless cars has suddenly been opened up to us, as described in last month's issue of *IEEE Spectrum*. • At the turn of the millennium, I was a member of a committee of the National Academy of Engineering whose task was to select the most outstanding engineering achievements of the 20th century. First was electrification, followed by the automobile. Because an important criterion was social impact, we reasoned that the development of the automobile profoundly changed where we lived and how we lived. At about the same time, people were making lists of important future achievements for the 21st century–grand challenges with social impacts. But as far as I know, driverless cars were not on any of those lists. • It is amazing that automobiles have changed so little since the Ford Model T was introduced in 1908. The basic function is still about the same, and some of those Model Ts are still on the road. But now we have the chance to really make a difference. The technology is ripe, but it won't be easy. • Someone who recently had the opportunity to sit in a driverless car on a San Francisco freeway described his experience as initially terrifying but later simply boring. I was thinking about that description as I watched television ads for new cars. The ads featured cars that could climb mountains, ford streams, and had so much power that they could go from 0 to 60 miles an hour in almost nothing flat. They were fun to drive and sleek in appearance. I imagined instead an ad for a new, driverless car that stressed how boring the ride was. Are people really going to want these cars?

Every driver has an individual driving style and persona. I'm comfortable when I'm being driven by some people and uncomfortable with others. And when I drive, I don't like being stuck behind a slow driver, nor do I like being pushed by an impatient faster driver behind me. I'm wondering: Will driverless cars have an adjustable comfort level of speed and aggression?

Group behavior in traffic is a complex phenomenon. Some drivers believe this is a zero-sum game, while others believe that courtesy helps everyone. A classic case is a long line at an exit ramp, where traffic moves slowly because some drivers speed by the line of cars and cut in at the front. Will driverless cars be tempted into such behavior, or will they be unfailingly polite?

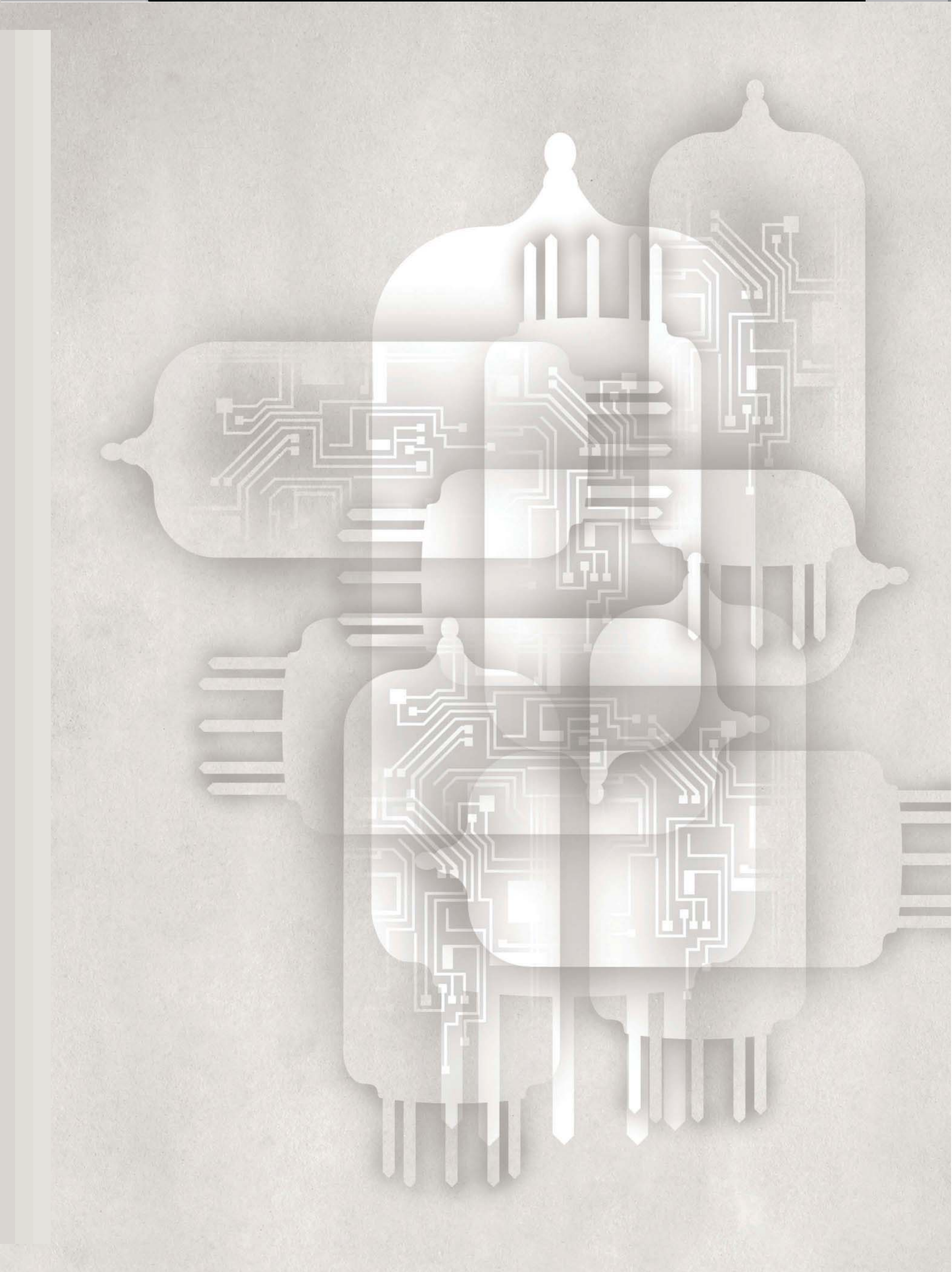
Then there are the classic routing decisions. Heading into New York City, you receive a radio bulletin that the Lincoln Tunnel is jammed, while at the Holland Tunnel traffic is moving well. Hearing this, many drivers will still go to the Lincoln Tunnel in the belief that everyone else will go to the Holland Tunnel. Enough drivers are siphoned off to make the traffic in both tunnels even out. But will all the driverless cars use identical routing algorithms and so jam the tunnel that was said to be good?

Will driverless cars know when it might be okay to break a law, like crossing a yellow center line to avoid an object? Can they exceed the speed limit while passing another vehicle? And if there is a traffic violation, who gets the ticket? In the event of an accident, who gets sued? And there are those ethical decisions that sometimes must be made almost instantaneously: Hit a deer or crash the car?

So as powerful as the technology is, there will be social problems. Moreover, a lot of people like to drive and want to feel in control. Driverless cars could save lives in the future, but I'm afraid that there could well be a strong market for old cars that still permit human driving, even when it's inept and dangerous. ■

ILLUSTRATION BY Matthew Hollister


Reservoir
of energy
Reservoir
of talent



THE DEVICE MADE OF NOTHING

The vacuum transistor could one day replace traditional silicon

By Jin-Woo Han & Meyya Meyyappan

ILLUSTRATION BY Chad Hagen

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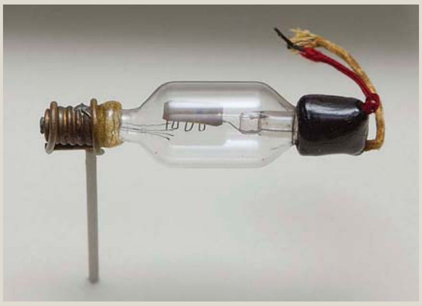
IN SEPTEMBER 1976, in the midst of the Cold War, Victor Ivanovich Belenko, a disgruntled Soviet pilot, veered off course from a training flight over Siberia in his MiG-25 Foxbat, flew low and fast across the Sea of Japan, and landed the plane at a civilian airport in Hokkaido with just 30 seconds of fuel remaining. His dramatic defection was a boon for U.S. military analysts, who for the first time had an opportunity to examine up close this high-speed Soviet fighter, which they had thought to be one of the world's most capable aircraft. What they discovered astonished them. • For one thing, the airframe was more crudely built than those of contemporary U.S. fighters, being made mostly of steel rather than titanium. What's more, they found the plane's avionics bays to be filled with equipment based on vacuum tubes rather than transistors. The obvious conclusion, previous fears aside, was that even the Soviet Union's most cutting-edge technology lagged laughably behind the West's.

After all, in the United States vacuum tubes had given way to smaller and less power-hungry solid-state devices two decades earlier, not long after William Shockley, John Bardeen, and Walter Brattain cobbled together the first transistor at Bell Laboratories in 1947. By the mid-1970s, the only vacuum tubes you could find in Western electronics were hidden away in certain kinds of specialized equipment–not counting the ubiquitous picture tubes of television sets. Today even those are gone, and outside of a few niches, vacuum tubes are an extinct technology. So it might come as a surprise to learn that some very modest changes to the fabrication techniques now used to build integrated circuits could yet breathe vacuum electronics back to life.

At the NASA Ames Research Center, we've been working for the past few years to develop vacuum-channel transistors. Our research is still at an early stage, but the prototypes we've constructed show that this novel device holds extraordinary promise. Vacuum-channel transistors could work 10 times as fast as ordinary silicon transistors and may eventually be able to operate at terahertz frequencies, which have long been beyond the reach of any solid-state device. And they are considerably more tolerant of heat and radiation. To understand why, it helps to know a bit about the construction and functioning of good old-fashioned vacuum tubes.

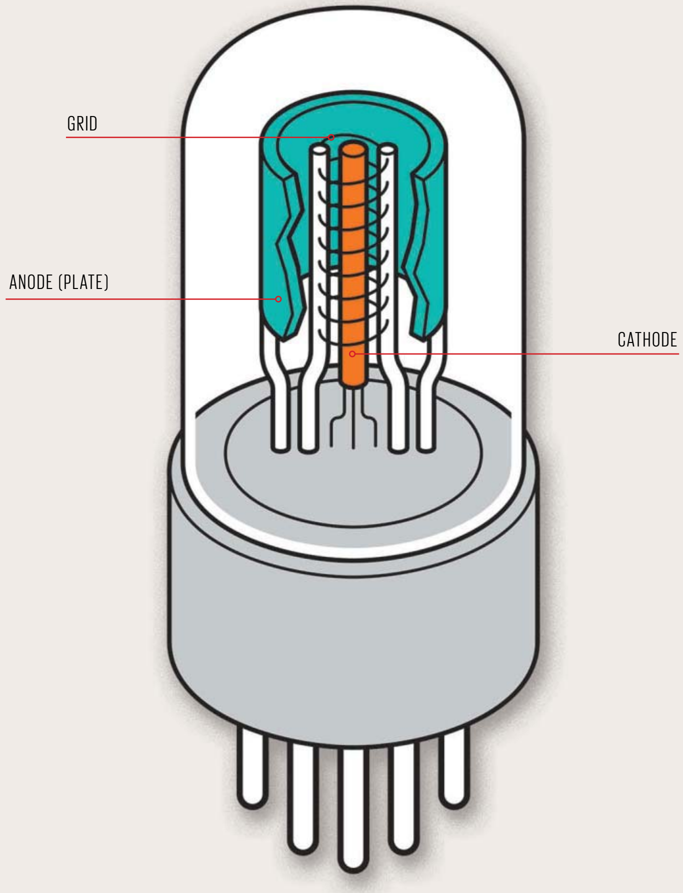
The thumb-size vacuum tubes that amplified signals in countless radio and television sets during the first half of the 20th century might seem nothing like the metal-oxide semiconductor field-effect transistors (MOSFETs) that regularly dazzle us with their capabilities in today's digital electronics. But in many ways, they are quite similar. For one, they both are three-terminal devices. The voltage applied to one terminal–the grid for a simple triode vacuum tube and the gate for a MOSFET–controls the amount of current flowing between the other two: from cathode to anode in a vacuum tube and from source to drain in a MOSFET. This ability is what allows each of these devices to function as an amplifier or, if driven hard enough, as a switch.

How electric current flows in a vacuum tube is very different from how it flows in a transistor, though. Vacuum tubes rely on a process called thermionic emission: Heating the cathode causes it to shed electrons into the surrounding vacuum. The current in transistors, on the other hand, comes from the drift and diffusion of electrons (or of "holes," spots where electrons are missing) between the



LIGHTBULB DESCENDANT: Vacuum tubes were an outgrowth of ordinary lightbulbs, a development spurred on by Thomas Edison's investigations into the ability of heated filaments to emit electrons. This 1906 example, an early Audion tube, shows the close resemblance to a lightbulb, although the filament in this particular tube is not visible, having long ago burned out. That filament once acted as the cathode from which electrons flew toward the anode or plate, which is located in the center of the glass tube. Current flow from cathode to anode could be controlled by varying the voltage applied to the grid, the zigzag wire seen below the plate.

GREGORY MAXWELL



CHIP IN A BOTTLE

The simplest vacuum tube capable of amplification is the triode, so named because it contains three electrodes: a cathode, an anode, and a grid. Typically, the structure is cylindrically symmetrical, with the cathode surrounded by the grid and the grid surrounded by the anode. Operation is similar to that of a field-effect transistor, here with the voltage applied to the grid controlling the current flow between the other two electrodes. (Triode tubes often have five pins to accommodate two additional electrical connections for the heated filament.)

source and the drain through the solid semiconducting material that separates them.

Why did vacuum tubes give way to solid-state electronics so many decades ago? The advantages of semiconductors include lower costs, much smaller size, superior lifetimes, efficiency, ruggedness, reliability, and consistency. Notwithstanding these advantages, when considered purely as a medium for transporting charge, vacuum wins over semiconductors. Electrons propagate freely through the nothingness of a vacuum, whereas they suffer from collisions with the atoms in a solid (a process called crystal-lattice scattering). What's more, a vacuum isn't prone to the kind of radiation damage that plagues semiconductors, and it produces less noise and distortion than solid-state materials.

The drawbacks of tubes weren't so vexing when you just needed a handful of them to run your radio or television set. But they proved really troublesome with more complicated circuits. For example, the 1946 ENIAC computer, which used 17,468 vacuum tubes, consumed 150 kilowatts of power, weighed more than 27 metric tons, and took up almost 200 square meters of floor space. And it kept breaking down all the time, with a tube failing every day or two.

The transistor revolution put an end to such frustrations. But the ensuing sea change in electronics came about not so much because of the intrinsic advantages of semiconductors but because engineers gained the ability to mass-produce and combine transistors in integrated circuits by chemically engraving, or etching, a silicon wafer with the appropriate pattern. As the technology of integrated-circuit fabrication progressed, more and more transistors could be squeezed onto microchips, allowing the circuitry to become more elaborate from one generation to the next. The electronics also became faster without costing any more.

That speed benefit stemmed from the fact that as the transistors became smaller, electrons moving through them had to travel increasingly shorter distances between the source and the drain, allowing each transistor to be turned on and off more quickly. Vacuum tubes, on the other hand, were big and bulky and had to be fabricated individually by mechanical machining. While they were improved over the years, tubes never benefited from anything remotely resembling Moore's Law.

But after four decades of shrinking transistor dimensions, the oxide layer that insulates the gate electrode of a typical MOSFET is now only a few nanometers thick, and just a few tens of nanometers separate its source and drain. Conventional transistors really can't get much smaller. Still, the quest for faster and more energy-efficient chips continues. What will the next transistor technology be? Nanowires, carbon nanotubes, and graphene are all being developed intensively. Perhaps one of these approaches will revamp the electronics industry. Or maybe they'll all fizzle.

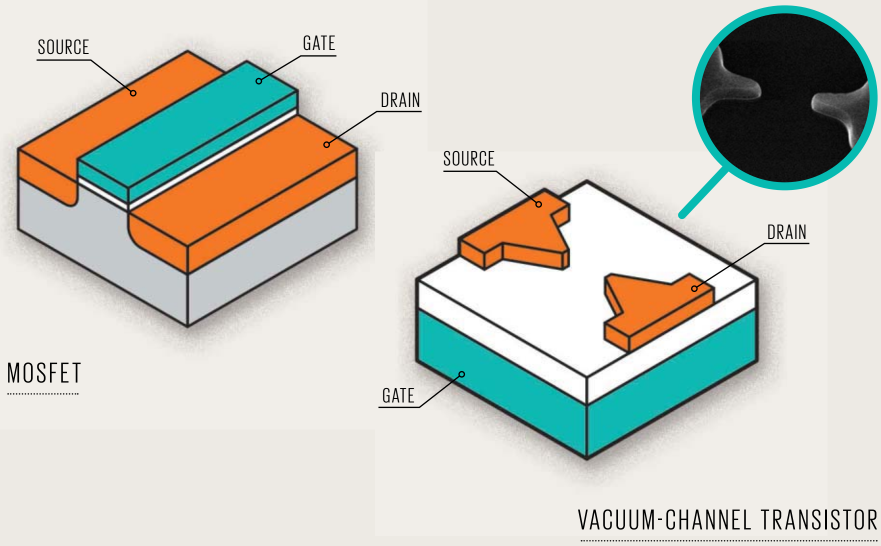
W**e've been working to develop** yet another candidate to replace the MOSFET, one that researchers have been dabbling with off and on for many years: the vacuum-channel transistor. It's the result of a marriage between traditional vacuum-tube technology and modern semiconductor-fabrication techniques. This curious hybrid combines the best aspects of vacuum tubes and transistors and can be made as small and as cheap as any solid-state device. Indeed, making them small is what eliminates the well-known drawbacks of vacuum tubes.

In a vacuum tube, an electric filament, similar to the filament in an incandescent lightbulb, is used to heat the cathode suffi-

ILLUSTRATION BY James Provost

TRANSISTORIZING THE VACUUM TUBE

A vacuum-channel transistor closely resembles an ordinary metal-oxide semiconductor field-effect transistor or MOSFET [left]. In a MOSFET, voltage applied to the gate sets up an electric field in the semiconductor material below. This field in turn draws charge carriers into the channel between the source and drain regions, allowing current to flow. No current flows into the gate, which is insulated from the substrate below it by a thin oxide layer. The vacuum-channel transistor the authors developed [right] similarly uses a thin layer of oxide to insulate the gate from the cathode and anode, which are sharply pointed to intensify the electric field at the tips.



ciently for it to emit electrons. This is why vacuum tubes need time to warm up and why they consume so much power. It's also why they frequently burn out (often as a result of a minuscule leak in the tube's glass envelope). But vacuum-channel transistors don't need a filament or hot cathode. If the device is made small enough, the electric field across it is sufficient to draw electrons from the source by a process known as field emission. Eliminating the power-sapping heating element reduces the area each device takes up on a chip and makes this new kind of transistor energy efficient.

Another weak point of tubes is that they must maintain a high vacuum, typically a thousandth or so of atmospheric pressure, to avoid collisions between electrons and gas molecules. Under such low pressure, the electric field causes positive ions generated from the residual gas in a tube to accelerate and bombard the cathode, creating sharp, nanometer-scale protrusions, which degrade and, ultimately, destroy it.

These long-standing problems of vacuum electronics aren't insurmountable. What if the distance between cathode and anode were less than the average distance an electron travels before hitting a gas molecule, a distance known as the mean free path? Then you wouldn't have to worry about collisions between electrons and gas molecules. For example, the mean free path of electrons in air under normal atmospheric pressure is about 200 nanometers, which on the scale of today's transistors is pretty large. Use helium instead of air and the mean free path goes up to about 1 micrometer. That means an electron traveling across, say, a 100-nm gap bathed in helium would have only about a 10 percent probability of colliding with the gas. Make the gap smaller still and the chance of collision diminishes further.

But even with a low probability of hitting, many electrons are still going to collide with gas molecules. If the impact knocks a bound electron from the gas molecule, it will become a positively charged ion, which means that the electric field will send it flying toward the cathode. Under the bombardment of all those positive ions, cathodes degrade. So you really want to avoid this as much as possible.

Fortunately, if you keep the voltage low, the electrons will never acquire enough energy to ionize helium. So if the dimensions of the vacuum transistor are substantially smaller than the mean free path of electrons (which is not hard to arrange), and the working voltage is low enough (not difficult either), the device can operate just fine at atmospheric pressure. That is, you don't, in fact, need to maintain any sort of vacuum at all for what is nominally a miniaturized piece of "vacuum" electronics!

But how do you turn this new kind of transistor on and off? With a triode vacuum tube, you control the current flowing through it by varying the voltage applied to the grid—a meshlike electrode situated between the cathode and the anode. Positioning the grid close to the cathode enhances the grid's electrostatic control, although that close positioning tends to increase the amount of current flowing into the grid. Ideally, no current would ever flow into the grid, because it wastes energy and can even cause the tube to malfunction. But in practice there's always a little grid current.

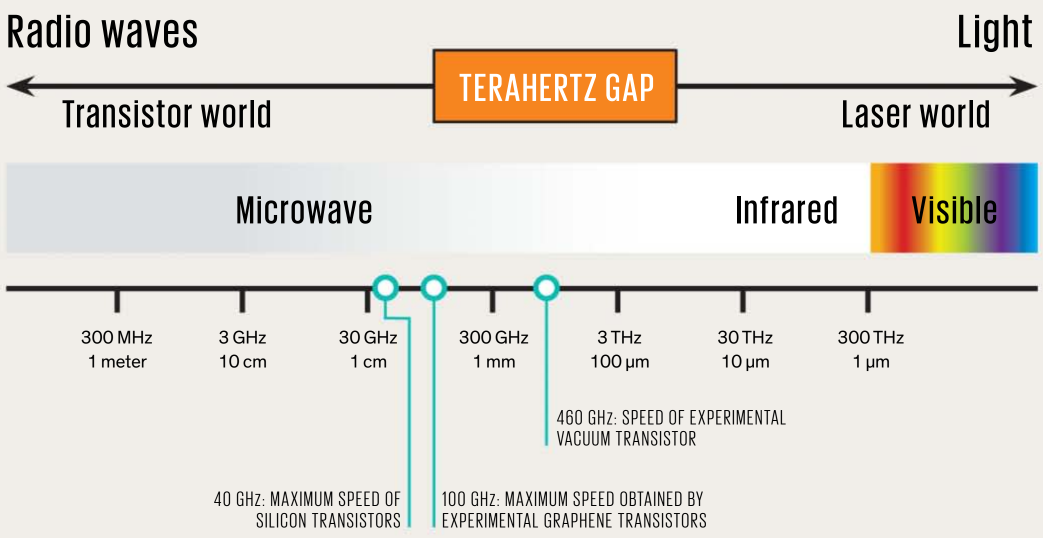
To avoid such problems, we control current flow in our vacuum-channel transistor just as it's done in ordinary MOSFETs, using a gate electrode that has an insulating dielectric material (silicon dioxide) separating it from the current channel. The dielectric insulator transfers the electric field where it's needed while preventing the flow of current into the gate.

So you see, the vacuum-channel transistor isn't at all complicated. Indeed, it operates much more simply than any of the transistor varieties that came before it.

INSET IMAGE: NASA AMES RESEARCH CENTER

ILLUSTRATION BY James Provost

FILLING THE GAP



Vacuum-channel transistors hold the promise of being able to operate at frequencies above microwaves and below infrared—a region of the spectrum sometimes known as the terahertz gap because of the difficulty that most semiconductor devices have operating at those frequencies. Promising applications for terahertz equipment include directional high-speed communications and hazardous-materials sensing.

Although we are still at an early stage with our research, we believe the recent improvements we've made to the vacuum-channel transistor could one day have a huge influence on the electronics industry, particularly for applications where speed is paramount. Our very first effort to fashion a prototype produced a device that could operate at 460 gigahertz—roughly 10 times as fast as the best silicon transistor can manage. This makes the vacuum-channel transistor very promising for operating in what is sometimes known as the terahertz gap, the portion of the electromagnetic spectrum above microwaves and below infrared.

Such frequencies, which run from about 0.1 to 10 terahertz, are useful for sensing hazardous materials and for secure high-speed telecommunications, to give just a couple of possible applications. But terahertz waves are difficult to take advantage of because conventional semiconductors aren't capable of generating or detecting this radiation. Vacuum transistors could—pardon the expression—fill that void. These transistors might also find their way into future microprocessors, their method of manufacture being completely compatible with conventional CMOS fabrication. But several problems will need to be solved before that can happen.

Our prototype vacuum transistor operates at 10 volts, an order of magnitude higher than modern CMOS chips use. But researchers at the University of Pittsburgh have been able to build vacuum transistors that operate at just 1 or 2 V, albeit with significant compromises in design flexibility. We're confident we can reduce the voltage requirements of our device to similar levels by shrinking the distance between its anode and cathode. Also, the sharpness of these electrodes determines how much they concentrate the electric field, and the makeup of the cathode material governs how large a field is needed to extract electrons from it. So we might also be able to reduce the voltage needed by designing electrodes with sharper points or a more advantageous chemical composition that lowers the barrier for the electron escaping from the cathode. This will no doubt be something of a balancing act, because changes made to reduce operating voltage could compromise the long-term stability of the electrodes and the resultant lifetime of the transistor.

The next big step for us is to build a large number of vacuum-channel transistors into an integrated circuit. For that, we should be able to use many of the existing computer-aided design tools and simulation software developed for constructing CMOS ICs. Before we attempt this, however, we'll need to refine our computer models for this new transistor and to work out suitable design rules for wiring lots of them together. And we'll have to devise proper packaging methods for these 1-atmosphere, helium-filled devices. Most likely, the techniques currently used to package various microelectromechanical sensors, such as accelerometers and gyroscopes, can be applied to vacuum-channel transistors without too much fuss.

Admittedly, a great deal of work remains to be done before we can begin to envision commercial products emerging. But when they eventually do, this new generation of vacuum electronics will surely boast some surprising capabilities. Expect that. Otherwise you might end up feeling a bit like those military analysts who examined that Soviet MiG-25 in Japan back in 1976: Later they realized that its vacuum-based avionics could withstand the electromagnetic pulse from a nuclear blast better than anything the West had in its planes. Only then did they begin to appreciate the value of a little nothingness. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/vacuum0714

RECIPE FOR A BETTER OVEN

IT'S TIME TO REENGINEER A TECHNOLOGY INVENTED TO BAKE BRICKS

By **NATHAN MYHRVOLD & W. WAYT GIBBS**

MOST OF US BAKE, ROAST, AND BROIL our food using a technology that was invented 5,000 years ago for drying mud bricks: the oven. The original oven was clay, heated by a wood fire. Today, the typical oven is a box covered in shiny steel or sparkling enamel, powered by gas or electricity. But inside the oven, little has changed. • Is a brick dryer really the best system for cooking food? Not even close. The typical modern oven—even a US $10,000 unit used by professional chefs or a $5,000 model used in a high-end home kitchen—has a host of problems. It can't cook food equally well whether full or nearly empty, left alone or regularly checked, or with food placed in any position inside. Yet oven manufacturers could solve every problem with existing technology, if only they would apply it.

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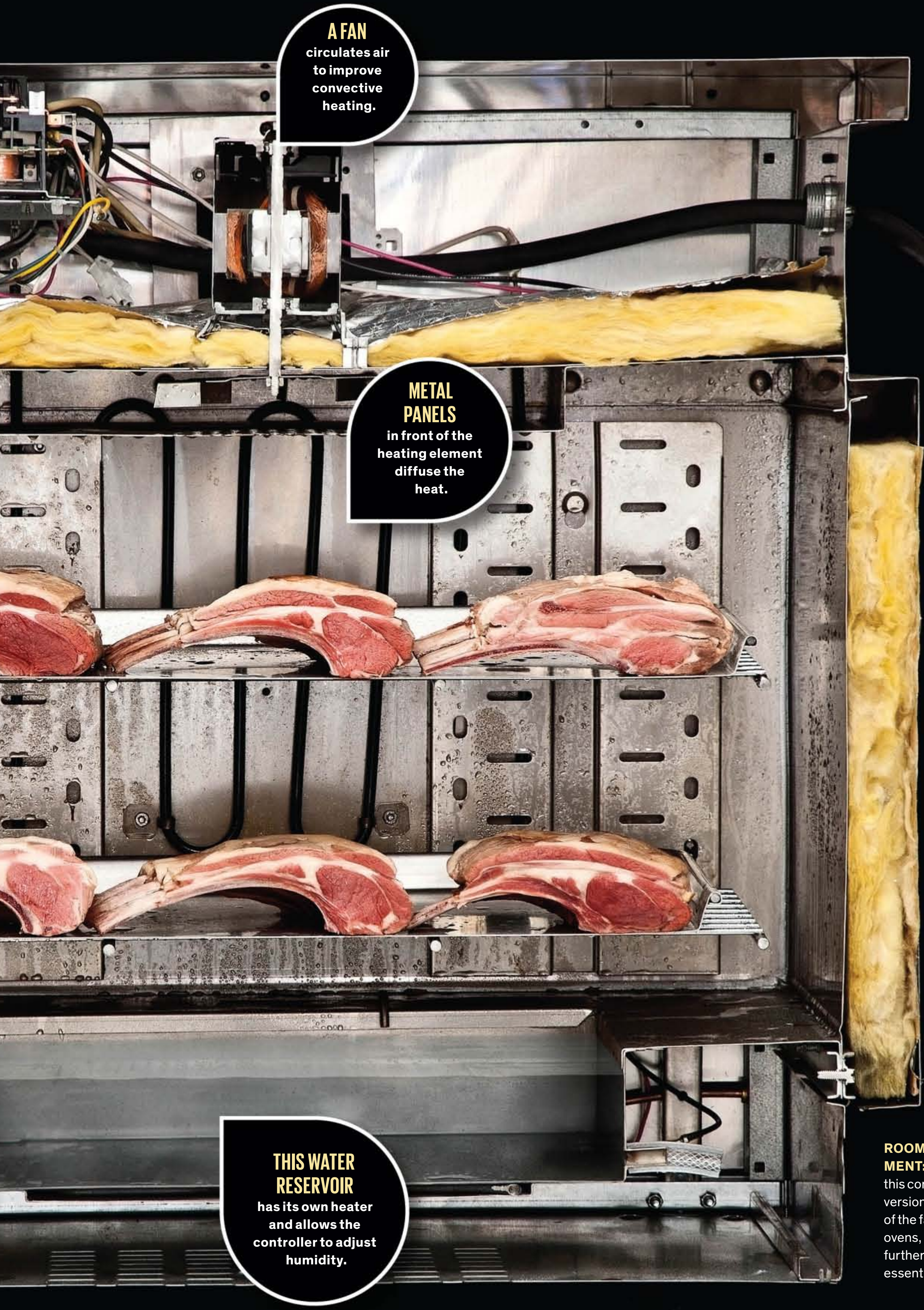

ROOM FOR IMPROVEMENT: A modern oven, like this controlled-vapor (CVap) version, overcomes many of the failings of traditional ovens, but there's room for further improvement of this essential cooking tool.

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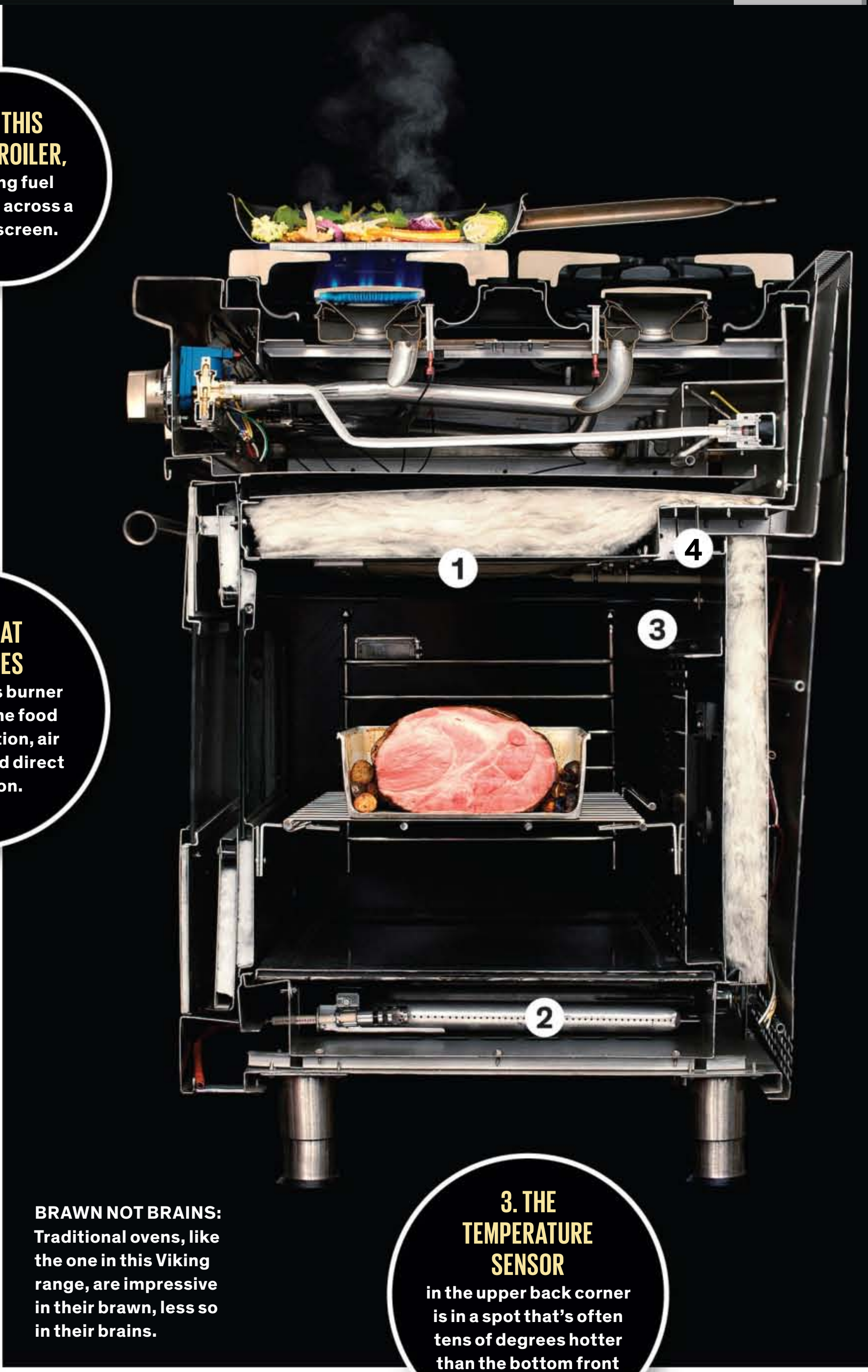

BRAWN NOT BRAINS: Traditional ovens, like the one in this Viking range, are impressive in their brawn, less so in their brains.

The problems with ovens start as soon as you turn them on. Preheating always seems to take an unreasonably long time because ovens waste most of the hot air they generate. The actual amount of energy required to reach baking temperature is quite small: Just 42 kilojoules will heat 0.14 cubic meters of air to 250 °C. The heating element in a typical domestic electric oven supplies this much energy in a mere 21 seconds.

It's the oven walls you want to preheat, however, not the air. Unfortunately, the heat, which originates in the heating coils of an electric oven or the burner of a gas oven, must pass through the air to get to the walls, and air is an awful conductor of heat, only slightly better than Styrofoam. Even worse, air expands when heated, so much of it flows out of the vent, heating the kitchen rather than the oven. And if you try to save that heat by closing the vent and adding a latch to the door, the oven might explode.

The time it takes an oven to heat up, however, is the least of the problems. Oven walls radiate heat unevenly because they vary in thickness and in their proximity to the heating elements. So the temperature can fluctuate by tens of degrees from one spot to another. And many oven doors contain a window, which radiates a lot less heat into the oven cavity than the walls do.

At low temperatures, these fluctuations don't matter much, because radiant heat is weak compared to the heat transferred through conduction and convection; at high baking temperatures, the unevenness matters a lot. The power of radiant heat emitted from part of an oven wall at 270 °C is 16 percent more intense than the power coming from part of a wall that is slightly cooler, at 250 °C.

Food itself also absorbs radiant heat unevenly, which exacerbates the problem. Some parts of the surface naturally dry faster and brown earlier. Because dark surfaces absorb more radiant heat than light surfaces do, small variations quickly grow. If a darkening part of the food is particularly close to an intense spot of radiant heat, that part of the food will likely burn.

And you, the cook, will inevitably make the situation worse. As soon as you open the oven door to adjust or check on the food, nearly all the hot air spills out. The puny electric element or gas burner is no match for such large surges of cool air, so the temperature in the oven plummets, and it recovers slowly.

Oven designers could do a lot to make ovens heat more evenly by taking advantage of the different ways ovens transfer heat at different cooking temperatures. At 200 °C or below, convection moves most of the heat. But at 400 °C, radiant energy starts doing a fair amount of the heat transfer. At 800 °C, radiation overwhelms convection. Why couldn't we have an oven designed to cook primarily by convection at low temperatures that switches to radiant heating for high-temperature baking?

And you're not going to be able to stop a cook from opening the oven door on occasion—peeking through a grease-splattered window just doesn't cut it. But designers could prevent that blast of cold air by building a blower into the door frame that generates a "curtain" of air whenever

PREVIOUS PAGE: RYAN MATTHEW SMITH/MODERNIST CUISINE; THIS PAGE: MELISSA LEHUTA/MODERNIST CUISINE the door is opened, retaining more of the preheated air in the oven. Larger versions of air doors are already in wide commercial use for refrigerated warehouses. Designing one for an oven is trickier because the chamber is small and turbulent currents could do more harm than good. Still, it could be done.

Hot spots affect broiling as well as baking. Electric broilers use bars or rods made from Nichrome, an alloy of nickel and chromium (and often iron) that heats up when electricity passes through it. With reasonable energy efficiency, electric broilers can heat quickly and reliably to temperatures as high as 2,200 °C. Maximum settings are typically restricted to 1,200 °C in order to extend the life of the heating element and avoid charring the food.

4. THE EXHAUST VENT keeps smoke from filling the kitchen but allows hot air to escape.

Every broiler has a sweet spot–or perhaps we should call it a "sweet zone"–where the heat is at its most intense. If you place the food above or below this zone, it will cook unevenly. Moving the food closer to the heating elements won't make it hotter; it will simply make the cooking more uneven.

Surprisingly, however, the opposite problem occurs when food is too far from the element: Cold spots appear directly below the rods, and hot spots fall in between. What has changed is that the distance to the element no longer causes heat intensity to vary much from side to side, but there are still variations in the way heat reflects.

You can make a broiler cook more evenly with a simple DIY project: Install some shiny vertical reflectors near the edges of the compartment. Another good way to ensure that food browns evenly under a broiler is to wrap the dish with a reflective foil collar. But why should you have to jury-rig a fix? It wouldn't be hard for oven manufacturers to build reflective materials into the oven. Viking Range is developing stainless steel cavities that are more reflective, but they need better materials that are easy to clean and don't discolor when heated to high temperatures.

Such reflectors wouldn't entirely solve the problem of uneven broiling. The food itself can cause variations. The shiny skin of raw fish reflects heat, but as the skin browns, it reflects less and less energy. That's why food under a broiler can seem to cook slowly at first and then burn in the blink of an eye.

But technology offers a fix here, too. Oven designers could put optical sensors in the oven chamber to sense the reflectivity of the food, and then the oven controller could adjust the heat automatically or at least alert the cook as the surface browns. And a camera in the oven could feed to a color display on the front panel, giving the chef a clearer view of the food than a small window in the door can. Indeed, a decent optics system could allow designers to dispense with the glass in the door altogether, reducing the gap between the hottest and coolest corners of the oven and obviating the need to open the door and rotate the food midway through cooking.

We could also broil food more evenly by switching from standard electric or gas broilers to gas catalysis, a technology that has begun to get the attention of oven designers. Although still more expensive than other broilers, catalytic broilers are beginning to show up in professional kitchens and some high-end consumer ovens.

Instead of burning gas, flameless catalytic broilers push it through a catalytic metal that either permeates or forms a mesh around a porous ceramic plate. As the gas mixes with air, the catalyst makes it oxidize, creating heat, water vapor, and carbon dioxide. The ceramic plate absorbs the heat and radiates it out into the oven far more evenly than a conventional broiler.

Even though these catalytic broilers can reach only 540 °C, they brown food just fine. They are also very energy efficient, converting about 80 percent of the chemical energy in the gas to infrared light. This technology, however, needs work before it can be cost effective for the home kitchen. In the meantime, oven designers should be seeking less expen-

FROM TOP: TYSON STOLE/MODERNIST CUISINE (2); MELISSA LEHUTA/MODERNIST CUISINE

HOW TO CALIBRATE YOUR OVEN

You can make that cantankerous contraption in your kitchen more predictable

1 PREHEAT AND MEASURE: Preheat the oven, then clip the oven-safe probe of a digital thermometer to a rack. Close the door, wait 3 minutes, and record the temperature you set on the dial and the temperature reading on the thermometer.

2 MOVE AND REPEAT: Move the probe around and repeat the process to identify the hot spots (usually a back corner) and the cooler zones (typically near the door).

3 RESET AND RETEST: Change the set temperature by, say, 50 °C and take new measurements. Expect to see the oven's accuracy fall at cooler temperatures. Use this data to compensate for your oven's irregularities the next time you set its thermostat.

sive, similarly compact technologies to produce heat from gas that rival the efficiency of catalytic elements.

Another way to cook food more evenly is to turn it. Thick cuts of meat roast to more consistent doneness on a rotisserie because each part of the roast receives regular pulses of heat as it rotates toward, and then away from, the heat source. Between pulses, the heat diffuses into the center while the exterior cools. Some modern ovens do include rotating spits that can be used in conjunction with the broiler to make a rotisserie, but these can be awkward to set up and are limited in the sizes and kinds of foods they can cook.

A more advanced oven could offer the benefits of rotisserie cooking by pulsing the heat rather than rotating the food. The walls of the oven would have to quickly cycle between the high temperatures at which radiant heat transfer kicks in and those that are much cooler. That would probably require integrating a heat exchanger of some kind into each wall. A circulating fluid, for example, could draw heat off the walls and transfer it to a water-filled chamber at the bottom of the oven.

Heating with high-intensity light, from halogen lamps, say, might offer one way to create pulsating heat. And halogen ovens are available. General Electric makes ovens that incorporate halogen elements. LG Electronics makes a line of ovens, the Solardom series, that combine a conventional electrical heating element with a convection fan, a microwave generator, a halogen broiling element, and a water tray for generating steam (but without any accurate control of humidity level).

You can also create pulses of heat with oven wall panels that quickly change their conductance. One way might be through the use of variable-emittance coatings, which NASA and others have been developing for 20 years; these change their transparency or reflectivity when a current is applied. Another method would use tiny shutters made out of microelectromechanical systems or electrostatically actuated flaps.

HEAT *AND* HUMIDITY: Some ovens add humidity in the form of steam, such as [from top] LG Electronics' Solardom, AccuTemp's Steam'N'Hold, Rational's combi oven, and Wolf's steam oven.

FROM TOP: LG ELECTRONICS; ACCUTEMP PRODUCTS; RATIONAL; WOLF

So oven designers could indeed create appliances that heat both faster and more evenly. But a fundamental problem with today's ovens would remain: We can't control them properly because we can never accurately gauge just how hot they are! Sure, they have a purported control knob on the front labeled with various temperatures, but turning the control knob is a bit like spinning a roulette wheel—you never know exactly where the cooking temperature will end up (and, as we'll explain later, the cooking temperature is very different from the temperature measured by your oven thermometer).

A brick-drying oven's temperature can vary by 50 °C or even 100 °C and still produce a functional brick. Food is vastly less forgiving. Beef cooks nicely to an internal temperature of 55 °C, but raise the temperature to just 63 °C and the individual muscle strands in the meat contract dramatically, squeezing out the juices and leaving a dry, unappetizing entrée.

Domestic ovens tend to swing in temperature and can be off by as much as 5 percent at any point during cooking. At 205 °C—a temperature at which you might cook a turkey—that 5 percent isn't a big deal. But consider a style of cooking known as *sous vide*, in which you cook food in bags in a water bath at low temperatures such as 60 °C, near the threshold at which bacteria can survive. Here, 5 percent can be the difference between safe and unsafe.

Controlling temperature would be easier were it not for more frustrating facts about ovens that conspire against consistency. The thermostats in nearly all traditional ovens are just plain inaccurate. As technologies go, the oven thermostat is underwhelming: It is nothing more than a switch that opens and closes in response to the temperature it senses. In the worst case, the sensing probe is behind the oven walls. In the best case, it protrudes into the oven cavity (it's a metal tube with a crimped end). It's filled with an incompressible fluid that responds to changes in temperature, just like an alcohol-filled glass thermometer.

This probe reads the dry-bulb temperature, the same type of temperature that an ordinary thermometer measures when it's shielded from direct sunlight and moisture. Because the oven probe is some distance from the food, it typically mismeasures the real dry-bulb temperature by as much as 15 °C at high baking temperatures, typically around 220 °C and above, and often by even more at low temperatures, like 120 °C. The greater the distance between the sensor and the food, the bigger the error. You can calibrate the thermostat of your oven to compensate for these errors [see "How to Calibrate Your Oven"].

Even when perfectly calibrated, however, the standard oven thermometer has a big problem. Water evaporating from the surface of the food carries away heat, leaving the food cooler than the surrounding air. Scientists call this temperature at the surface of the food the wet-bulb temperature (that is, the dry-bulb temperature minus any cooling by evaporation). The lower the relative humidity, the more evaporative cooling, so the greater the difference between the two temperatures.

Because most of the humidity in an oven comes from the food, adding food to the oven raises the humidity and, therefore, the wet-bulb temperature at the food's surface. This means that bigger batches bake faster. Did you burn the holiday cookies last year? Blame your oven's ignorance of its own humidity.

Oven makers have two separate but related technologies that address this problem. Though not standard in commercial kitchens, these are gaining popularity. But they have yet to come to the home cook.

The first is the water-vapor oven, developed in the early 1980s by Winston Shelton, a former General Electric engineer. Shelton wasn't new to kitchen innovation; in the early 1970s he worked with Colonel Harland Sanders to design and manufacture the Collectramatic pressure fryer, which became the standard cooker for the Kentucky Fried Chicken chain of restaurants.

Shelton's Winston Industries calls its water-vapor technology CVap (short for controlled vapor). The basic concept is simple: Heat a pan of water in the bottom of an oven enclosure until enough evaporates to raise the relative humidity to almost 100 percent. CVap ovens sell for $4,000 to $9,000, depending on size.

A second type of vapor oven, the Steam'N'Hold unit from the Indiana-based company AccuTemp Products, works by creating a partial vacuum that reduces the air pressure until the boiling point of water equals the temperature that the cook selects for steaming. This approach works only for temperatures below 100 °C. These ovens retail for around $6,000.

Neither kind of vapor oven can brown food, however, unless the surface of the food is dry. The combi oven, invented in 1976 by German engineers at the company that would later become Rational, is designed to both brown and steam food. Steaming goes beyond 100 percent humidity to put moisture into food. Combi ovens can cook with ambient air (as an ordinary convection oven does), with injected steam, or with a combination of both.

A combi oven is not cheap. It costs roughly $15,000 for an oven the size of a half sheet pan and several times that for larger configurations. Miniature combi ovens designed for commercial kitchens have recently come on the market for as little as $2,000, but these use very small pans. And the technology is starting to come into the home kitchen—Cuisinart makes a $300 oven that can toast or steam food.

Combi ovens offer far greater control of temperature than conventional ovens do, and they allow you to control the humidity, too—but unfortunately, not as well as we'd like. Our experiments show that the dry- and wet-bulb temperatures in these ovens tend to fluctuate by several degrees around the set point. Gas-fired ovens are worse than electric ones because the flame produces large pulses of heat as it turns on and off.

Modern humidity-controlled ovens such as CVaps and combi ovens share a common flaw. They don't let you set the wet-bulb and dry-bulb temperatures directly. So our entreaty to the innovative engineers and designers in the appliance industry is simple. Please give us ovens that let us select separate wet- and dry-bulb temperatures! And while you're at it, perhaps you could solve a related problem: the inadequate precision of the humidity- and temperature-control systems. Both temperature and humidity levels stray from the set points more than they should.

Precisely controlling the temperature and humidity of an oven means you can better control the actual temperature of the food inside it. And that's what really matters. A chicken breast cooked to 60 °C is moist and delicious; cooked to 65 °C, it's dry. An oven-baked omelet can be exquisite. But in today's ovens it is nearly impossible to cook one properly, because a difference of even a few degrees from the perfect conditions—82 °C and 100 percent humidity—will produce either a runny omelet or one that's dry and brittle.

Some other interesting technologies that make ovens more useful are already on the market. Newer models of steam ovens by Wolf Appliance have a "slow roast" mode that allows the cook to enter a serving time. Ovens made by Rational measure the core temperature of the food using a probe. The probe has five separate sensors; the machine's digital control chooses the one placed deepest into the food. That way, you don't need to hit the food dead center with the tip of the probe. The oven adjusts the temperature of the oven cavity automatically to control the rate at which the core temperature of the food rises.

These developments are encouraging but isolated. An oven could be manufactured today that could incorporate many of the technologies now available and go a long way toward turning today's mere brick dryer into a true food cooker. It would have wet- and dry-bulb temperature controls, better thermostats, probes to go inside food, and sensors that detect hot and cold spots. All these features would add just a few hundred dollars to the cost of the parts.

And adding just a little more intelligence to the oven could take us even further. A smarter oven would use both advanced sensing and mathematical modeling to observe and project the temperature trajectory within the food. It could then adjust its heating mode and intensity to create the optimal conditions for cooking that type of food or simply to have good, if not perfect, food ready at a selected time.

But why stop there? With ideal technology, you could put different parts of your meal in a single oven and it could figure out how to cook them so that they were all done at the same time in the way you want them. To do that, we need a way to focus just the right amount of energy on each part of the food and to measure how it responds to the energy. This would likely require ovens made out of new materials—not just sheet metal—that could be monitored and controlled in finely grained detail: Imagine an LCD in which each pixel gives off not colored light but powerful infrared energy. When you put a slice of toast on top, you could control how much heat is delivered to each spot on the toast—resulting in evenly toasted bread, or, perhaps, toast with a shaded image on its surface. That would be the ultimate cooking technology. ■

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ENGINEERING NEEDS MORE HEROES

THERE'S NO LACK OF WORTHY CHARACTERS, SO WHY DOESN'T THE PROFESSION CELEBRATE THEM? BY G. PASCAL ZACHARY

ILLUSTRATIONS BY TAVIS COBURN

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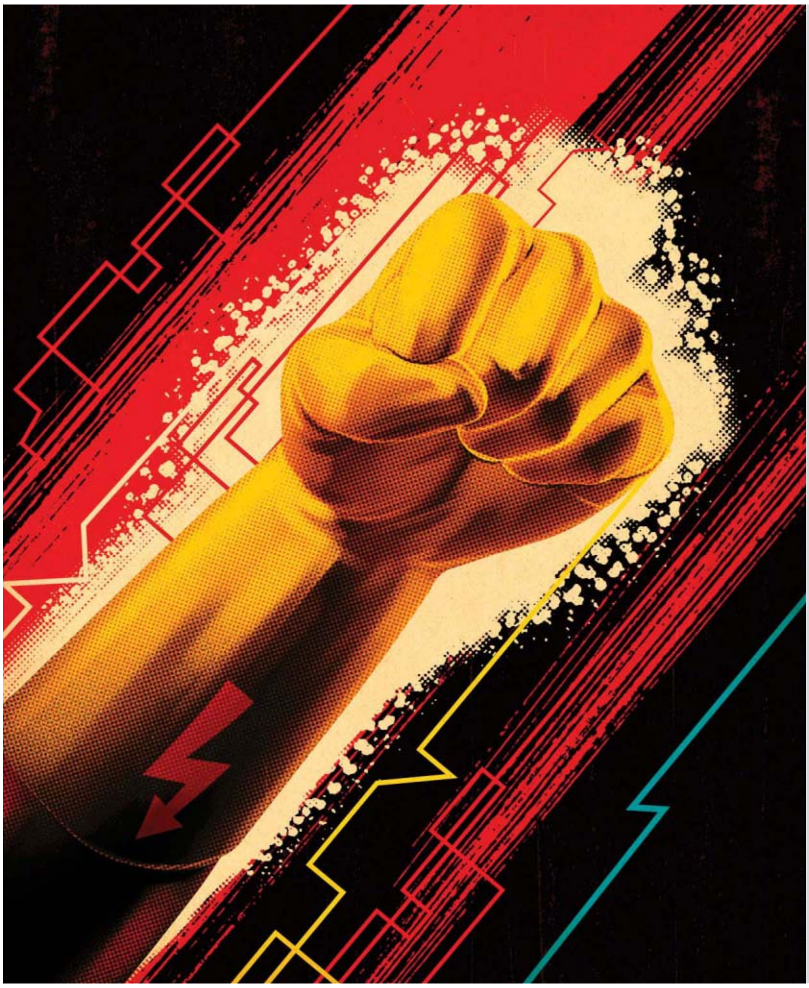
Some 25 years ago, I set out to write a biography of one of the most notable electrical engineers in American history. A professor at MIT, he designed the most powerful analog computers of the 1930s, and he cofounded Raytheon. An advisor to two U.S. presidents, he initiated the Manhattan Project, which produced the first atomic bombs, and he directed the research that led to the mass production of penicillin. In 1945, he conceived of the U.S. National Science Foundation, which continues to support groundbreaking research and has become the model for research funding in many countries. And he wrote a provocative magazine article that later was credited with accurately describing the personal computer and the Internet–decades before either came into being. I would argue that within the engineering pantheon, only Benjamin Franklin had as great an influence in as many spheres.



If by now you've identified my subject as Vannevar Bush, congratulations! If you haven't, don't feel bad. The most frequent question that I, his sole biographer, receive about him is whether he is related to the first and the second presidents Bush. (He is not.)

Writing the book got me thinking about engineering heroes, or rather the lack of them. Over the years that thought has turned into something of a personal obsession. And now with the help of this magazine and its readers, I'm making it a public crusade: Engineering needs more heroes.

Celebrating heroes is a good way to inspire young people and inform the public, of course. But it's not just a luxury or diversion that the profession can do without. The hero deficit is in fact bad for engineering because it diminishes the enterprise in the eyes of the public, and it constricts the flow of talent into the field. We live in a hero-worshipping society, where the pursuit of celebrity sometimes seems to border on the fanatical. In such a society, serious fields that lack serious heroes are seriously disadvantaged.

HOLD ON, YOU'RE THINKING, I can name lots of engineering heroes. There's Thomas Edison, Nikola Tesla, Hewlett and Packard. There's, hmm, Steve Jobs, and uh, Bill Gates, and um.... At this point, you whip out your smartphone and google "engineering heroes." But that's cheating. (And by the way, can you name any of the engineers who worked on the iPhone? Or on NTT Docomo's earlier, ingenious smartphones? I didn't think so.)

Now let's take a look at that list. Edison, no question. Tesla, sure. But Hewlett, Packard, Jobs, and Gates are celebrated chiefly, I would argue, because they built up big corporations and big fortunes through the technological accomplishments of others.

The bottom line is that these days, the engineers who make the most money get the widest acclaim. In other words, to be a hero, you must first achieve stupendous financial success.

There's no crime in profiting from your ideas (or even the ideas of others). But in my view, it shouldn't be the sole or even the main marker for heroism. So where else are we to look for exemplary engineers?

That's a surprisingly tough question to answer. For one thing, engineering may very well be bereft of heroes because nobody really understands the work of engineers anymore. When Edison invented the phonograph, for instance, everybody could relate to that. But when Intel engineers design a microprocessor with 2 billion transistors rather than, say, 1.5 billion, a layperson has no real clue what that means or why it's important. To be sure, increasing abstraction and complexity also dogs modern physics, chemistry, and many other fields, with the unsurprising result that there are no physicist heroes, chemist heroes, and so on. Pursuits like sports, movies, and music, meanwhile, are intuitively comprehensible, so it's no wonder that those fields are chockfull of heroes.

Engineering also faces a sort of structural impediment–namely, there is no Nobel Prize for engineering, nor is there an engineering award with similar global status and prestige. While it's true that a few engineers have received Nobels in other fields, without a Nobel of their own, engineers can't routinely anoint their heroes in quite the same way that physicists, economists, and novelists can. Critics of the Nobel may deride it for, among other things, obscuring the complexity of modern research, but they can't dispute that nothing can confer instant superstardom quite like a Nobel.

Sure, engineering has the Kyoto Prize in Advanced Technology, the Charles Stark Draper Prize of the U.S. National Academy of Engineering, and the IEEE's own Medal of Honor. Outside of certain circles, though, none of these prizes is widely known. And inadvertently or otherwise, these prizes underscore the abiding stereotype that engineers are brainy males of formidable nerdiness. Only one of the 34 recipients of the Kyoto Prize in Advanced Technology and one of the 47 recipients of the Draper prize has been a woman. And of the 95 people who received the IEEE Medal of Honor, zero have been women.

This gender bias in engineering heroes isn't easily remedied–unless you adopt the definition that Ruth Schwartz Cowan, an eminent historian of technology, suggested to me in an e-mail. Every woman engineer is essentially heroic, she wrote, "because they are double stereotype breakers. Most people do not break any stereotypes. Some are brave enough to break one. Women engineers break two: the stereotype for a 'good woman' and the stereotype for a 'good engineer.' I'd like to salute the people who sustain stereotype breaking, day in and day out." Now, you may agree or disagree with Cowan's reasoning, but she's getting at some essential truths. Our engineering heroes should look more like the society they come from, not reflect just one small segment of that society. And in even seemingly slight or everyday acts, we are each capable of feats of heroism.

Cowan's remarks also raise a bigger question: What exactly does it take to be an engineering hero? I would argue that overcoming adversity–whether personal, institutional, or technological–is a valid criterion for heroism. Computer scientist Grace Hopper, who developed the first compiler, broke ground in all three respects: She not only indelibly shaped the course of computer programming, she succeeded in a male-dominated field and a male-dominated institution, eventually rising to the rank of rear admiral in the U.S. Navy.

Contributing to the social and cultural well-being of humanity is another criterion for engineering heroism. And yet throughout the history of engineering, people have tackled important problems simply because they were there and without considering the greater good. Vinton Cerf and Robert Kahn, for instance, are justly celebrated for their formative work in computer networking, and they also have a rightful claim to having benefited humanity. The same can be said for Norwegian electrical engineer Thomas Haug. He's a seminal figure in the emergence of mobile phones, the worldwide adoption of which has led to many social and cultural advances. Yet the quests for computer networks and mobile telephony weren't motivated chiefly by good intentions. So is virtue in fact a prerequisite for engineering heroism?

Of course, talk of virtue–or any other human value–inevitably leads to disagreement. No doubt that's why engineering-prize committees tend to stick with "objective" technological achievements when doling out their accolades. Yet only a certain subset of young people are drawn to engineering purely out of a desire to tackle tough technological challenges. Many students are motivated by wanting to make the world a better place. If they don't see engineering as a means to that end, they won't consider it as a career option.

Nurturing aspirations for what engineering can accomplish on behalf of humanity is another way of saying that individuals matter in the course of technological history. Instinctively, engineers themselves embrace this notion. The careers of Tesla and Edison attest to the fact that a single person–even a misfit or a dreamer–can profoundly influence the trajectory of a technology. In retrospect at least, maybe their achievements seemed inevitable–someone had to invent the AC induction motor. But progress

THE ENGINEERING PANTHEON

Engineering has no shortage of achievers worthy of our respect and admiration. Here are just a few–some of them you'll know, others you should know better.

NIKOLA TESLA Creator of the AC induction motor, pop culture icon

VANNEVAR BUSH Conceived the U.S. National Science Foundation

THOMAS EDISON Invented the incandescent bulb, among many things

LOUIS POUZIN Computer-networking visionary

THOMAS HAUG Cellular telephone pioneer, made text messaging happen

GRACE HOPPER Pathbreaking computer programmer

GLUEKIT

WHO'S A HERO?

WE NEED YOUR HELP. This month, *IEEE Spectrum* is inviting readers to identify today's unsung engineering heroes—exemplars of engineering excellence who, for whatever reason, have not received the recognition they deserve. What makes a hero? Someone who meets at least one of the following criteria:

- Has overcome major adversity in the pursuit of his or her career
- Is doing great good in the world
- Has solved a significant technical challenge with wide-reaching impact
- Has brilliantly led a meaningful and important project

To weigh in with your suggestions, go to http://spectrum.ieee.org/heroes0714 and complete the online form. You can also e-mail heroes@ieee.org or write to *IEEE Spectrum*, 3 Park Avenue, 17th Floor, New York, NY 10016 U.S.A. Please include your hero's name, where he or she lives and works, and why you consider this person a hero. A URL for the person's Web page, Facebook page, or LinkedIn page would be helpful. And tell us how we can contact you if we have questions.

A selection of these heroes will be featured in next year's annual **Dream Jobs for Engineers** special report.

isn't preordained, nor are aspirations irrelevant. If they were, then engineers, even great ones, would be mere robotic servants of a mathematical dance in which their personalities and values don't count. When we judge the quality of engineering, our hopes and dreams have to matter.

I'm not suggesting that a hero's character need be spotless. Fields like sports and entertainment have a host of heroes with conspicuously troubling attributes. Perhaps that's how you know you have enough heroes: Your field has so many that there's room for antiheroes. Even in the world of engineering and technology, which many people tend to regard as relatively "clean" and orderly, William Shockley and Wernher von Braun, among others, led lives that were less than exemplary. Ultimately, each of us decides who our heroes are.

Which raises the stubborn question: Can heroism be taught, or is it innate? I firmly believe that heroes are made, not born. They learn from their experiences, they react to opportunities and crises, and when others around them stick to the safe middle ground, they reach for something higher, or at least more on the fringe. And through the pressure cooker of technoscientific experiences, the engineering hero achieves, in a phrase coined by the German sociologist Max Weber, "charismatic authority": the ability to influence, inspire, and lead others.

As Weber defined it, such charisma doesn't just refer to those who gain outsize status through media acclaim. Charismatic engineers can also work their magic on an intimate, unsung level, by persuading peers behind the scenes or by challenging the status quo through their designs or their testimony.

"The history of engineering is replete with examples of unheralded engineers who refused to accept designs that compromised the public welfare, no matter how profitable they were," historian Matthew Hersch told me. "Inventions like the safety match and the safety bicycle not only worked better than their predecessors, but more ethically. To me, the creators of these technologies are the real heroes." I can't argue with Hersch's logic. So who were these engineering heroes, and why does nobody know their names?

Heroes try, but they also fail. Indeed, the most accomplished engineers notched striking failures in their careers. You probably know who Cerf and Kahn are, but have you ever heard of Louis Pouzin? The creator of an early packet-switching network called Cyclades, Pouzin envisioned the democratizing potential of computer networking. In 1975, he and Cerf led a group who tried but failed to get a packet-switching standard adopted by the International Telegraph and Telephone Consultative Committee. After publicly criticizing the telecom industry's conservatism, Pouzin then saw his research funding drain away, along with his career prospects. Meanwhile, Cerf and Kahn incorporated aspects of Pouzin's ideas into the TCP/IP design for the Internet. These days Pouzin is finally getting some of the recognition he richly deserves.

Pouzin, Cerf, and Kahn didn't work alone; their accomplishments always occurred in parallel with the efforts of others. That's the nature of engineering. And even though the lone inventor is a staple of heroic narratives in the history of engineering, that version of events slights those heroes who are part of teams. Engineering heroism, I would argue, can arise through devotion to an organization and through the management of the complex technological systems that underpin our daily lives.

Consider James Webb, the NASA chief who oversaw Project Apollo in its glory days, which delivered astronauts to the moon and brought them back alive–repeatedly. Or Robert Taylor, the legendary program manager of the Advanced Research Projects Agency, who commissioned research that produced the ARPANET as well as many of the building blocks of the personal computer. Webb and Taylor were visionary leaders of engineering enterprises, and their heroism arose from their undeniable talent at coaxing results from mercurial geeks.

ALL THIS TALK OF HEROES may make you uncomfortable. The culture of engineering values modesty and suspects that promotion, especially self-promotion, conceals distortion or possibly even fraud. In today's societies, where image often trumps genuine achievement, engineers justly admire their own penchant for humility and obscurity. But, as I hope I've made clear, heroes and heroism are essential if engineers are to win the respect their activities and passions deserve.

Here, then, is the challenge: Find the unsung engineering heroes of our own times. They may have fought back against impossible odds; they may have elegantly untied a seemingly hopeless knot; they may have inspired others to greater heights and bigger breakthroughs; they may have challenged an unsafe practice or system, at great personal risk, and carried the day. And the world is a far better place because of them. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/heroes0714

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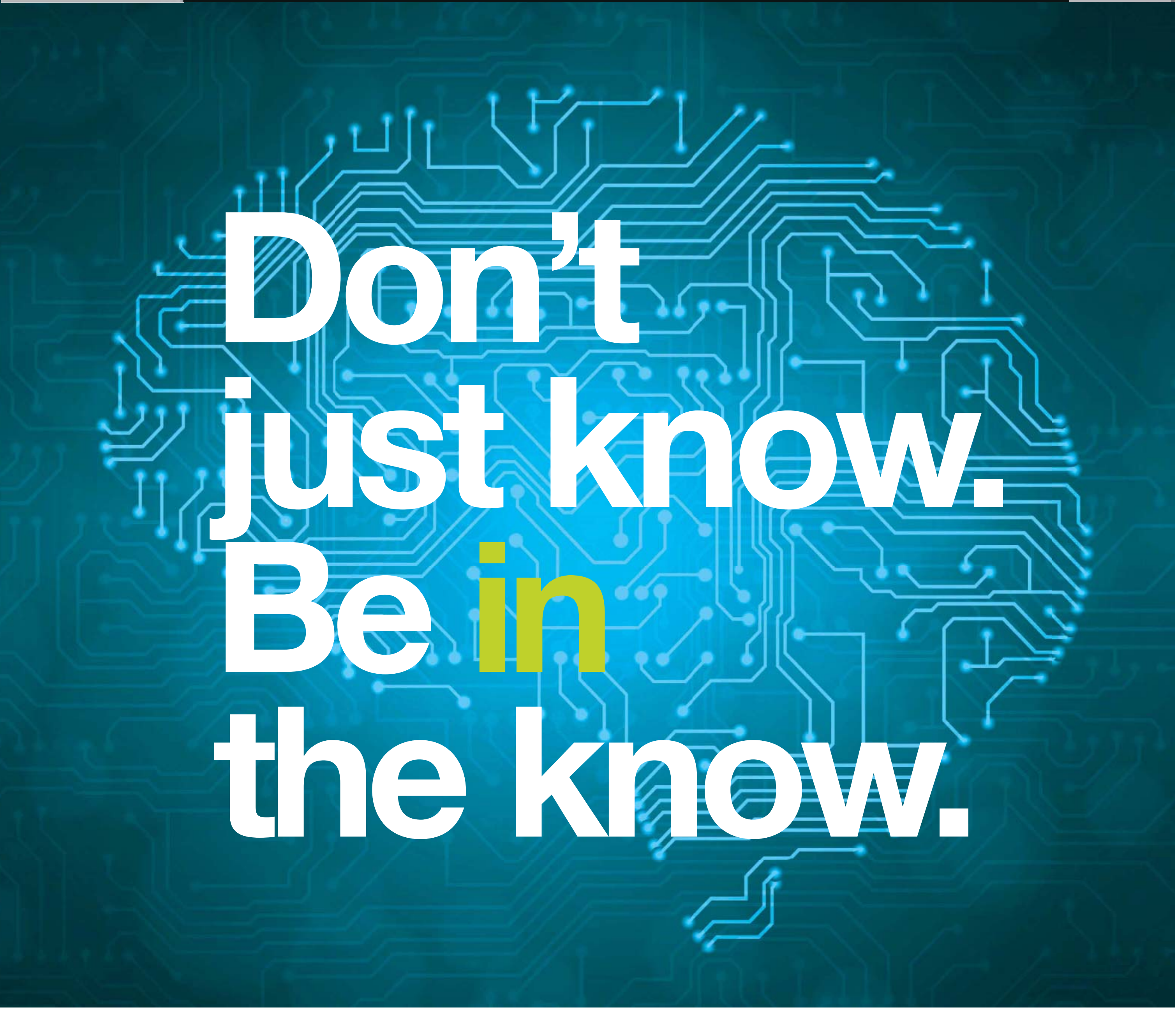
Don't
just know.
Be in
the know.

Go-bot, go

AIs may use randomness to finally master this ancient game of strategy

By **Jonathan Schaeffer**, **Martin Müller** & **Akihiro Kishimoto**
Photography by **Dan Saelinger**

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Chou Chun-hsun,

one of the world's top players of the ancient game of Go, sat hunched over a board covered with a grid of closely spaced lines. To the untrained eye, the bean-size black and white stones scattered across the board formed a random design. To Chou, each stone was part of a complex campaign between two opposing forces that were battling to capture territory. The Go master was absorbed in thought as he considered various possibilities for his next move and tried to visualize how each option would affect the course of the game. Chou's strategy relied on a deep understanding of Go, the result of almost 20 years of painstaking study. • Although Chou looked calm, he knew he was in big trouble. It was 22 August 2009, and Chou was matched against a Go-playing computer running Fuego, an open-source program that we developed at the University of Alberta, in Canada, with contributions from researchers at IBM and elsewhere. The program was playing at the level of a grand master—yet it knew nothing about the game beyond the basic rules.

For decades, researchers have taught computers to play games in order to test their cognitive abilities against those of humans. In 1997, when an IBM computer called Deep Blue beat Garry Kasparov, the reigning world champion, at chess, many people assumed that computer scientists would eventually develop artificial intelligences that could triumph at any game. Go, however, with its dizzying array of possible moves, continued to stymie the best efforts of AI researchers.

But that climactic competition in 2009 showed that a computer might yet become a Go champion. In that match, an AI defeated a world-class human Go player in a no-handicap game for the first time in history. Although that game was played on a small board, not the board used in official tournaments, Fuego's win was seen as a major milestone.

Remarkably, the Fuego program didn't triumph because it had a better grasp of Go strategy. And although it considered millions of possible moves during each turn, it didn't come close to performing an exhaustive search of all the possible game paths. Instead, Fuego was a know-nothing machine that based its decisions on random choices and statistics.

THE RECIPE FOR BUILDING A SUPERHUMAN CHESS PROGRAM IS now well established. You start by listing all possible moves, the responses to the moves, and the responses to the responses, generating a branching tree that grows as big as computational resources allow. To evaluate the game positions at the end of the branches, the program needs some chess knowledge, such as the value of each piece and the utility of its location on the board. Then you refine the algorithm, say by "pruning" away branches that obviously involve bad play on either side, so that the program can search the remaining branches more deeply. Set the program to run as fast as possible on one or more computers and voilà, you have a grand master chess player. This recipe has proven successful not only for chess but also for such games as checkers and Othello. It is one of the great success stories of AI research.

Go is another matter entirely. The game has changed little since it was invented in China thousands of years ago, and millions around the world still enjoy playing it. Beginners often learn Go on a board composed of a grid of 9 lines by 9 lines before working their way up to the official board with its 19-by-19 grid. Game play sounds simple in theory: Two players take turns placing stones on the board to occupy territories and surround the opponent's stones, earning points for their successes. Yet the scope of Go makes it extremely difficult—perhaps impossible—for a program to master the game with the traditional search-and-evaluate approach.

For starters, the complexity of the search algorithm depends in large part on the branching factor—the number of possible moves at every turn. For chess, that factor is roughly 40, and a typical chess game lasts for about 50 moves. In Go, the branching factor can be more than 250, and a game goes on for about 350 moves. The proliferation of options in Go quickly becomes too much for a standard search algorithm.

There's also a bigger problem: While it's fairly easy to define the value of positions in chess, it's enormously difficult to do so on a Go board. In chess-playing programs, a relatively simple

THIS PAGE AND PREVIOUS PAGES, PROP STYLING BY **Dominique Baynes** evaluation function adds up the material value of pieces (a queen, for example, has a higher value than a pawn) and computes the value of their locations on the board based on their potential to attack or be attacked.

Compared with that of chess pieces, the value of individual Go stones is much lower. Therefore the evaluation of a Go position is based on all the stones' locations, and on judgments about which of them will eventually be captured and which will stay safe during the shifting course of a long game. To make this assessment, human players rely on both a deep tactical understanding of the game and a clear-eyed appraisal of the overall board situation. Go masters consider the strength of various groups of stones and look at the potential to create, expand, or conquer territories across the board.

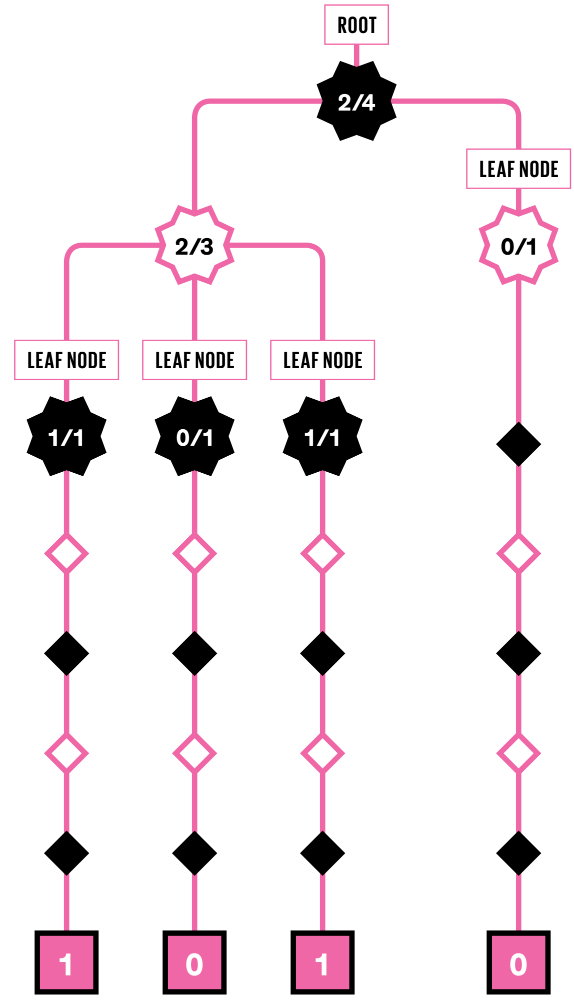
Rather than try to teach a Go-playing program how to perform this complex assessment, we've found that the best solution is to skip the evaluation process entirely. Over the past decade, several research groups have pioneered a new search paradigm for games, and the technique actually has a chance at cracking Go. Surprisingly, it's based on sequences of random moves. In its simplest form, this approach, called Monte Carlo tree search (MCTS), eschews all knowledge of the desirability of game positions. A program that uses MCTS need only know the rules of the game.

From the current configuration of stones on the board, the program simulates a random sequence of legal moves (playing moves for both opponents) until the end of the game is reached, resulting in a win or loss. It automatically does this over and over. The magic comes from the use of statistics. The evaluation of a position can be defined as the frequency with which random move sequences originating in that position lead to a win. For instance, the program might determine that when move A is played, random sequences of moves result in a win 73 percent of the time, while move B leads to a win only 54 percent of the time. It's a shockingly simple metric.

It may seem counterintuitive to try to win a deeply strategic game with a program that uses random moves to evaluate its different choices. But there are lots of precedents that show the efficacy of this statistical approach. For example, most Internet search engines do not attempt to analyze a query to try to understand the semantics of what is being asked for—they just apply some simple numerical schemes to rank results. Monte Carlo methods are also standard in disciplines such as particle physics, weather forecasting, chemistry, and finance. They are often the best approach for solving complex problems in which problem-specific knowledge is hard to formalize.

A GO-PLAYING AI CAN REPEATEDLY APPLY ITS MCTS ALGORITHM until resources—time or memory—run out. Like many other search methods, MCTS constructs a game tree, in which each possible move creates branches of new possible moves, which are conventionally drawn pointing downward. For a basic example of this algorithm, imagine that a Go program is trying to decide on its next move. It would therefore repeat these four steps:

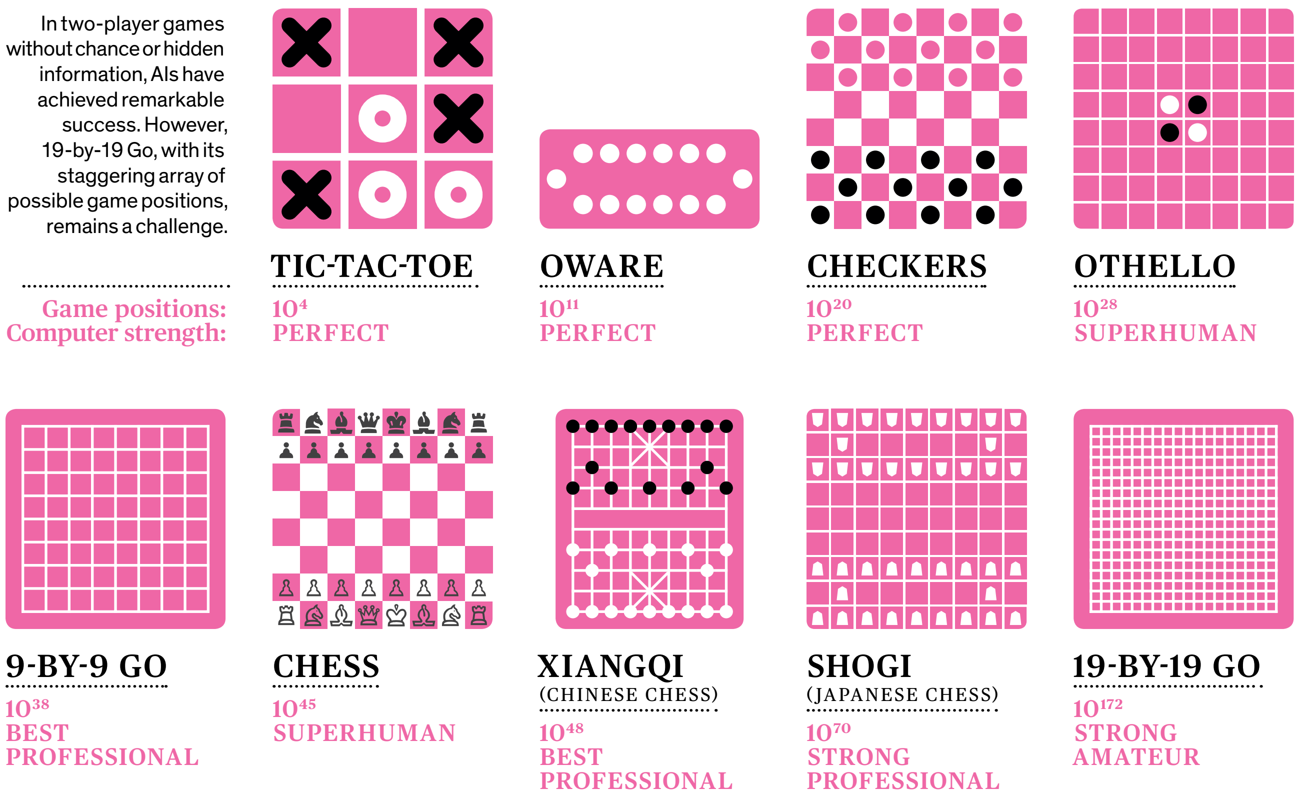
1. Tree descent: From the existing board position (the root



GROWING the Tree

In these four simulations of a simple Monte Carlo tree search, the program, playing as black, evaluates the winning potential of possible moves. Starting from a position to be evaluated (the leaf node), the program plays a random sequence of legal moves, playing for both black and white. It plays to the end of the game and then determines if the result is a win (1) or a loss (0). Then it discards all the information about that move sequence except for the result, which it uses to update the winning ratio for the leaf node and the nodes that came before it, back to the root of the game tree.

The GAMES Computers Play



node of the search tree), select a candidate move (a leaf node) for evaluation. At the very beginning of the search, the leaf node is directly connected to the root. Later on, as the search deepens, the program follows a long path of branches to reach the leaf node to be evaluated.

2. Simulation: From the selected leaf node, choose a random sequence of alternating moves until the end of the game is reached.

3. Evaluation and back propagation: Determine whether the simulation ends in a win or loss. Use that result to update the statistics for each node on the path from the leaf back to the root. Discard the simulation sequence from memory–only the result matters.

4. Tree expansion: Grow the game tree by adding an extra leaf node to it.

An MCTS-based program needs some intelligent way to select which branches of the game tree to grow. Good policies for doing that strike a balance between exploration (branching off nodes with few simulations and therefore high uncertainty about their prospects for leading to a win) and exploitation (pursuing moves that branch off the most promising nodes).

The best policies for expanding the tree also rely on a decision-making shortcut called rapid action value estimation (RAVE). The RAVE component tells the program to collect another set of statistics during each simulation. If the random sequence of moves results in a win, every grid point where the program placed one of its stones (thus roughly half the locations on the board) is given a numerical bonus. In this quick and dirty method, each board location accumulates a RAVE statistic as simulations are played out. Then, when the program is considering a move, it can look at both the win-loss statistic for that move as well as the RAVE statistic for that location.

These policies control the selective growth of the game tree. In typical MCTS programs, this growth is uneven: Promising lines of play are explored much more deeply than other lines. Because the search tree is grown one node at a time, the algorithm can be stopped at any time, and it will return the best move found so far.

Determining the best move is tricky, however. The most natural approach would be to pick the move with the highest probability of leading to a win. But this is usually too risky. For example, a move with 7 wins out of 10 trials may have the highest odds of winning (70 percent), but because this number comes from only 10 trials, the uncertainty is high. A move with 65,000 wins out of 100,000 trials (65 percent) is a safer bet. This suggests a different strategy: Choose the move with the largest number of wins. And this is indeed the standard approach.

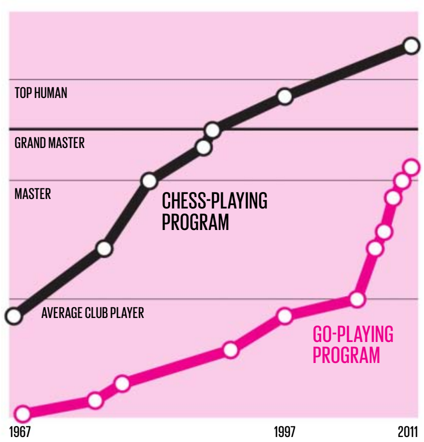
SINCE METHODS BASED ON MCTS REPLACED THE TRADITIONAL knowledge-based approaches, we have seen amazing improvements in the playing strength of Go programs. On the 9-by-9 board, top programs are on a par with the best human players. On the standard 19-by-19 board, a program called Crazy Stone has convincingly defeated a top professional while playing with a handicap of only four stones, indicating that the program plays as well as a very strong amateur.

The most basic Go-playing program using MCTS would employ only minimal knowledge of the game—namely, which moves are legal and who wins at the end of the game. This produces surprisingly successful Go-playing programs. But the latest research indicates that a little bit more knowledge can boost the performance of MCTS programs.

At the University of Alberta, we are finding ways to include some game-specific knowledge to give the program certain tendencies as it chooses its random moves. For example, a program can be biased so that its random move sequences aren't really so random. Instead, they often incorporate moves that would naturally follow from the opponent's previous move. Such obvious actions would include a move that would defend the program's stones from immediate capture, and a move that would seize an immediate opportunity to capture an opponent's stones.

The program can also be given some pieces of knowledge that can be applied without requiring it to perform true evaluations of game positions. For example, a program may have a database of simple patterns of stones that can occur within a 3-by-3 region of lines. After an opponent's move, the program checks the areas around that stone to see whether the resultant configurations match any of the stored patterns. If it does find a match, it plays the next move associated with that pattern in its database. If it finds several matching patterns, it chooses among the associated next moves at random.

When AI researchers first applied Monte Carlo methods to Go around 2005, computer Go programs improved dramatically and rapidly. Over the past few years, progress has been slower, but the research community is still optimistic. If we continue to refine our programs, enhancing the power of randomness with a dash of knowledge, we believe our AIs will eventually perform as well as Go's human grand masters.



GOING FOR IT: Chess-playing programs bested human grand masters more than a decade ago, but Go-playing programs weren't contenders until their coders embraced Monte Carlo tree search techniques in the late 2000s.

IN THE EARLY DAYS OF DEVELOPING CHESS-PLAYING PROGRAMS, researchers tried to get computers to play chess the way people do. Very quickly, it became clear that chess AIs couldn't efficiently learn and apply enough strategic knowledge to be successful. Programmers then adopted a search-intensive approach that required only enough knowledge to understand the rules and to evaluate the strength of a given board configuration. MCTS takes this one step further by questioning the need for making any such evaluations. It may seem paradoxical, but we're already seeing the benefits of such intelligence-free artificial intelligence in the game of Go—and that may be just the beginning.

In recent years, AI researchers have been trying to develop a program that can learn to play any game well—Go, tic-tac-toe, chess, whatever—given only the rules of the game as input. Historically, all the strong game-playing programs have been able to play only one specific game. They were "idiot savants" that could do one thing very well, but nothing else. If AI researchers can develop a program capable of more general learning, however, we might create a more flexible kind of computer intelligence. This would be a big step toward the real goal of artificial intelligence research: fashioning a general-purpose learner.

The AI community has been able to gauge progress in this area at the General Game Playing (GGP) competition, held at the annual conference of the Association for the Advancement of Artificial Intelligence. There, programs are given only the rules of a game and then have to play it in a tournament. From the rules, a GGP program can usually infer the appropriate search algorithm to find suitable moves. But these programs quickly run into trouble as they try to learn the game-specific knowledge that will allow them to make evaluations. One program might try to make deductions based on the rules of the game. Another might learn by playing against itself and making inferences. Yet neither strategy has proven effective. To date, there have been no truly successful approaches to machine learning in this sphere.

Instead, in recent tournaments virtually all the GGP programs have used a variation of MCTS to avoid the knowledge-acquisition problem altogether. These programs still have a long way to go. But there may come a day soon when an AI will be able to conquer any game we set it to, without a bit of knowledge to its name. If that day comes, we will raise a wry cheer for the triumph of ignorance. ■

POST YOUR COMMENTS at **http://spectrum.ieee.org/go0714**

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ShanghaiTech University Faculty Search

The newly launched 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 or demonstrate strong potential in cutting-edge research areas of information science and technology. They must be fluent in English. Overseas academic connection or background is highly desired. ShanghaiTech is built as a world-class research university for training future generations of scientists, entrepreneurs, and technological leaders. Located in Zhangjiang High-Tech Park in the cosmopolitan Shanghai, ShanghaiTech is ready to trail-blaze a new education system in China. Besides establishing and maintaining a world-class research profile, faculty candidates are also expected to contribute substantially to graduate and undergraduate education within the school.

Academic Disciplines:
We seek candidates in all cutting edge areas of information science and technology. Our recruitment focus includes, but is not limited to: computer architecture and technologies, nano-scale electronics, high speed and RF circuits, intelligent and integrated signal processing systems, computational foundations, big data, data mining, visualization, computer vision, bio-computing, smart energy/power devices and systems, next-generation networking, 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 ShanghaiTech faculty members will be within its new tenure-track system commensurate with international practice for performance evaluation and promotion.

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

Applications:
Submit (in English, PDF version) 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 August 1st, 2014 (until positions are filled). For more information, visit **http://www.shanghaitech.edu.cn.**

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

The Hong Kong Polytechnic University is a government-funded tertiary institution in Hong Kong. It offers programmes at various levels including Doctorate, Master's, and Bachelor's degrees. It has a full-time academic staff strength of around 1,250. The total consolidated expenditure budget of the University is about HK$5 billion per year.

DEPARTMENT OF ELECTRICAL ENGINEERING

The Department of Electrical Engineering is one of the six academic units in the Faculty of Engineering. It is the major education provider in electric power/energy engineering, power electronics and utilisation as well as railway engineering among the universities in Hong Kong. The Department is playing an important role in educating the electrical engineers for Hong Kong, and to some extent for the Chinese mainland arising from its continuous expansion in the electrical infrastructure. Please visit the website at http://www.ee.polyu.edu.hk for more information about the Department.

Professor / Associate Professor / Assistant Professor in Energy and Power Systems / Underpinning Key Technologies / Utilisation and Power Electronics

The appointee will be required to (a) teach at undergraduate and postgraduate levels; (b) conduct research that leads to publications in top-tier refereed journals and awards of research grants; (c) lead in research, programme/curriculum development and administration; (d) supervise student projects and theses; and (e) engage in scholarly research/consultancy in at least two of the following areas: (i) electromagnetic interference and compatibility studies, (ii) condition monitoring of electrical systems, (iii) smart sensors and energy harvesting, (iv) electrical vehicle and fast battery chargers, (v) power converter studies, (vi) optimization of electromagnetic devices, (vii) smart grid and renewable energy research, and (viii) electrical machines and drives.

Applicants should have (a) a PhD in a relevant discipline, plus substantial years of experience in teaching, research and industry; and (b) excellent communication skills and the ability to use English as the medium of instruction.

Candidates with less experience will be considered for appointment at the level of Associate Professor / Assistant Professor.

Remuneration and Conditions of Service
A highly competitive remuneration package will be offered. Initial appointment for Assistant Professor will be on a fixed-term gratuity-bearing contract. Re-engagement thereafter is subject to mutual agreement. An appropriate term will be provided for appointment at Associate Professor and Professor levels. Applicants should state their current and expected salary in the application.

Application
Please submit application form via email to hrstaff@polyu.edu.hk; by fax at (852) 2364 2166; or by mail to **Human Resources Office, 13/F, Li Ka Shing Tower, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong**. If you would like to provide a separate curriculum vitae, please still complete the application form which will help speed up the recruitment process. Application forms can be obtained via the above channels or downloaded from http://www.polyu.edu.hk/hro/job.htm. **Recruitment will continue until the position is filled**. Details of the University's Personal Information Collection Statement for recruitment can be found at http://www.polyu.edu.hk/hro/jobpics.htm.

For further details about the University, please visit **www.polyu.edu.hk**

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Argonne NATIONAL LABORATORY

The Argonne Named Fellowship Program

Argonne National Laboratory is accepting applications for the 2015 Named Fellowship. Argonne awards these special fellowships internationally on an annual basis to outstanding doctoral-level scientists and engineers who are at early points in promising careers. The fellowships are named after scientific and technical luminaries who have been associated with Argonne and its predecessors, and the University of Chicago, since the 1940's.

Candidates for these fellowships must display superb ability in scientific or engineering research, and must show definite promise of becoming outstanding leaders in the research they pursue. Fellowships are awarded annually and may be renewed up to three years. The 2015 fellowship carries a highly competitive salary with an additional allocation research support and travel. The deadline for submission of application materials is October 7, 2014.

Applicants should identify an Argonne staff member to sponsor the nomination. The sponsor could be someone who is already familiar with your research work and accomplishments through previous collaborations or professional societies. If you have not yet identified an Argonne sponsor, visit the detailed websites of the various research efforts at www.anl.gov/science.

Applications must be submitted online through: http://www.anl.gov/careers/apply-job. Correspondence and supporting letters of recommendation should be submitted to Named-Postdoc@anl.gov.

For more information visit the Argonne Postdoc Blog at https://blogs.anl.gov/postdoc/ or by contacting the Postdoctoral Program Coordinator, Kristene Henne at khenne@anl.gov.

Argonne is an equal opportunity employer and we value diversity in our workforce. Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

POSITION OPEN

Toyota Technological Institute

has an opening for a tenured- or tenure-track faculty position in the Graduate School of Engineering. Applications are encouraged from all relevant areas. For more information, please refer to the website **http://www.toyota-ti.ac.jp/english/employment/associate.html**

Position: Associate Professor

Research field: Condensed matter physics, materials science, and nanotechnology for developing advanced energy materials, such as thermoelectric materials, thermal rectifiers, high-T_c superconductors, highly conductive nano-wires, etc.

Qualifications: A Ph.D. in a relevant field. The successful candidate is expected to demonstrate potential to develop strong and outstanding programs in the above research field. It is also necessary for him/her to supervise students, and to teach advanced and basic courses both at the undergraduate and graduate levels.

Start date: At the earliest convenience

Documents: (1) A curriculum vitae

(2) A list of research activities

(3) Copies of 5 representative papers

(4) A brief summary and future plan of your research and educational statement (within three pages each)

(5) Names of two references including phone numbers and e-mail addresses

(6) An application form (available on our website)

Deadline: September 1, 2014

Inquiry: Search Committee Chair Professor Yasutake Ohishi

(Phone) +81-52-809-1860, (e-mail) y-ohishi1@toyota-ti.ac.jp

The above documentation should be sent to:

Mr. Takashi Hirato
Administration Division
Toyota Technological Institute
2-12-1, Hisakata, Tempaku-ku
Nagoya, 468-8511 Japan

Please write "Application for Energy Materials" in red on the return envelope.

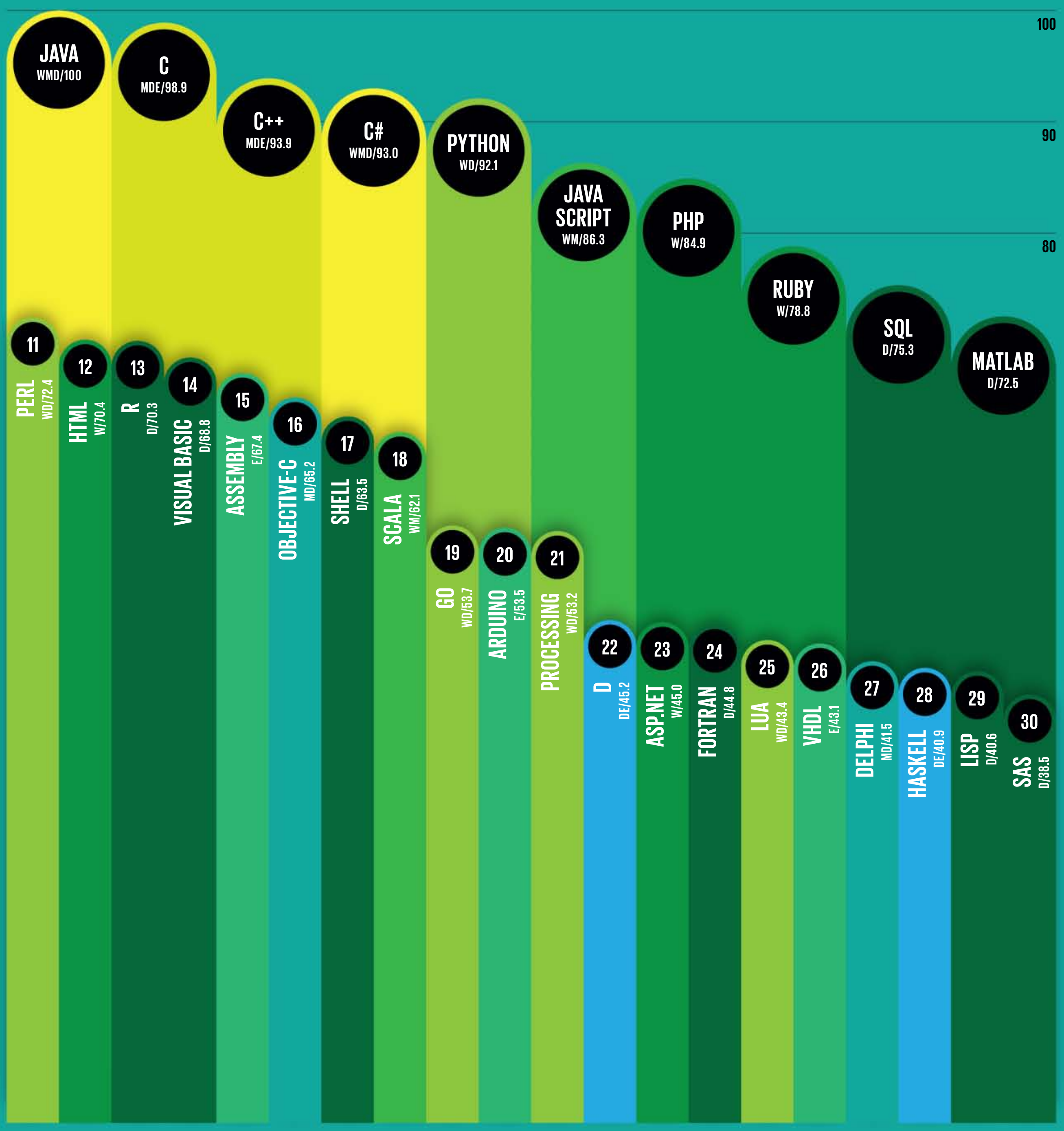
DATAFLOW_

THE TOP 10 PROGRAMMING LANGUAGES
SPECTRUM'S 2014 RANKING

Working with computational journalist Nick Diakopoulos, *IEEE Spectrum* has weighted and combined 12 metrics from 10 sources (including IEEE Xplore, Google, and GitHub) to rank the most popular programming languages. If you don't agree with our weighting, want to see more languages, or are interested in what's dominant in a specific subsector, such as mobile, go to our online interactive version. There you can adjust the weight of each metric and create your own custom ranking. —STEPHEN CASS

KEY | W - Web | M - Mobile
D - Desktop and Enterprise
E - Embedded

Scores are normalized so that the top-ranked language's score is set to 100.



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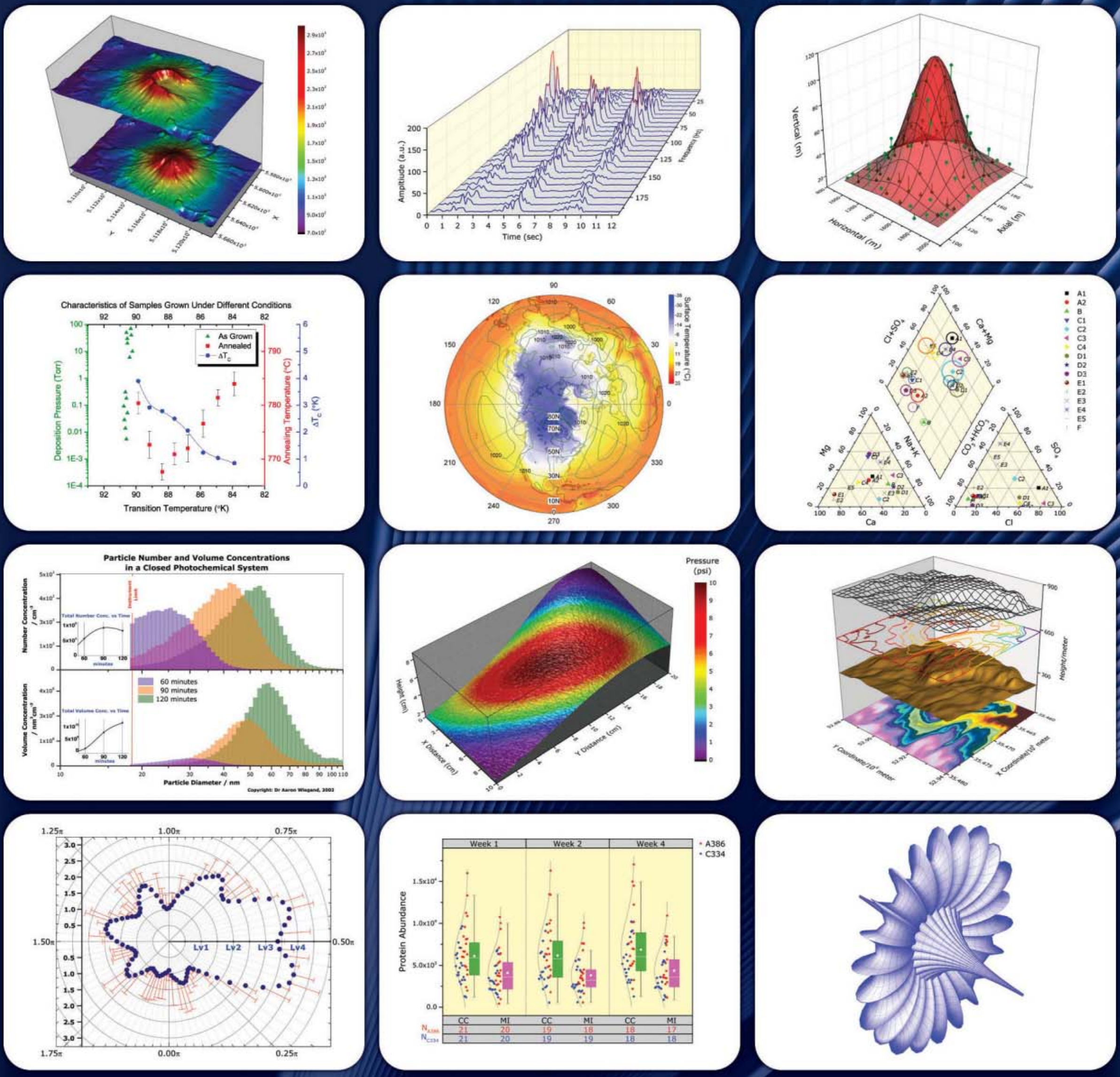

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