IEEE Spectrum

THE MAGAZINE OF TECHNOLOGY INSIDERS

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# GROWING UP SMARTPHONE

It'll start as a nanny and end as a nurse. But it might make you long for the days when you could turn it off

## How I Became A Lab Mouse—In My Own Home

## Solar-Powering The Military

## Time to Get Realistic About Terahertz Waves

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IEEE


IF WE™ can help people who have a damaged skeleton, could they walk again?
A robotic skeleton
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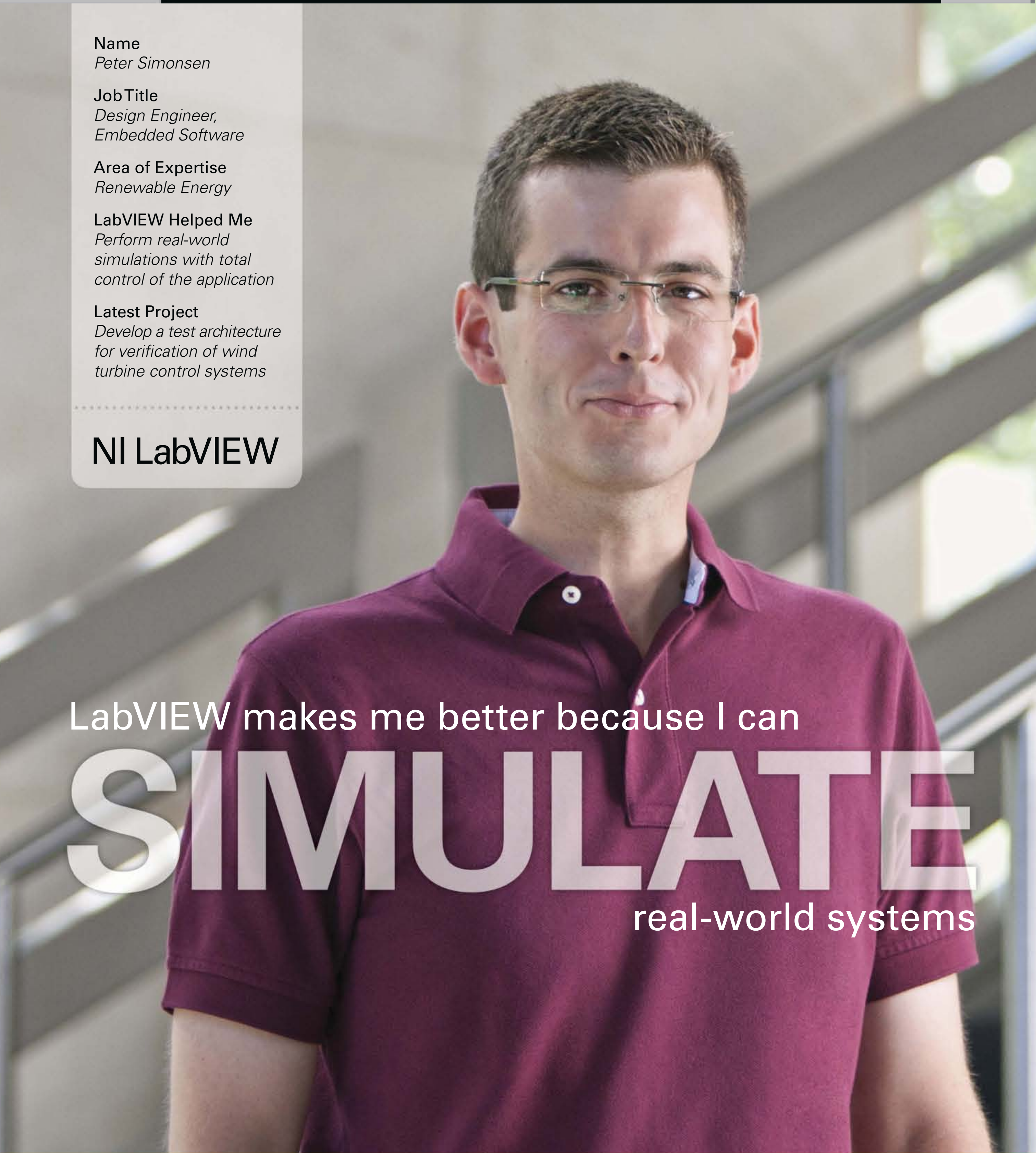
Name
Peter Simonsen
Job Title
Design Engineer, Embedded Software
Area of Expertise
Renewable Energy
LabVIEW Helped Me
Perform real-world simulations with total control of the application
Latest Project
Develop a test architecture for verification of wind turbine control systems
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## UPDATE



## OPINION



## DEPARTMENTS



## SPECTRUM.IEEE.ORG AVAILABLE 1 SEPTEMBER

### A Robot Ankle for Amputees

The BiOM is one of the world's most advanced prosthetics. Created by iWalk, this robotic ankle can tell whether the user is walking, running, climbing a ramp, or walking down stairs. Its sensors measure where it is in space, and its microprocessors determine how much it should flex and how hard it should push off from the ground in order to produce a natural gait. It's a smart, self-powered prosthetic, and a huge stride forward in bionics.

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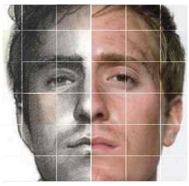
**WORKING WITH SKETCHY IMAGES**
Television shows like "CSI: Crime Scene Investigation" feature high-tech computer systems that can easily identify suspects. But the face-matching technology of real-life law-enforcement agencies is not yet that sophisticated. In this issue, read about how several IEEE members at Michigan State University, in East Lansing, are working to make matching forensic sketches to mug shots a reality.



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CLOCKWISE FROM LEFT: STAN HONDA/AFP/GETTY IMAGES; IWALK; GETTY IMAGES; MICHAEL J. RUPLE

# back story

## DIY Publishing

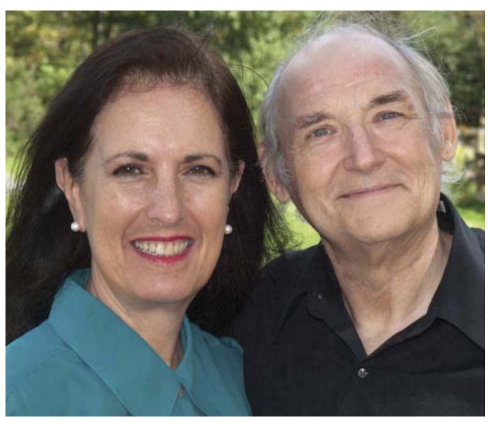
IT'S NO SECRET that publishing is going through its greatest upheaval since the industrialization of printing presses in the 19th century. Electronic books and print-on-demand services now allow anyone with the know-how to reach millions of potential readers without securing publishing's traditional go-ahead: the backing of a publishing house.

But getting that know-how can be a challenge. So for this issue, we asked the husband-and-wife team of Daniel and Sally Wiener Grotta to walk prospective authors through the technical details of taking a book from a word processor to selling it online (see "Hands On: Publishing Yourself").

For the Grottas, the shift to digital publishing came as no surprise: In 1967, Daniel attended the Publishing Procedures course at Radcliffe College, then the only academic program in publishing in the United States. He recalls discussions about "having automatic fax machines that would send readers pages, or having text displayed on a television-like tablet, like the ones they had on 'Star Trek.' "

The Grottas are quick to point out that it's not just technology that's driving authors toward digital publishing. Publishing houses themselves sped along the exodus by alienating writers. The old guard of "gentleman publishers" were bought out by financiers "who didn't invest in their inventory, didn't invest in authors, but wanted content they could roll over quickly," says Sally. "Publishers no longer had loyalty to their authors, so authors stopped feeling loyal to publishers."

The Grottas have published several books in the traditional way, including the first biography of J.R.R. Tolkien (by Daniel), but have now moved to digital publishing. They believe that the notion of a publishing house still has one important thing to offer in the digital age: a stamp of approval, allowing readers to find books they are likely to enjoy amid a flood of titles. However, the Grottas think that the future of these houses lies in boutique operations that offer specialized content and greater support for writers. To that end, they have recently founded their own digital imprint, Pixel Hall Press. It will concentrate on character-driven adult and young adult fiction, and art and photography nonfiction. ❏



DANIEL GROTTA

CITING ARTICLES IN IEEE SPECTRUM

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IEEE Spectrum, 3 Park Ave., 17th Floor, New York, NY 10016-5997
Attn: Editorial Dept. Tel: +1 212 419 7555 Fax: +1 212 419 7570
Bureau: Palo Alto, Calif.; Tekla S. Perry +1 650 328 7570
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# contributors

## CARTER M. ARMSTRONG

is vice president of engineering in the electron devices division of L-3 Communications, in San Carlos, Calif. In "The Truth About Terahertz" [p. 28], he discusses the promise and perils of trying to exploit this region of the electromagnetic spectrum. A vacuum-device scientist, he says one of his favorite *IEEE Spectrum* articles is Robert S. Symons's "Tubes: Still Vital After All These Years," in the April 1998 issue. "It was true then, and it's still true today," Armstrong says.

## DAN SIEWIOREK

is a professor at Carnegie Mellon University. He is also director of the Quality of Life Technology Center, which is run jointly by CMU and the University of Pittsburgh and sponsored by the National Science Foundation. He is developing virtual-coaching applications for smartphones—precursors, he hopes, of the ones he describes in "Generation Smartphone" [p. 46]. While his two daughters were growing up, he fantasized about apps like these, which might have saved him much consternation.

## STEVEN J. FRANK

is a graduate of Harvard Law School and a partner at Boston's Bingham McCutchen. He writes in this issue about his experience taking MIT's large-scale remote-learning course in circuit design [p. 21]. Although he knew something about the subject, "the level of challenge was, shall we say, a bit unexpected. But so were the rewards." Frank is the author of *Intellectual Property for Investors and Technology Managers* (Cambridge University Press, 2006).

## RICHARD STEVENSON

returns to photovoltaic cells in "Tapping the Power of 100 Suns" [p. 40], a topic he last covered for *Spectrum* in 2008. This time he looks not at the immediate commercial possibilities but rather at an effort funded by the U.S. Defense Advanced Research Projects Agency to drastically increase the efficiency of PV modules that soldiers might carry into the field. His Ph.D. in physics from the University of Cambridge centered on the compound semiconductors used in such PVs.

## ALFRED POOR

writes in "Reformulating Displays" [p. 22] about new materials coming soon to big-screen televisions. A senior member of the Society for Information Display, Poor also reported on displays in *Spectrum*'s July issue, where he covered the ongoing shift to smart TV. At *PC Magazine*, Poor was a contributing editor for more than 20 years and the publication's first lead analyst for business displays.

## EMILY WALTZ,

a freelance journalist based in Nashville, frequently writes for *Nature* and *Nature Biotechnology*. For "How I Quantified Myself" [p. 34], she spent two months trying out various health-, fitness-, and sleep-monitoring gadgets that recorded her biological statistics. She says her tennis buddies were enthusiastic about the experiment and quizzed her after games on how many calories they'd burned and how many steps they'd taken.

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SENIOR DIRECTOR; PUBLISHER, ***IEEE SPECTRUM***
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Marion Delaney, m.delaney@ieee.org
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BUSINESS MANAGER Robert T. Ross
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INTERACTIVE MARKETING MANAGER Ruchika Anand, r.t.anand@ieee.org
LIST SALES & RECRUITMENT SERVICES PRODUCT/MARKETING MANAGER
Ilia Rodriguez, i.rodriguez@ieee.org
REPRINT SALES +1 212 221 9595, EXT. 319
MARKETING & PROMOTION SPECIALIST Faith H. Jeanty, f.jeanty@ieee.org
SENIOR MARKETING ADMINISTRATOR Simone Darby, simone.darby@ieee.org
RECRUITMENT SALES ADVISOR Liza Reich +1 212 419 7578
ADVERTISING SALES +1 212 705 8939
ADVERTISING PRODUCTION MANAGER Felicia Spagnoli
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HUMAN RESOURCES Betsy Davis, SPHR
+1 732 465 6434, e.davis@ieee.org
PUBLICATIONS Anthony Durniak
+1 732 562 3998, a.durniak@ieee.org
EDUCATIONAL ACTIVITIES Douglas Gorham
+1 732 562 5483, d.g.gorham@ieee.org
STANDARDS ACTIVITIES Judith Gorman
+1 732 562 3820, j.gorman@ieee.org
MEMBER & GEOGRAPHIC ACTIVITIES Cecelia Jankowski
+1 732 562 5504, c.jankowski@ieee.org
GENERAL COUNSEL AND CHIEF COMPLIANCE OFFICER Eileen Lach
+1 212 705 8990, e.m.lach@ieee.org
CORPORATE STRATEGY & COMMUNICATIONS Matthew Loeb, CAE
+1 732 562 5320, m.loeb@ieee.org
CHIEF MARKETING OFFICER Patrick D. Mahoney
+1 732 562 5596, p.mahoney@ieee.org
CHIEF INFORMATION OFFICER Alexander J. Pasik, Ph.D.
+1 732 562 6017, a.pasik@ieee.org
CHIEF FINANCIAL OFFICER Thomas R. Siegert
+1 732 562 6843, t.siegert@ieee.org
TECHNICAL ACTIVITIES Mary Ward-Callan
+1 732 562 3850, m.ward-callan@ieee.org
MANAGING DIRECTOR, IEEE-USA Chris Brantley
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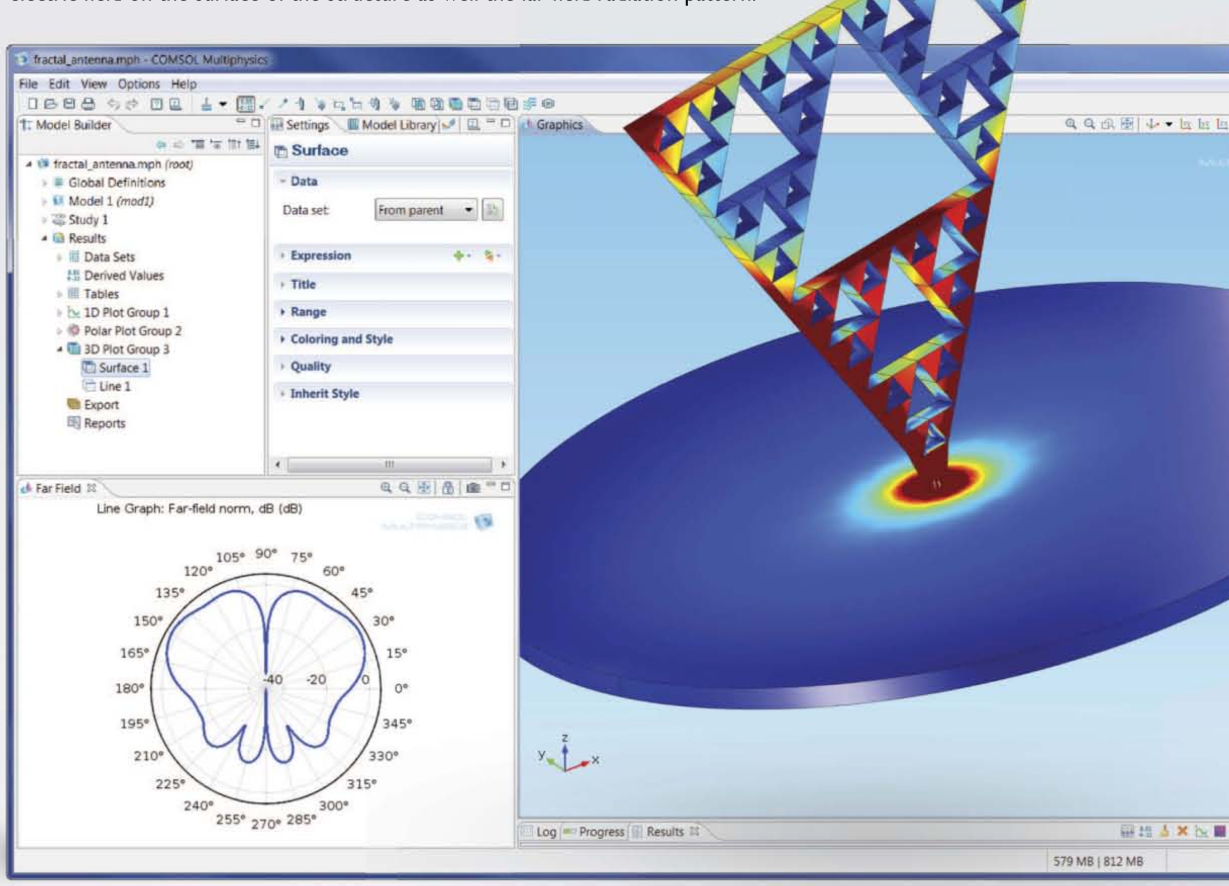
CLOCKWISE FROM TOP LEFT: MIKE MARTIN; THE ROBOTICS INSTITUTE/CARNEGIE MELLON UNIVERSITY; KATHARINE STEVENSON; MALCOLM BROWN; COMPUTER SHOPPER; GOODWIN PROCTER

# Verify and optimize
# COMSOL M

ANTENNAS: The Sierpinski fractal monopole antenna shows multiband responses inherited from the nature of a fractal structure. Results show the magnitude of the electric field on the surface of the structure as well the far field radiation pattern.



spectral lines

# Our Smartphones, Ourselves

When my family goes on a long drive, we take our US $79 Garmin GPS locator along to help us out. It talks to us in what sounds like a female British voice, and so we talk to her, and about her, along the way. Allison (as we call her) usually seems to want to take the scenic route. She wants to turn around. She says to take exit 44, not 42. She recalculates. We also carry a map to validate her directions. Happily enough, she never complains about our second-guessing. Having turned "it" into "she," we feel a little guilty when we ignore her advice. We also tell her when we're stopping for gas and even thank her for a job well done.

So just imagine what will happen when smartphones get really smart—like the devices described in Dan Siewiorek's "Generation Smartphone." Siewiorek tells the story of Tom, a man from the future, who is accompanied throughout his life's journey by a series of "SmartPhone 2*x*.0s." Each acts as a surrogate guardian, personal assistant, teacher, life coach, and companion, presumably vigilant and loyal to the very end—or at least until it's replaced by the next version.

We'd certainly be drawn to such a thing in my home. We're already overly attached to the vibrating, marimba-chiming boxes we carry around the clock. Today's smartphones are remarkable pieces of technology, but they have only just begun to communicate with us naturally, using voice interfaces like the iPhone's Siri.

But outside of a few specific areas—dining, calendaring, and so on—let's face it: Siri is still pretty clueless. Future generations of smartphones, however, will exploit much more powerful processors and software to "learn" about our environment and us. They'll absorb vast amounts of data, much of it coming from sensors and the so-called Internet of Things that they will be immersed in.

Among the sensors feeding these future phones will be personal health and wellness devices, of the sort described in Emily Waltz's article in this issue, "How I Quantified Myself." They'll monitor our sleep patterns, blood pressure, heart rate, and glucose levels. Naturally, we'll want our phones to send this data to our physicians and compare them with our own baselines as well as medical databases.

But what happens when this brilliant smartphone of yours is able to evaluate your health data in real time and quickly give you diagnoses, exhortations, and admonitions in a Siri-like voice—with or without a British accent? Will you be more or less likely to take seriously the advice of a phone, compared to that of a flesh-and-blood physician?

The potential quagmires posed by a souped-up Siri are not hard to imagine. Perhaps your phone will report health problems in such a way that they could be accessed by prospective employers, love interests, or insurance companies. Noticing your distractibility and device addiction while you text and drive, perhaps it will turn off your car and send one report to the police and one to your therapist. And when it makes mistakes—you weren't driving erratically, the phone's accelerometer was on the fritz—rectifying the situation could prove tough.

Despite such caveats, a future of smartphone companions may be upon us before we know it. Silicon Valley venture capitalist Marc Andreessen predicts that just 10 years from now, 5 billion people will have smartphones like the ones that already rule many of our homes and offices. What will it mean for our cultures, our work, and our lives when all these smartphones are able to talk to us, and then to each other? —Susan Hassler

PHOTO: DAN SAELINGER; STYLIST: MARIA-STEFANIA VAVYLOPOULOU

# update

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**SPANISH SOLAR:** Photovoltaics like these in Cuervo, Spain, are under scrutiny. New research suggests they produce too little energy.

PHOTO: FLIP FRANSSEN/ HOLLANDSE HOOGTE/ REDUX

## Argument Over the Value of Solar Focuses on Spain

Analysts disagree on whether the energy returned from solar is worth the energy invested

OIL PRODUCERS are working harder than ever to replace their reserves and, increasingly, turning to nonconventional petroleum sources such as Canada's tarry bitumen and ultra-deepwater offshore wells. As they do so, they are investing more energy to deliver each new barrel of oil. Similar trends are playing out for natural gas and coal, and a growing number of energy analysts are worried. They see these accelerating trends—what they call fossil fuels' declining energy return on investment, or EROI—as an ill portent for the global economy.

The critical question for the future is whether renewable energy sources can fill the gap, sustaining the energy surplus that has supported explosive growth in human life span and population since the industrial revolution. A book due out later this year promises a hard-nosed look at solar energy—the fastest growing form of renewable energy—and is likely to raise plenty of eyebrows.

Coauthored by ecologist Charles A.S. Hall and Spanish telecom and solar systems engineer Pedro A. Prieto, the book is a case study of Spain's utility-scale installations of photovoltaics. It will be, the authors claim, the first comprehensive analysis of large-scale PV based on data rather than models. Hall—a professor at the State University of New York College of Environmental Science and Forestry, in Syracuse—formalized the concept of EROI more than 40 years ago, as the energy yielded by an energy-gathering activity divided by the energy invested in that activity.

While mum on their EROI numbers, Hall and Prieto say the book will demonstrate that building and operating PV requires considerably more energy than its promoters claim. And, they add, fossil fuels provide the bulk of the energy investment.



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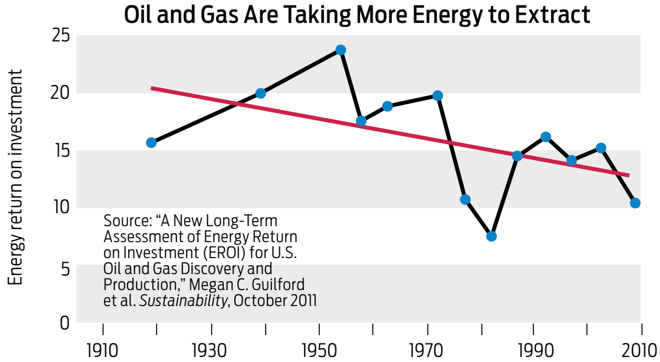
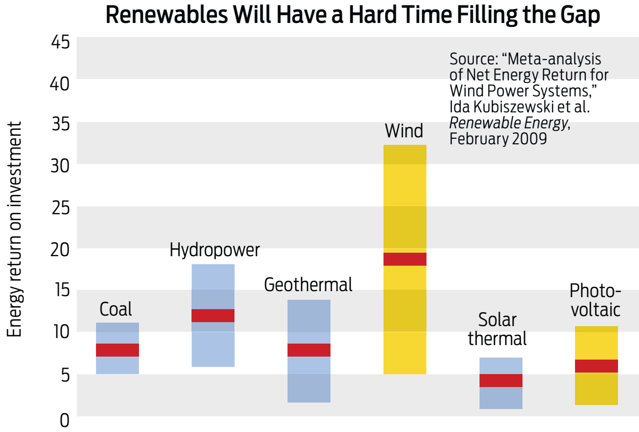
# update

## Oil and Gas Are Taking More Energy to Extract




Energy return on investment, the amount of energy produced divided by the energy needed to acquire it, has been on the decline in the United States [above] and the rest of the world.

## Renewables Will Have a Hard Time Filling the Gap




Estimates of the energy return on investment for several energy sources vary widely, especially for renewables. (Shown are the mean estimate and standard deviation from a meta-analysis of many studies.)

"The conclusion is that solar PV systems are very much underpinned by a fossil fuel society," says Prieto.

Prieto cites two dozen energy inputs left out of many life-cycle analyses of photovoltaic systems. He witnessed these inputs directly while building one of Spain's earliest utility-scale solar facilities—a 1-megawatt plant in Extremadura that began operating in 2006—and while supporting subsequent PV installations. The factors include construction of roads, water pipes, and transmission lines to serve the often-remote solar sites, and even international flights to get on-site help from specialist engineers.

All told, says Prieto, the result could be an EROI figure even lower than the already controversial EROI of 6.8 that Hall previously cited for PV, which would make it inferior to most other forms of power generation [see charts, above]. According to Prieto we are "very far" from having solar power systems that provide substantial net energy to society, and he is not much more optimistic about similarly fast-growing wind power.

Not all energy analysts tracking EROI accept this dim view of renewable energy. For one thing, analyses of fossil fuels likely neglect to count many real-world energy inputs such as those that Prieto is adding to solar's baggage. For another, PV efficiency is rising fast. An updated analysis published this March by Marco Raugei, a life-cycle expert at Barcelona's Universitat Pompeu Fabra, and two U.S.-based colleagues calculates EROIs of 19 to 38 for various PV module types.

Joshua Pearce, an associate professor of materials science and engineering at Michigan Technological University, notes that energy policies could improve real returns from solar energy by offering incentives for the use of the highest-EROI systems. Centralized solar farms full of cheap crystalline silicon modules—which EROI studies show to be the most energy intensive of PV installations—dominate the market because they are the most profitable to build. A deployment scheme designed to reward EROI instead would shift the calculus, says Pearce: "Before a single centralized PV facility was erected, we would have thin-film PV panels integrated into every appropriate rooftop."

Stanford University energy systems expert Adam Brandt, meanwhile, discounts PV's current reliance on fossil energy. What's important, he says, is that a PV installation can use fossil energy to produce carbon-free power—a critical response to climate change. "If you consume one unit of fossil fuel and get something like 8 or 12 units of solar energy out, that's a positive story," Brandt says.

If the optimists are wrong, however, prepare for a shock. In a 2009 paper, Hall and his colleagues estimated that energy supplies with an EROI of at least 12 to 13 were required to support the trappings of modern developed nations, such as higher education, technological progress, and high art. Oil and gas production in the United States may have already fallen below that threshold, the paper says, and global production appears to be following fast.

The implications, according to Prieto and Hall, are sobering. In fact, Prieto believes he is already witnessing economic decline caused, in part, by petroleum's dwindling EROI. He sees it manifested in Spain's debt crisis. "Energy is the ability to do work. If we do not have more energy one year than the preceding year, we will hardly be able to grow," he says. "And, if there is no growth, the financial system collapses." —Peter Fairley

## "THE NORTHERN GRID HAS FAILED AGAIN."

—Arvinder Singh Bakshi, chairman of the Central Electricity Authority, after some 600 million Indians lost power on 31 July.

# Tech Industry Money in U.S. Elections

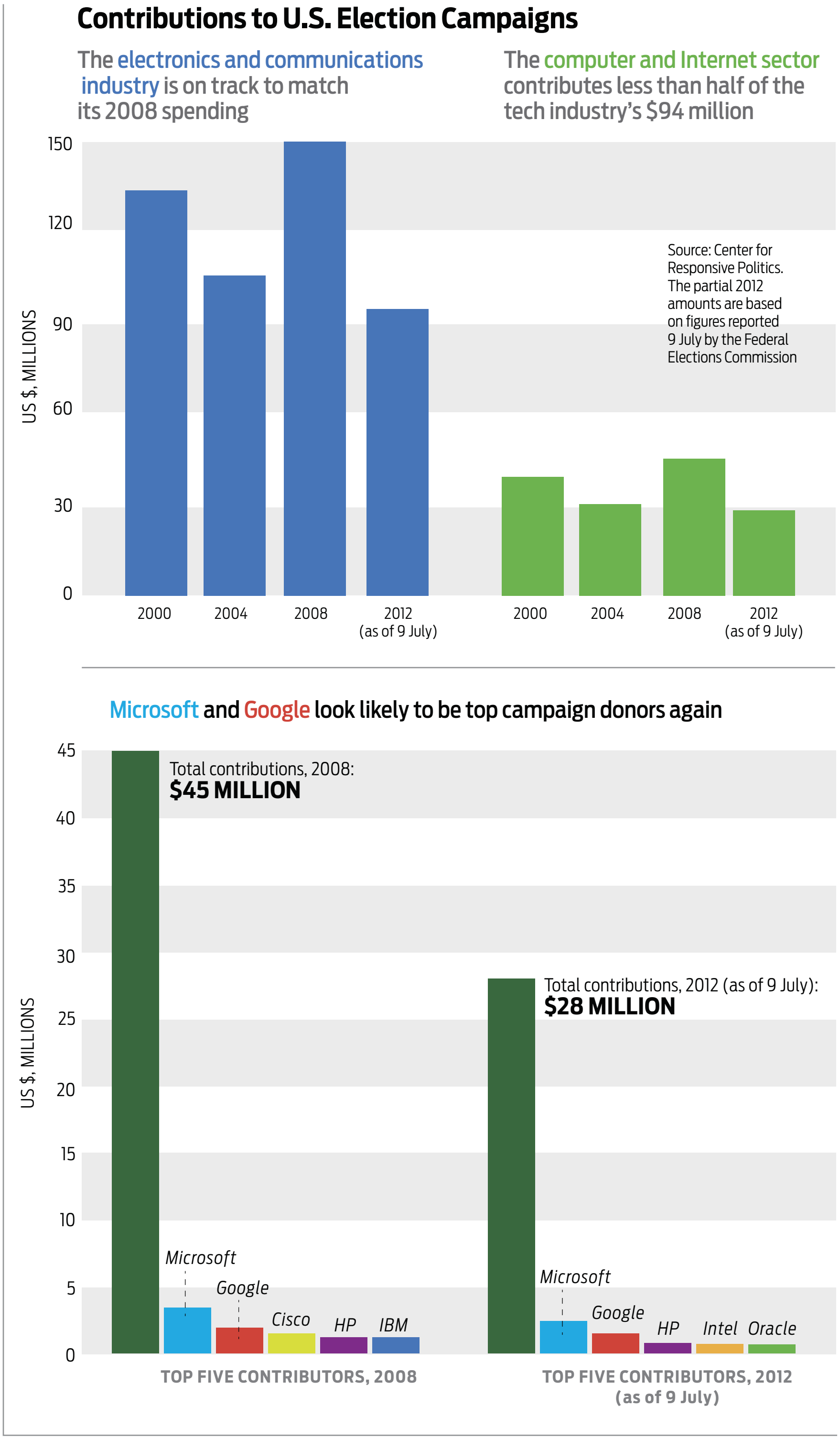
With stakes low, so are campaign contributions

When it comes to funding political campaigns, the technology industry maintains a pretty low profile. In fact, figures from the Center for Responsive Politics (CRP) show the industry is spending about the same amount as in previous presidential election years [see chart, "Contributions to U.S. Election Campaigns"]. That's despite overall campaign spending that's set to beat 2008's record by US $400 million.

As of the end of July, numbers tallied by the CRP showed that contributors from the electronics and communications category (which includes computer and Internet companies) had spent $94 million. Following historical giving patterns, that put the category on pace to match total 2008 spending of $149 million. "Contributions tend to peak close to the election—that's when you typically see the most money flowing into the system," says Douglas H. Weber, a senior researcher at the CRP.

Ever since the watershed year of 2000, the end of a decade in which the Microsoft antitrust trial showed the tech industry that it needed to pay attention to Washington, Silicon Valley has been experimenting with ways of flexing its political muscle. Yet it still doesn't give nearly as much money as other industries, such as finance and banking, and legal.

Betsy Mullins, senior vice president for policy and political affairs at the tech industry advocacy group TechNet, says the industry is still in its adolescence



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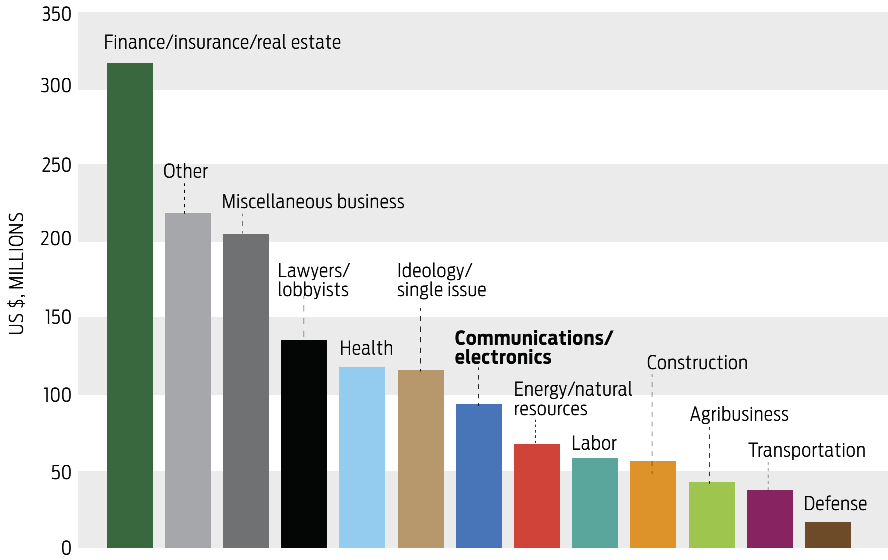
The **tech industry** is not among the biggest contributors for the current campaign




when it comes to political giving. "Over time, this unregulated industry gradually bumped into more issues and realized it needed stronger relationships in D.C.," she says. Even though tech companies have risen in the Fortune 500 (Google is currently ranked 73), their political giving pales in comparison to some of their peers on that list, she says. "Banks and telecommunications companies have political giving and lobbying down to an art form, because they've been doing it for 100 years," she says.

At the same time, the shifting rules in campaign finance make it hard to be certain exactly how much the tech industry—or any industry—is giving and how. "Our suspicion is that there may be a lot of money that we're not seeing, that's following a different pattern," says Bill Allison, editorial director at the government watchdog group Sunlight Foundation. "But unfortunately we can't say with any certainty because we just don't know who the donors are."

Those shifting rules have changed and will probably continue to change how companies give. "All of these variables are still shaking themselves out," says Mullins. "I think in four years you're going to see a very different type of political activity than what the tech community is doing today. I can't predict what that's going to be, but all these factors influence what tech does in the political space."

Already, tech companies are exploring giving more than just money, such as offering free training. "Facebook and Twitter both have active efforts to recruit members of Congress to use their platforms to communicate with their constituents," says Allison. "That's not necessarily a campaign contribution or a lobbying campaign, but clearly it's an attempt to both sell their services and to get members of Congress to have a good impression of them." —Tam Harbert

# THE RICH AND THEIR REACTORS

Many countries are backing away from nuclear power, but some of the world's most visible entrepreneurs are throwing their weight behind one version of the technology or another. Here are the nuclear ambitions of a triumvirate with a collective fortune of US $83.6 billion. *—Dave Levitan*

**SIR RICHARD BRANSON**

The Virgin Group chairman is known for some extravagant investments, perhaps most notably Virgin Galactic, which plans to send you—yes, *you*—into space. Branson recently sent a letter to U.S. president Barack Obama asking for a meeting and urging him to reopen government research into integral fast reactors (IFR), although he apparently has not yet thrown any money into the idea. Also known as fast breeders, IFRs can burn the waste uranium and plutonium generated by standard fission reactors, potentially solving the ongoing nuclear waste question and reducing the risk of nuclear weapons proliferation. Still, there is plenty of controversy surrounding these reactors—enough for Obama to decline the request.

**BILL GATES**

The world's second-richest person is actually spending some dough on nuclear power, as a significant investor in a company called TerraPower, based in Bellevue, Wash. The company is working on a design called a traveling-wave reactor (TWR). These reactors need a small amount of enriched uranium to start up, but once on line, they can sustain themselves using spent uranium from standard reactors. In a TWR, a slow-moving wave of neutrons converts adjacent waste products into fissile isotopes. It would, theoretically, require far less fuel and maintenance than today's reactors. Gates has reportedly invested tens of millions of dollars.

**JEFF BEZOS**

Amazon's founder is throwing his money further into the reaches of science fiction than his cobillionaires. His investment company, Bezos Expeditions, contributed in 2011 some unknown portion of $19.5 million raised by the Canadian company General Fusion. As the name suggests, General Fusion is going for the sun-in-a-bottle approach to nuclear power, focusing on a technique known as magnetized target fusion. It's a hybrid of the magnetic fusion scientists are working on at ITER, in France, and the inertial confinement fusion research at the National Ignition Facility, in California. The Bezos-backed scheme may seem like pie in the sky, but... well, it probably is.

FROM LEFT: STUART WILSON/GETTY IMAGES; NELSON CHING/BLOOMBERG/GETTY IMAGES; ANDREW KELLY/REUTERS



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**83 MILLION** Number of illegitimate Facebook accounts. The social network says about half of these were just duplicate accounts, but it labeled 14 million accounts "undesirable."

**SCORCHED EARTH:** The U.S. Midwest is just the latest in a string of drought-stricken areas.
*PHOTO: SCOTT OLSEN/ GETTY IMAGES*

# Predicting the Future of Drought Prediction

## Better instruments and models could help scientists forecast droughts years in advance

As extreme weather events go, droughts—like the one that singed Russia's wheat crop two summers ago and the one that engulfed the United States in July—are about as tricky as it gets. Unlike hurricanes and tornadoes, drought does not have an obvious start or end. In fact, there isn't even a clear definition for it, making it hard to measure and monitor, let alone predict. But with better observations of the earth, oceans, and atmosphere and improvements in computer modeling, scientists think they'll be able to foresee the chances of drought up to a decade in advance, and better predict droughts that arise suddenly or last longer than a few months.

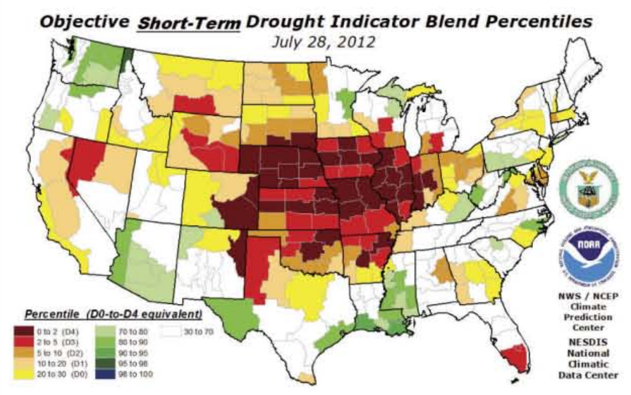
Today, scientists can forecast drought only about three months ahead for most parts of the world with any significant certainty.

"Forecasting drought is an inexact science," says Brian Fuchs, a climatologist at the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln. "Drought is typically characterized by slow onset and slow recovery. To pick up signals of something that happens over weeks or months is hard for computer models."

Drought involves a seemingly inexhaustible list of factors—from local ones such as groundwater level, stream flow, soil moisture, and vegetation, to large-scale global weather patterns such as El Niño and La Niña. All of these change over different time periods, from days to decades, and many are tied to each other. Global warming tops off the chaotic mix.

Nevertheless, scientists in the United States have produced some of the most sophisticated tools to monitor and predict drought. Resource planners and policymakers rely mainly on the U.S. Drought Monitor, an online map of dryness that has been updated weekly since it was unveiled in 2000 by the Department of

# update




**DRYING UP:** A screen shot from the U.S. Drought Monitor in late July. Other countries are working on similar systems.

*IMAGE: NATIONAL DROUGHT MITIGATION CENTER*

Agriculture, the National Oceanic and Atmospheric Administration (NOAA), and the NDMC. The monitor combines several mathematical indices calculated by feeding computer models with temperature, precipitation, and soil moisture data. The physical data comes from NOAA's polar-orbiting satellites and on-the-ground temperature, rain, and snow gauges. "The U.S. leads in drought monitoring," Fuchs says. "Many other countries are trying to emulate the U.S. Drought Monitor."

While monitoring has been done for decades, forecasting drought is still in its infancy. Today, it blends science and art, and the only place it's done on a national scale is at NOAA's Climate Prediction Center (CPC) in Camp Springs, Md. Twice every month, meteorologists there subjectively produce the U.S. Seasonal Drought Outlook, which predicts conditions for the next three months.

To create the Drought Outlook, scientists mix data from the Drought Monitor with soil moisture information and the CPC's three-month forecast of temperature and rainfall. They also incorporate current climate conditions along with past heat and precipitation.

The temperature and rainfall outlook comes from NOAA's climate model, which runs on an IBM Power6 mainframe computer, and takes half a day to finish one simulation run. The model, which was unveiled seven years ago, couples ocean and atmosphere models that had to be run separately before, explains Dan Collins, a forecaster at the CPC. The newer, improved version that went into operation this year also includes things like sea- and land-ice melting and changing levels of carbon dioxide in the atmosphere.

## 5 HOURS 49 MINUTES

Time from Kazakhstan to the International Space Station using a new launch plan tested in August. Ordinarily the trip takes three days.

Collins says that more-powerful computers would make it possible to include more-detailed physics and more climate system components. "You want to better simulate the way in which clouds are formed or water evaporates from soil," he says. Greater computing prowess would also mean that each simulation step would cover a shorter time and distance—a few minutes and a few kilometers as opposed to the hours and tens of kilometers used now. This would improve the ability to capture smaller, more rapid changes in temperature and precipitation.

Other advances expected in the coming years include more extensive ground observation networks and NOAA's next-generation polar satellite, which is scheduled for launch in 2016 and will be equipped with advanced visual and infrared imagers that produce data with a higher temporal and spatial resolution. These will give better temperature, precipitation, and soil moisture data, which will improve the accuracy of drought prediction, says Fuchs. Already, the Drought Monitor maps have gotten more refined over 12 years because of resolution improvements in satellite gear, he says. What's more, NASA is developing satellite-based instruments that are better at measuring soil moisture, he adds. The Drought Monitor currently uses soil moisture that is indirectly estimated by computer models based on rainfall and temperature observations.

Collins anticipates that longer-term drought prediction could be possible five years from now. That's when NOAA scientists are expecting to next upgrade the climate model, to include decade-long climate fluctuations. They hope to do this by simulating known long-term ocean fluctuations such as the Atlantic multidecadal oscillation. Fuchs says, "I anticipate continuing to see drought monitoring and prediction evolve, and technology will be a driving factor."

—Prachi Patel



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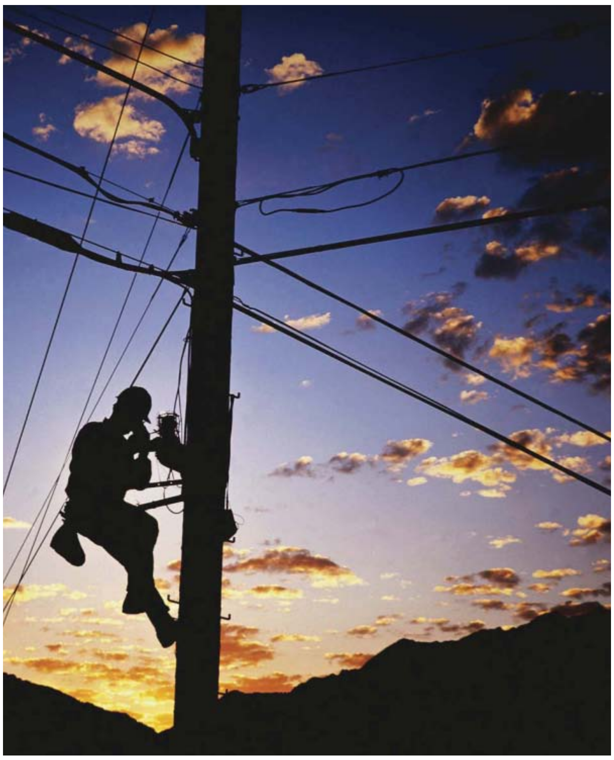
# the big picture

**The Final Frontier**

The space shuttle *Enterprise* has completed its last trek. The winged craft, shown at the Intrepid Sea, Air & Space Museum, in New York City, has been on public display there since 19 July. It began its life in 1976 as the original prototype of the fleet that would famously take off like rockets and land like planes. Though the shuttle was named after the fictional USS *Enterprise* from the TV show "Star Trek," it has never flown in space. The craft, built without an engine or heat shields, was first used to test the design's gliding and landing ability before the introduction of its successor shuttles. In retirement, it became a source for parts used in newer shuttles and in the post-accident investigation of the 2003 shuttle *Columbia* disaster.

*PHOTO: STAN HONDA/ GETTY IMAGES*

# careers



## WHERE THE JOBS ARE: 2012

### In a warming job market, the hottest sector is power

NEW ELECTRICAL and computer engineers stepping out into the real world this year might not get the multiple job offers and off-the-charts starting pay of the precrash days, but they can rest assured that their skills will be put to good use. Hiring is up by 10 percent over last year, and pay has increased slightly for electrical and computer engineers of the class of 2012.

EEs looking for stable jobs and high salaries should consider the power sector in particular. In the United States, millions of government and industry dollars are now flowing into a reviving utility industry. Renewables and the smart grid are about to breathe new life into a rusty power transmission and distribution system, while half of the workforce is expected to retire in the next 5 to 10 years, creating thousands of jobs. The U.S. utility industry hired 120 000 new bachelor's graduates this year across majors, and it paid the highest starting salaries—averaging US $64 000—among all industries, according to the National Association of Colleges and Employers (NACE) in Bethlehem, Pa. Gregory Reed, director of the Power & Energy Initiative at the University of Pittsburgh, says that EE masters graduates with a power engineering concentration are starting at around $80 000, while recent Ph.D.s are making over $90 000.

Meanwhile, in China and India, the power grid is nascent, and all energy sectors, from coal and nuclear to solar and wind, are undergoing prolific growth. "They need engineers more than ever," Reed says.

"I don't think there's anything more exciting than this career right now," says Wanda Reder, a vice president at S&C Electric Co., in Chicago. "There are a lot of empty seats due to attrition. At the same time, there's a lot of new technology coming in. We need really good minds to figure out how to integrate those technologies and operate the power system better, more efficiently, and cleaner than has been possible in the past."

The energy jobs outlook in Europe is more mixed. Utilities there face the same aging workforce issues as in the United States: Between 19 and 38 percent of workers at eight major European electricity companies are due to retire within the next decade. However, not all those positions will need to be filled, and many of them will require different skills, says Charlotte Renaud, a policy officer at the electricity industry association Eurelectric, in Belgium. That's mainly because of a phaseout of nuclear power in many EU countries and an increasing switch to renewables. "You need less people to run windmills than a nuclear power plant," she says.

Outside the power industry, salary offers to engineering grads haven't changed much in a year overall, according to NACE. Among engineers, computer and aerospace engineers are the top earners, bringing in median offers of $67 800 and $64 200. And as was the case a year ago, electrical engineers saw the biggest jump in starting salaries—2.2 percent over last year—to reach $57 300.

The profusion of smartphones and tablets, the health-care industry's increasing use of computer systems, and concerns about cybersecurity are all keeping software engineers in high demand, according to the U.S. Bureau of Labor Statistics. The median salary of new computer-science grads went up by 2.4 percent to $56 383, with new graduates being hired in the information sector making an impressive $64 400, according to NACE. According to the Bureau of Labor Statistics, employment for software developers should grow by 30 percent in the decade leading up to 2020: The average growth rate for all occupations is 14 percent.

—PRACHI PATEL

*A version of this article appeared online in July 2012.*

GETTY IMAGES

# education

## Review: MITx's Online Circuit and Analysis Course

The university's first massively scaled course is not for casual students


Anant Agarwal

M. SCOTT BRAUER

MIT'S ANANT AGARWAL has a thing for chain saws. The professor of electrical engineering and computer science said so himself as he welcomed his vast horde of online students. And it *was* a horde: More than 150 000 of us from dozens of countries had signed up for MIT's inaugural MOOC, or massively open online course, which began in early March and ended in June. The course, dubbed 6.002x, was an adaptation of MIT's undergraduate class in circuit design and analysis and was part of the university's MITx initiative, which aims to offer anyone with an Internet connection access to a selection of its courses. Participants were lured by some powerful enticements: MIT's prestige, the opportunity to learn from a renowned professor, and the price—free. Although MIT has made course materials publicly available for over a decade, this is its first online class involving scheduled instruction, supervision, and testing. Only participants who formally signed up for the 6.002x course were eligible to earn a credential certifying successful completion; MIT has not announced when the course will be offered again.

In an early recorded lecture, which plays as a YouTube video, Agarwal dons full Blues Brothers regalia to demonstrate noise margins, a chain saw his source of system noise as he bobs to a disco tune, while laughter resounds in the classroom. But any 6.002xers who mistook his professorial charisma for a lack of seriousness, expecting a gentle tiptoe through circuitry basics, were swiftly disillusioned. The curriculum, identical to that of the classroom MIT course, was challenging. Spanning almost the entirety of the 1000-page course textbook, which Agarwal coauthored, each of the 14 weeks of class included 2 to 4 hours of lectures, online exercises interspersed with lecture sequences, a homework problem set, and an online lab, which involved building and testing simulated circuits. Optional video tutorials supplemented the lectures with solved problems and math refreshers. Midterm and final examinations rounded out the busy calendar.

"Massively open" means massively scalable, and the MITx organizers managed to create an impressive suite of shared resources. These included an online version of the course textbook; an always-available "circuit sandbox" lab environment complete with virtual signal probes, sweep generators, and oscilloscopes; and—most critically—a lively and well-managed discussion board.

So how did it all compare to a live class? Astonishingly well, it seemed to me. The ability to pause lectures, which were delivered on virtual blackboard slides that Professor Agarwal marked up as he spoke, was something of a revelation: Gone was the multitasking stress of trying to take notes and listen at the same time. The lecture sequences "remembered" where you left off, so segments could be viewed outside a fixed schedule. And the lectures themselves felt surprisingly personal.

The problem sets, while self-marking, tended to escalate in difficulty. You entered an answer, clicked on the "check" button, and after a pregnant pause, the grading software delivered a scarlet letter *X* or a green check mark. For the exercises and homework problems, you could answer as many times as

# tools & toys

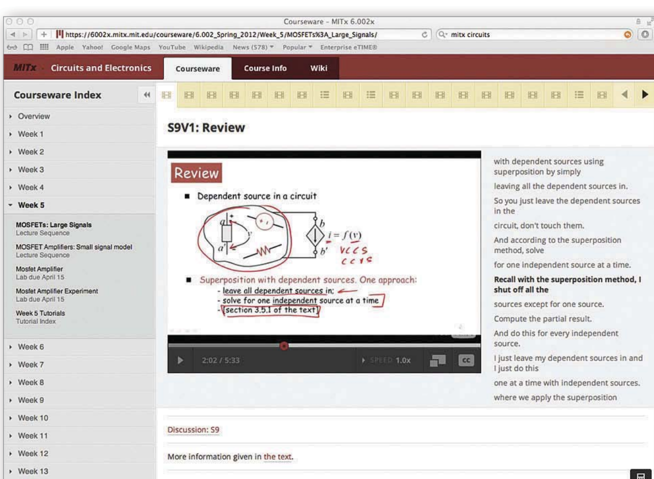
you liked. Participants quickly learned one reason that engineering is so amenable to online instruction: Guessing is pointless, and answers are not a matter of opinion. Hours were spent fighting the scarlet letter, and when the green check mark of achievement at last arrived, it did so with embarrassingly potent psychic force. But the "aha moment," as Agarwal likes to call it, must necessarily precede it.

Here is where the discussion board proved indispensable. While many a pleasant undergraduate hour may be spent groping for enlightenment with equally clueless classmates, posting a question in this forum could get you the right answer in 20 minutes—or provoke some fascinating exchanges. The social dimension of the educational experience did not feel slighted by the remote format.

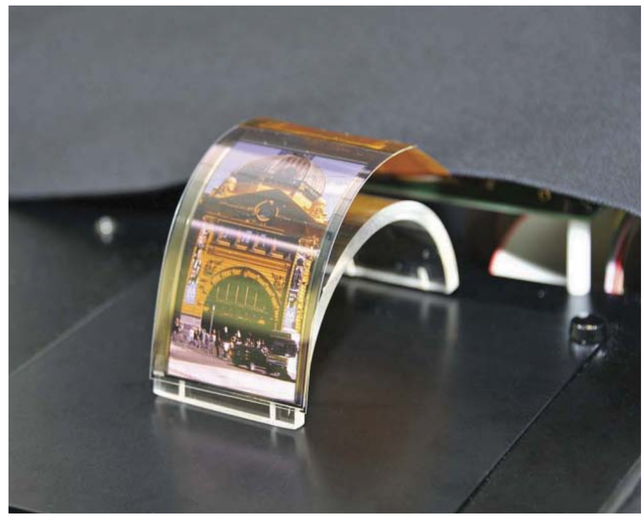
Of the original city-size class population, 5800 passed the final exam, and 7157 earned enough credit overall to pass the course and receive a certificate of completion. MITx offers no course credit, and who knows what value the marketplace will ascribe to the credential we received? But we've dipped our oars in MIT waters, and we're secretly, insufferably, pleased with ourselves.

—STEVEN J. FRANK

*A version of this article appeared online in July 2012.*




**CLASS SYSTEM:** MITx course lectures are delivered using a virtual blackboard. Students listen to a prerecorded narration, watch slides being marked up, and read a line-by-line transcript as the lecture proceeds. Supplementary material, such as video demonstrations, can also be called up on demand.



SHARP

## REFORMULATING DISPLAYS

New recipes for making screens will power the next generation of televisions

THE MESSAGE from Display Week, June's annual gathering of the Society for Information Display, is that while the current big trend in the industry—smart televisions—is driven by processors and software [see "Smart TV," *IEEE Spectrum*, July 2012], the momentum for the next wave of display products is coming from advances in materials. These advances will mean bigger screens and higher resolutions at lower cost and could even open the door to radically new devices, such as an information display that wraps around a cylindrical pillar.

The materials in question are used in a critical component of flat-panel displays: the backplane responsible for turning pixels on and off. If you tear down a typical LCD, you'll find that the actual pixel switching is done by thin-film transistors. Generally, these TFTs are formed on a thin layer of silicon deposited on a glass substrate, and these layers make up the backplane. The simplest and cheapest way to deposit the silicon layer produces amorphous silicon. However, the electrical properties of amorphous silicon translate to relatively large transistors and thus relatively large pixels—adequate for the LCD panels of yesteryear, but at the resolution of Apple's Retina screens, for example, smaller transistors are needed.

One way to produce tiny transistors is to make the backplane using a single crystal of silicon, similar to the wafers that microprocessors are made from. However, it's not feasible to make wafers large enough for displays. The



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**SCREEN SHOTS:** Sharp used the new IGZO (indium gallium zinc oxide) material to create a prototype of a flexible 3.4-inch OLED display [opposite page]. Cheaper manufacturing processes and displays that can be built to fit curved surfaces are likely to result from backplanes made with very thin glass, such as Corning's Willow Glass [this page]. *PHOTO: CORNING*

current compromise solution is to use a laser annealing process that heats and cools a regular amorphous silicon layer. The result is a layer containing many small crystals, like frost on a car window. Much smaller transistors can be fabricated on this polycrystalline silicon, or polysilicon, than with amorphous silicon. The problem is that laser annealing works fine for the small- to medium-size displays used with cellphones and tablets, but not as well at the scale of TVs.

Fortunately, at Display Week 2012, in Boston, an entirely different approach was bearing fruit after about 30 years of research and development. Instead of silicon in the backplane, engineers are turning to a metal oxide composed of indium, gallium, and zinc in equal parts, giving the material its name: IGZO, for indium gallium zinc oxide. Its electrical properties are roughly between those of amorphous silicon and polysilicon, and IGZO is compatible with existing LCD manufacturing technology.

Sharp showed a 6.1-inch LCD, suitable for mobile devices, with an IGZO backplane and an incredible 498-pixel-per-inch resolution (for comparison, a Retina display on an iPhone has 326 ppi). In addition to providing higher resolutions without an expensive polysilicon backplane, the metal oxide is more energy efficient than amorphous silicon.

Going beyond LCDs, IGZO has made it possible to create large backplanes that can provide the power required to drive organic light-emitting diode displays. OLEDs are challenging the dominance of LCDs, because each OLED pixel emits its own light, just as the pixels of old cathode ray tube TVs did (LCDs work by selectively filtering a backlight). Emitting rather than filtering light eliminates the narrow viewing angle problem of LCDs. OLEDs can also be more power efficient than LCDs, dispensing with the need for a continuously illuminated backlight, and can produce deeper blacks for better picture contrast.

OLEDs are already popular in small, high-end mobile device displays. The new metal oxide backplanes make it possible to create much larger panels, and LG has demonstrated 55-inch 1080p (1920- by 1080-pixel) OLED TVs that it intends to start selling by the end of this year. (Samsung also intends to ship a 55-inch OLED HDTV in 2012, although the company's backplane reportedly uses polysilicon rather than IGZO.)

IGZO also allows for smaller OLED pixels than are possible with amorphous silicon backplanes. Sharp has produced a prototype 13.5-inch panel in partnership with Semiconductor Energy Laboratory Co. with an amazing 3840- by 2160-pixel resolution. This is the equivalent of four 1080p panels tiled together. The panel has 326 ppi, extremely fine for a screen this large (for comparison, the latest iPad display comes in at 264 ppi).

However, even bigger changes in displays could come from the material used as the foundation of backplanes: glass.

Last year, both Corning and Asahi Glass Co. demonstrated glass substrates that were just 0.1 millimeters thick. This year, Corning announced the commercial availability of its new glass under the brand name Willow. Asahi has also put its new glass on the market, including a version laminated to a thicker carrier sheet so that it can be used in existing LCD manufacturing lines.

These glasses are thin enough to roll up into spools, which makes it possible to use them in roll-to-roll production. Until now, LCDs and OLEDs have been fabricated on discrete rectangular sheets of glass that are processed in batches. Roll-to-roll production, even for just a handful of manufacturing steps, could be much faster and more efficient, driving production costs down. In addition to making finished products that cost—and weigh—much less, roll-to-roll production using thin glass could lead to novel applications such as very large displays, or screens that conform to curves in walls or other architectural features. —Alfred Poor



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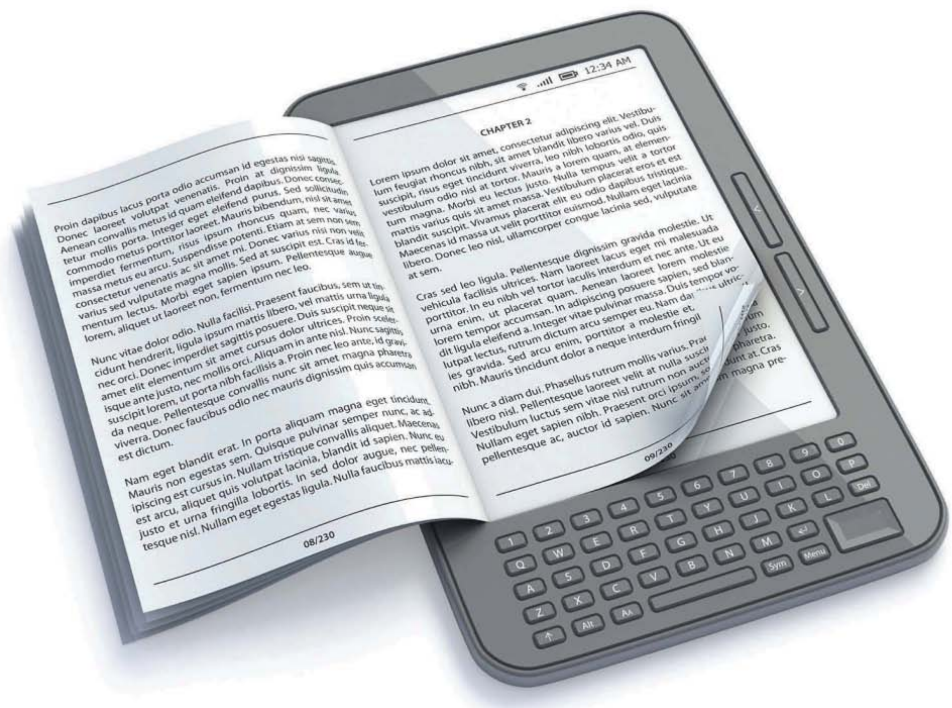
# hands on

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## I, PUBLISHER

### Electronic books offer authors a direct channel to readers

Journalist A.J. Liebling once famously noted, "Freedom of the press is guaranteed only to those who own one." But with the advent of electronic publishing—and ancillary technologies such as online stores, e-readers, and print-on-demand (POD) systems—anyone with a computer and an Internet connection can be a publisher. For better or worse, whether they're barely literate neophytes or *New York Times* best-selling authors, writers can publish whatever they want without having to get approval from an agent, a selection committee, or a peer review process. Online retailers like Amazon.com, Apple, and Barnes & Noble also pay a significantly higher percentage of per-copy revenue than traditional publishing houses, giving writers the potential to earn much more money. So it's no wonder that many authors (including us) are bypassing conventional publishers.

True, e-publishing means that authors are responsible for all stages of a book's production, including graphic design and marketing, but this isn't that much different from the trend authors have experienced with many print book publishers in recent years. For example, for our last three books, our publishers (Peachpit Press and John Wiley & Sons) provided a template for our word processing program to allow us to format our manuscripts so they could be sent directly to a printing house. We were expected to do (or pay someone else to do) our own editing, copyediting, and proofreading, as well as secure permissions to quote copyrighted material. The publishers' prepublication publicity consisted solely of sending out press releases and review copies.

While publishing electronically doesn't help with getting a book edited or marketed, it does offer writers direct access to many millions of potential readers. So how is it done?

A narrative book is the easiest type to e-publish. Essentially, you write it as you normally would, with a word processor. The preferred software is Microsoft Word, because it's accepted by all e-book services. Until recently, we recommended against Corel's WordPerfect, because it tended to generate code that didn't play well with some e-book formats. However, the recently released WordPerfect Office X6 has an e-book template especially designed for the Mobipocket (MOBI) format used by the Amazon Kindle. Corel says it will soon be supporting the EPUB format as well, which is used by just about every other e-reader, including Apple's iPad and iPhone, Barnes & Noble's Nook, and the Sony Reader.

You'll need to change some of your word processing habits. That's because e-readers have their own way of placing and flowing text, depending on things like the reader's preferences about font size. To get the best and most consistent results, for instance, don't use tabs or spaces to define where text will be positioned (such as at the beginning of a paragraph). Instead, use the word processor's Styles feature to define the arrangement and properties of different pieces of text, such as chapter headings, quotes, bullet points, and paragraphs. If you've done this styling correctly, converting a document into a ready-for-sale e-book can be simply a matter of uploading the file to an e-publisher's website. Just about everything you'll need to know about using a word processor for e-publishing is included in the *Smashwords Style Guide*, which is available free (more about Smashwords below).

If a book contains a lot of graphics or interactive elements, however, a word processor won't be enough. You'll need a desktop publishing (DTP) program. The top professional DTP programs—Adobe InDesign and Quark Xpress—both support e-book publishing. They can be used to insert photos, tables, illustrations, video, or interactive elements into a book. However, a big proviso is that different e-book formats have varying levels of support for visual and interactive elements. The more complex an e-book is, the fewer e-readers will be able to display it properly. Converting a manuscript to an e-book format is done either directly by the DTP program or when the file is uploaded to an online bookstore.

An author's first upload should be to Amazon. Amazon is far and away the largest bookstore in the world; it's been estimated that Amazon's sales represent up to 60 percent of all e-book sales (and about 75 percent of online printed book sales). In the United States, Amazon's royalties to authors are 35 to 70 percent, depending on factors such as the book's file size and where it will be sold. Authors create an account at Kindle Direct Publishing and follow the prompts to upload a book. The KDP site is very helpful, but valuable insights are also available on the Writers Café of the Kindleboards.

You can upload manuscripts to KDP in several formats: Word, EPUB, .txt, zipped HTML, Adobe PDF, or of course, MOBI. KDP will convert the format as required and check it to make sure the manuscript conforms to Amazon's standards for how the text should be arranged. You can preview onscreen how your book will look on the company's various Kindle devices. If you don't like what you see, you can reedit the manuscript and upload a new file.

Amazon would like writers to publish on its site only and nowhere else. So it offers programs for authors who give the company exclusivity, such as participation in Amazon's "borrowing library," in which the author gets paid every time an e-book is lent to an Amazon Prime member. That exclusivity is for a period of 90 days, renewed automatically unless you notify the company otherwise.

The second site that we recommend is Smashwords, a one-stop shop for e-publishing (and the same folks who offer that free guidebook on e-publishing). A single upload of a Word manuscript will generate e-book files in multiple formats—in addition to EPUB and MOBI, it will also create files in the PDF and HTML formats, among others. Like Amazon, Smashwords will check a document to make sure it meets the company's formatting standards (which are a bit stricter than Amazon's). If Smashwords determines that the formatting meets a certain quality level, then your e-book will qualify for its Premium treatment. This means that Smashwords, in addition to selling your book on its own site, will submit it to a bunch of online stores, including Apple's iBooks store, Barnes & Noble, Kobo, and others. (Yes, you could submit your work individually to each of those sites—and not have to give Smashwords a cut of your sales in addition to whatever the stores take—but we have found the service a nice time-saver.) In addition, once Smashwords has converted your manuscript, you can download and use the e-book files for your own purposes (including selling your book on your own website and keeping all the revenue for yourself). The royalty for books sold on Smashwords is 85 percent minus a transaction fee (which brings it down to about 82 percent). Royalties from Smashwords sales on other sites is 60 percent.

And that's it! Now it's up to you to spread the word and get people clicking and downloading.

—Sally Wiener Grotta & Daniel Grotta

*A version of this article appeared online in July 2012.*

## Paper Lives!

WRITERS WHO WANT to offer traditional paper books can also benefit from the revolution in publishing technology. A number of print-on-demand services allow you to list digitally produced books; when a reader buys one, a copy is printed, bound, and shipped. The process is, however, a little more complex than creating purely electronic books. A short guide to what's involved and a listing of some print-on-demand services are available at http://www.spectrum.ieee.org/pod0912.



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 BY ROBERT W. LUCKY

DANIEL HERTZBERG

# Disposable Electronics

IN THE BACK of my closet is a padded leather case containing my precious 35-mm film camera and lenses. I thought the investment in these things would last me forever. Now, however, that leather case is cracking, and the camera goes unused. Meanwhile, in a desk drawer lies a careless jumble of digital cameras, including the most recently purchased one. I feel no special affinity for them—they just come and go, and rather quickly at that.

Cellphones are just as bad. I understand that about a half million are thrown away every day in the United States alone. This means that the average life span is about two years, which puts dog years to shame. In human terms, the cellphone loses about a month of its life every day.

This all suggests a new perspective—for both users and designers—about electronics as disposable systems. As a consumer, I've had a hard time getting it right.

When a new gadget is announced, I feel an irresistible pull. It's an emotional thing, because I know that this will be version 1.0, full of bugs and ripe for improvement. No sooner do I buy this first model than a second-generation model hits the market. Then I face a choice: Stick with the old clunky one or put the same investment into the new one? Millions of people have experienced this dilemma, with the iPad, already in its third generation, as a leading example. When do you buy a new one? I remember worrying about how much memory I should get and whether I should purchase a protective film for the screen. But then I thought: Why bother? I won't have this thing very long.

How does this new calculus of consumption affect design? The approach would seem to be the polar opposite of that taken for military equipment, which focuses on durability, robustness, and longevity. The design cycle there takes years and ends with relatively small production quantities and high prices. Meanwhile, the commercial equivalents will have gone through multiple generations of large production runs and ever-lower prices.

I suspect that engineers don't really worry much about the philosophy and just try to do the best job they can. The question of timing must be foremost. You can't miss a generation in the market or your supernova company will turn into a dwarf star. We've seen it happen. So there's no time to tweak the design, and at some early point you have to stop seeking improvements or looking for bugs and just go with what you have. That's difficult for an engineer. Perhaps there is some analogy to the fruit market, where they ship green bananas and suggest a sell-by date. The big difference is that the electronics don't ripen on the way to the store. Quite the opposite.

What about the supposition that nobody is going to upgrade this thing? Maybe it's okay to glue the battery in, and perhaps a USB port would be an unnecessary expense. But there is a fine line past which it starts to look like the designer is going out of his way to ensure that we buy the next version instead of upgrading. When the memory is soldered in and special tools are required to remove the back, we can be forgiven our suspicions.

The chaos of time pressure comes in the context of dealing with a tremendously complex system. I think only an engineer has any appreciation of the deep complexity of a cellphone, largely hidden in the fossilized chips that have evolved over the fast-moving generations. I can never quite get over the experience of opening the back of a cellphone and seeing that there is apparently nothing inside—just a big battery and display. I think of it as a true work of art, but its transience may make a consumer think of it in terms of what it will soon be—a piece of junk.

I got my present cellphone about a year ago. It's already showing signs of senility, almost ready to join the digital-camera graveyard in the desk drawer. ❑



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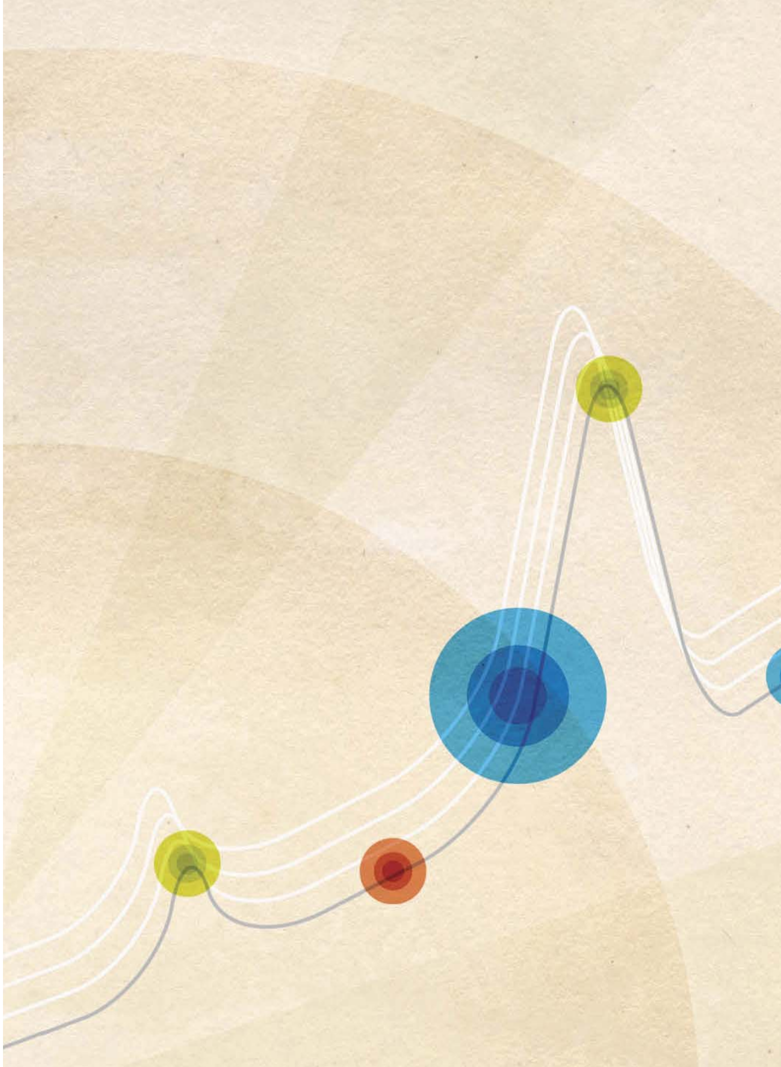
# The Truth About Terahertz

ANYONE HOPING TO EXPLOIT THIS PROMISING REGION OF THE ELECTROMAGNETIC SPECTRUM MUST CONFRONT ITS VERY DAUNTING PHYSICS

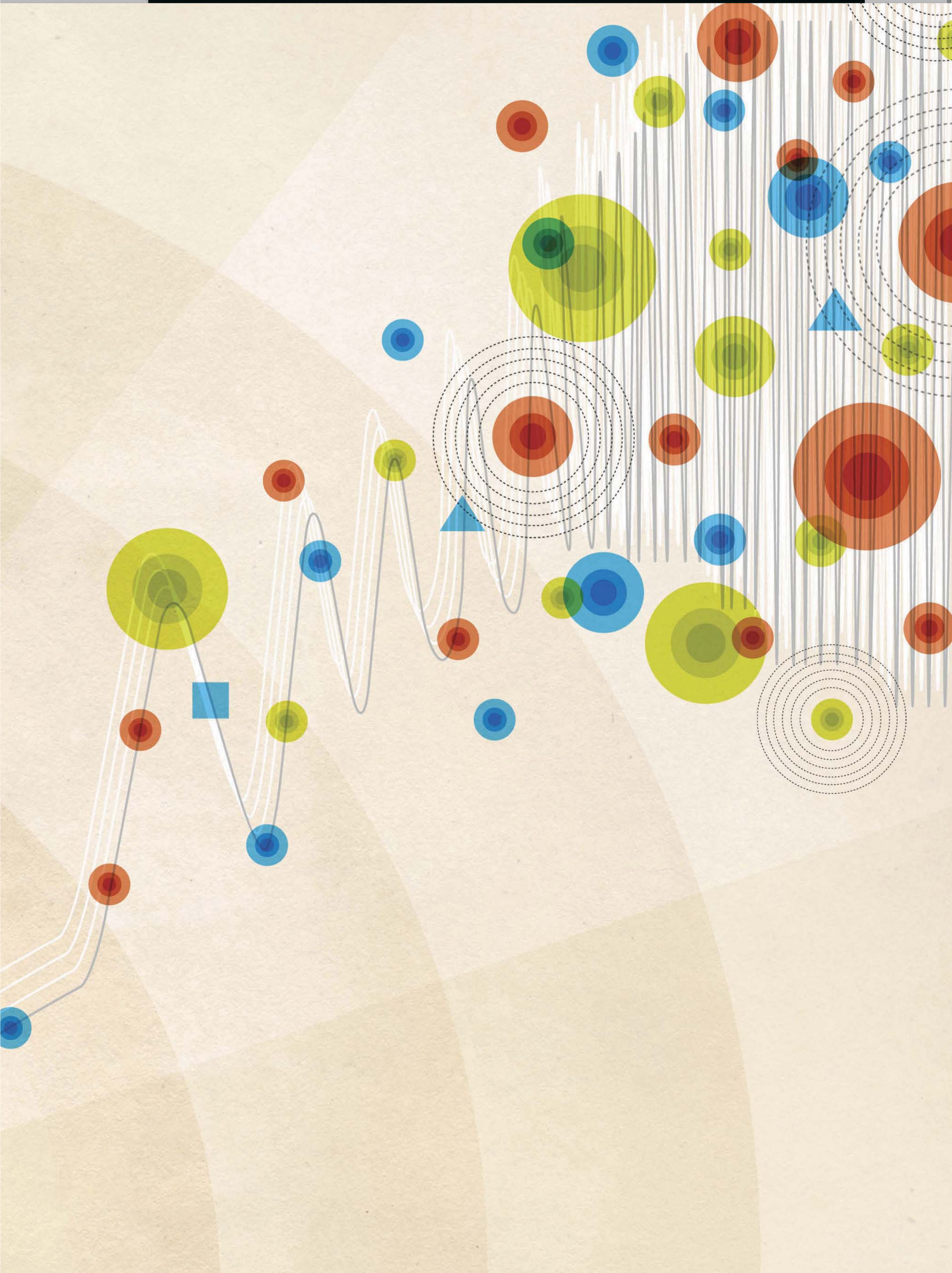
**By Carter M. Armstrong**

*Illustration By Chad Hagen*



WIRELESSLY TRANSFER HUGE FILES in the blink of an eye! Detect bombs, poison gas clouds, and concealed weapons from afar! Peer through walls with T-ray vision! You can do it all with terahertz technology—or so you might believe after perusing popular accounts of the subject.

The truth is a bit more nuanced. The terahertz regime is that promising yet vexing slice of the electromagnetic spectrum that lies between the microwave and the optical, corresponding to frequencies of about 300 billion hertz to 10 trillion hertz (or if you prefer, wavelengths of 1 millimeter down to 30 micrometers). This radiation does have some uniquely attractive qualities: For example, it can yield extremely high-resolution images and move vast amounts of data quickly. And yet it is nonionizing,



meaning its photons are not energetic enough to knock electrons off atoms and molecules in human tissue, which could trigger harmful chemical reactions. The waves also stimulate molecular and electronic motions in many materials—reflecting off some, propagating through others, and being absorbed by the rest. These features have been exploited in laboratory demonstrations to identify explosives, reveal hidden weapons, check for defects in tiles on the space shuttle, and screen for skin cancer and tooth decay.

But the goal of turning such laboratory phenomena into real-world applications has proved elusive. Legions of researchers have struggled with that challenge for decades.

The past 10 years have seen the most intense work to tame and harness the power of the terahertz regime. I first became aware of the extent of these efforts in 2007, when I cochaired a U.S. government panel that reviewed compact terahertz sources. The review's chief goal was to determine the state of the technology. We heard from about 30 R&D teams, and by the end we had a good idea of where things stood. What the review failed to do, though, was give a clear picture of the many challenges of exploiting the terahertz regime. What I really wanted were answers to questions like, What exactly are terahertz frequencies best suited for? And how demanding are they to produce, control, apply, and otherwise manipulate?

So I launched my own investigation. I studied the key issues in developing three of the applications that have been widely discussed in defense, security, and law-enforcement circles: communication and radar, identification of harmful substances from a distance, and through-wall imaging. I also looked at the 20 or so compact terahertz sources covered in the 2007 review, to see if they shared any performance challenges, despite their different designs and features. I recently updated my findings, although much of what I concluded then still holds true now.

My efforts aren't meant to discourage the pursuit of this potentially valuable technology—far from it. But there are some unavoidable truths that anyone working with this technology inevitably has to confront. Here's what I found.

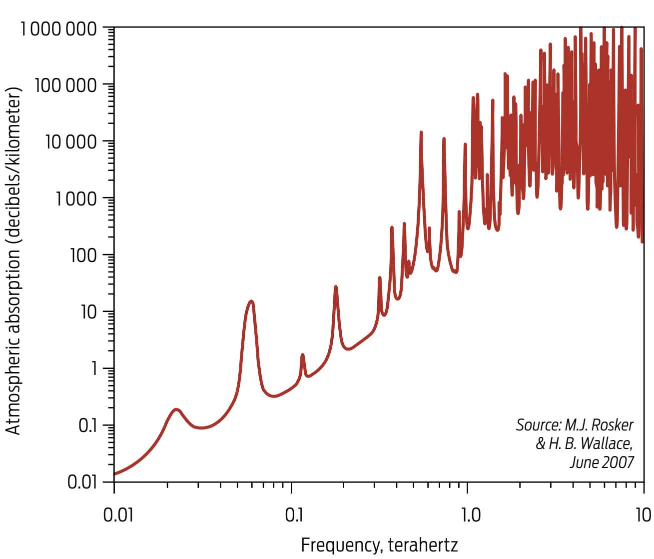
**ALTHOUGH TERAHERTZ** technology has been much in the news lately, the phenomenon isn't really new. It just went by different names in the past—near millimeter, submillimeter, extreme far infrared. Since at least the 1950s, researchers have sought to tap its appealing characteristics. Use of this spectral band by early molecular spectroscopists, for example, laid the foundation for its application to ground-based radio telescopes, such as the Atacama Large Millimeter/submillimeter Array, in Chile. Over the years a few other niche uses have emerged, most notably space-based remote sensing. In the 1970s, space scientists began using far-infrared and submillimeter-wave spectrometers for investigating the chemical compositions of the interstellar medium and planetary atmospheres. One of my favorite statistics, which comes from astronomer David Leisawitz at NASA Goddard Space Flight Center, is that 98 percent of the photons released since the big bang reside in the submillimeter and far-infrared bands, a fact that observatories like the Herschel Space Observatory are designed to take advantage of. Indeed, it's safe to say that the current state of terahertz technology rests in good measure on advances in radio astronomy and space science.

But orbiting terahertz instruments have a big advantage over their terrestrial counterparts: They're in space! Specifically, they operate in a near-vacuum and don't have to contend with a dense atmosphere, which absorbs, refracts, and scatters terahertz signals. Nor do they have to operate in inclement weather. There is no simple way to get around the basic physics of the situation. You can operate at higher altitudes, where it's less dense and there's less moisture, but many of the envisioned terahertz applications are for use on the ground. You can boost the signal's strength in hopes that enough radiation will get through at the receiving end, but at some point, that's just not practical, as we'll see.

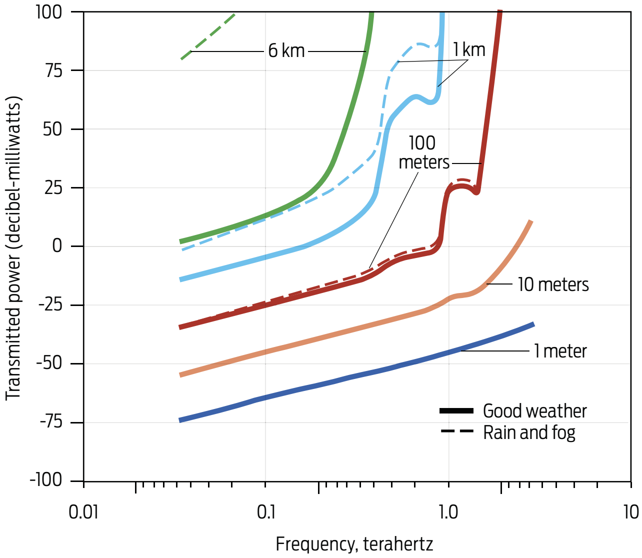
Obviously, atmospheric attenuation poses a problem for using terahertz frequencies for long-range communication and radar. But how big a problem? To answer that question, I compared different scenarios for horizontal transmission at sea level—good weather, bad weather, a range of distances (from 1 meter up to 6 kilometers), and specific frequencies between 35 gigahertz and 3 terahertz—to determine how much the signal strength degrades as conditions vary. For short-range operation—that is, for signals traveling 10 meters or less—the effects of the atmosphere and bad weather don't really come into play.

Try to send anything farther than that and you hit what I call the "terahertz wall": No matter how much you boost the signal, essentially nothing gets through. A 1-watt signal with a frequency of 1 THz, for instance, will dwindle to nothing after traveling just 1 km. Well, not quite nothing: It retains about $10^{-30}$ percent of its original strength. So even if you were to increase the signal's power to the ridiculously high level of, say, a petawatt, and then somehow manage to propagate it without ionizing the atmosphere in the process, it would be reduced to mere femtowatts by the time it reached its destination. Needless to say, there are no terahertz sources capable of producing anything approaching

**ATMOSPHERIC EFFECTS:** Terrestrial signals sent at terahertz frequencies can experience extreme atmospheric absorption, due primarily to water vapor and oxygen. For horizontal transmission at sea level and normal humidity, as shown here, the signal attenuation clearly peaks between 1 and 10 terahertz.




ILLUSTRATIONS: GEORGE RETSECK




**TERAHERTZ WALL:** The power needed to send data at terahertz frequencies would be impractically high in many cases. For a line-of-sight terrestrial communication link using fixed-gain antennas, shown here, transmitting at distances of less than 100 meters is the only way to avoid the "terahertz wall."

a petawatt; the closest is a free-electron laser, which has an output in the low tens of megawatts and isn't exactly a field-deployable device. (For comparison, the output power of today's compact sources spans the 1-microwatt to 1-W range—more on that later.) And that's under ordinary atmospheric conditions. Rain and fog will deteriorate the signal even more. Attenuation that extreme all but rules out using the terahertz region for long-range ground-based communication and radar.

Another potentially invaluable and much hyped use for terahertz waves is identifying hazardous materials from afar. In their gaseous phase, many natural and man-made molecules, including ammonia, carbon monoxide, hydrogen sulfide, and methanol, absorb photons when stimulated at terahertz frequencies, and those absorption bands can serve as chemical fingerprints. Even so, outside the carefully calibrated conditions of the laboratory or the sparse environment of space, complications arise.

Let's say you're a hazmat worker and you've received a report about a possible sarin gas attack. Obviously, you'll want to keep your distance, so you pull out your trusty portable T-wave spectrometer, which works something like the tricorder in "Star Trek." It sends a directed beam of terahertz radiation into the cloud; the gas absorbs the radiation with a characteristic spectral frequency signature. Unlike with communications or radar, which would probably use a narrowband signal, your spectrometer sends out a broadband signal, from about 300 GHz to 3 THz. Of course, to ensure that the signal returns to your spectrometer, it will need to reflect off something beyond the gas cloud, like a building, a container, or even some trees. But as in the case above, the atmosphere diminishes the signal's strength as it travels to the cloud and then back to your detector. The atmosphere also washes out the spectral features of the cloud because of an effect known as pressure broadening. Even at a distance of just 10 meters, such effects would make it difficult, if not impossible, to get an accurate reading. Yet another wrinkle is that the chemical signatures of some materials—table sugar and some plastic explosives, for instance—are so remarkably nondescript as to make distinguishing one from another impossible.

By now, you won't be surprised to hear that through-wall imaging, another much-discussed application of terahertz radiation, also faces major hurdles. The idea is simple enough: Aim terahertz radiation at a wall of some sort, with an object on the other side. Terahertz waves can penetrate some—but not all—materials that are opaque in visible light. So depending on what the wall is made of and how thick it is, some waves will get through, reflect off the object, and then make their way back through the wall to the source, where they can reveal an image of the hidden object.

Realizing that simple idea is another matter. First, let's assume that the object itself doesn't scatter, absorb, or otherwise degrade the signal. Even so, the quality of the image you get will depend largely on what your wall is made of. If the wall is made of metal or some other good conductive material, you won't get any image at all. If the wall contains any of the common insulating or construction materials, you might still get serious attenuation, depending on the material and its thickness as well as the frequency you are using. For example, a 1-THz signal passing through a quarter-inch-thick piece of plywood would have 0.0015 percent of the power of a 94-GHz signal making the same journey. And if the material is damp, the loss is even higher. (Such factors affect not just imaging through barriers but also terahertz wireless networks, which would require at the least a direct line of sight between the source and the receiver.) So your childhood dream of owning a pair of "X-ray specs" probably isn't going to happen any time soon.

It's true that some researchers have successfully demonstrated through-wall imaging. In these demonstrations, the radiation sources emitted impulses of radiation across a wide range of frequencies, including terahertz. Given what we know about attenuation at the higher frequencies, though, some scientists who've studied the results believe it's highly likely that the imaging occurred not in the terahertz region but rather at the lower frequencies. And if that's the case, then why not just use millimeter-wave imagers to begin with?

Before leaving the subject of imaging, let me add one last thought on terahertz for medical imaging. Some of the more creative potential uses I've heard include brain imaging, tumor detection, and full-body scanning that would yield much more detailed pictures than any existing technology and yet be completely safe. But the reality once again falls short of the dream. Frank De Lucia, a physicist at Ohio State University, in Columbus, has pointed out that a terahertz signal will decrease in power to 0.0000002 percent of its original strength after traveling just 1 mm in saline solution, which is a good approximation for body tissue. For now at least, terahertz medical devices will be useful only for surface imaging of things like skin cancer and tooth decay and laboratory tests on thin tissue samples.

**SO THOSE ARE SOME** of the basic challenges of exploiting the terahertz regime. The physics is indeed daunting, but that hasn't prevented developers from continuing to pursue lots of different terahertz devices for those and other



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applications. So the next thing I looked at was the performance of systems capable of generating radiation at terahertz frequencies. I decided to focus on these sources—and not detectors, receivers, control devices, and so on—because while those other components are certainly critical, people in the field pretty much agree that what's held up progress is the lack of appropriate sources.

There's a very good reason for the shortage of compact terahertz sources: They're really hard to build! For many applications, the source has to be powerful enough to overcome extreme signal attenuation, efficient enough to avoid having to wheel around your own power generator, and small enough to be deployed in the field without having to be toted around on a flatbed truck. (For some applications, the source's spectral purity, tunability, or bandwidth is more important, so a lower power is acceptable.) The successful space-based instruments mentioned earlier merely detect terahertz radiation that celestial bodies and events naturally emit; although some of those instruments use a low-power source for improved sensitivity, they don't as yet attempt to transmit at terahertz frequencies.

The government review in 2007 loosely defined a compact terahertz source as having an average output power in the 1-mW to 1-W range, operating in the 300-GHz to 3-THz frequency band, and being more or less "portable." (We chose average power rather than peak power because, ultimately, it's the average power that counts in nearly all of the envisioned applications.) In addition, we asked that the sources have a conversion efficiency of at least 1 percent—for every 100 W of input power, the source would produce a signal of 1 W or more. Even that modest goal, it turns out, is quite challenging.

**POST YOUR COMMENTS** *online at* http://spectrum.ieee.org/terahertz0912

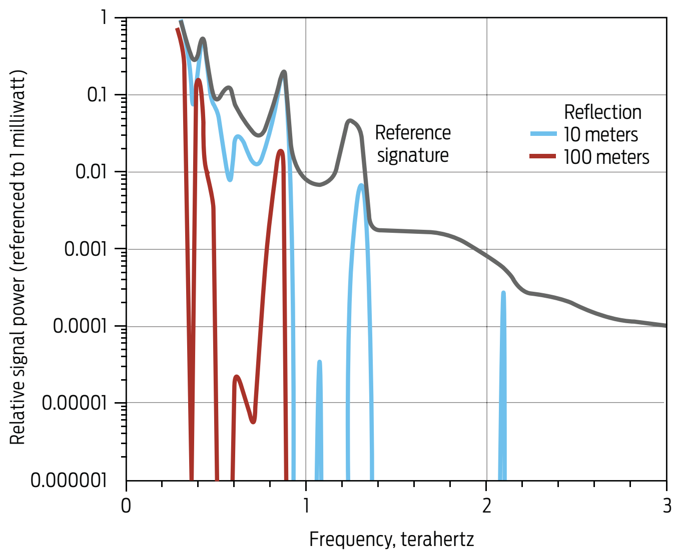
The 2007 review included about 20 terahertz sources. I don't have room here to describe how each of these devices works, but in general they fall into three broad categories: vacuum (including backward-wave oscillators, klystrons, grating-vacuum devices, traveling-wave tubes, and gyrotrons), solid state (including harmonic frequency multipliers, transistors, and monolithic microwave integrated circuits), and laser and photonic (including quantum cascade lasers, optically pumped molecular lasers, and a variety of optoelectronic RF generators). Vacuum devices and lasers exhibited the highest average power at the lower and upper frequencies, respectively. Solid-state devices came next, followed by photonic devices. To be fair, calling a gyrotron a compact source is quite a stretch, and while photonic sources can produce high peak power, ranging from hundreds of watts to kilowatts, they also require high optical-drive power.

Despite their considerable design differences and some variations in performance, these three classes of terahertz technology have similar challenges. One significant issue is their uniformly low conversion efficiency, which is typically much less than 1 percent. So to get a 1-W signal, you might need to start with kilowatts of input power, or greater. Other everyday electronic and optical devices are, by comparison, far more efficient. The RF power amplifier in a typical 2-GHz smartphone, for example, operates at around 50 percent efficiency. A commercial red diode laser can convert electrical power to light with an efficiency of more than 30 percent.

That low efficiency combined with the devices' small size leads to another problem: extremely high power densities (the amount of power the devices must handle per unit area) and current densities (the amount of current they must handle per unit area). For the vacuum and solid-state devices, the power densities were in the range of several megawatts per square centimeter. Suppose you want to use a conventional vacuum traveling-wave tube, or TWT, that's been scaled up to operate at 1 THz. Such an apparatus would require you to focus an electron beam with a power density of multiple megawatts per square centimeter through an evacuated circuit having an inner diameter of 40 μm—about half the diameter of a human hair. (The solar radiation at the surface of the sun, by contrast, has a power density of only about 6 kilowatts per square centimeter.) A terahertz transistor, with its nanometer features, operates at similarly high power density levels. And all of the electrical and photonic devices examined, even the quantum cascade laser, require high current densities, ranging from kiloamperes per square centimeter to multimega-amperes per square centimeter. Incidentally, the upper portion of that current density range is typical of what you'd see in the pulsed-power electrical generators used for nuclear effects testing, among other things.

Compact electrical and optical devices can handle conditions like that, but you're asking for trouble—if the device isn't adequately cooled, the internal power dissipation minimized, and the correct materials used, it can quickly melt or vaporize or otherwise break down. And of course, eventually you reach an upper limit, beyond which you simply can't push the power density and current density any higher.

As a device physicist, I was naturally interested in the relationship between the sources' output power and their frequency, what's known as power-frequency scaling. When you plot the device's average power along the *y*-axis and the frequency along the *x*, you want to see the flattest possible curve. Such




**THE UNDETECTED:** When attempting to identify unknown substances at a distance, nearly all of the terahertz signal will be lost or distorted by the atmosphere. Here, the gray line is a fictitious signature for a sample being probed in reflection mode. At distances of 10 meters and 100 meters [blue and red lines], the sample's distinct spectral features are washed away.

ILLUSTRATIONS: GEORGE RETSECK

flatness means that as the frequency increases, the output power remains steady or at least does not plummet. In typical radio-frequency devices, such as transistors, solid-state diodes, and microwave vacuum tubes, the power tends to fall as the inverse of the frequency squared. In other words, if you double the frequency, the output power drops by a factor of four.

Most of the electrical terahertz sources we reviewed in 2007, however, had much steeper power-frequency curves that basically fell off into the abyss as they were pushed into the terahertz range. In general, the power scaled as the inverse of the frequency to the fourth, or worse, which meant that as the frequency doubled, the output power dropped by a factor of 16. So a device that could generate several watts at 100 GHz was capable of only a few hundred microwatts as it went to 1 THz. Lasers, too, fell off in power in the terahertz region faster than you would expect.

Given what I mentioned earlier about extreme signal attenuation in the terahertz region and the sources' low conversion efficiencies, this precipitous drop-off in power represents yet another high hurdle to commercializing the technology.

**FINE, YOU SAY,** but can't all of these problems be attributed to the fact that the sources are still technologically immature? Put another way, shouldn't we expect device performance to improve? Certainly, the technology is getting better. In the several years between my initial analysis and this article, here are some of the highlights in the device technologies I reviewed:

- The average power of microfabricated vacuum devices rose two orders of magnitude, from about 10 μW to over a milliwatt at 650 GHz, and researchers are now working on multibeam and sheet-beam devices capable of higher power than comparable low-voltage single round-beam units.
- The average power of submillimeter monolithic microwave integrated circuits and transistors climbed by a factor of five to eight, to the 100 mW level at 200 GHz and 1 mW at 650 GHz.
- The operating frequency range for milliwatt-class cryogenically cooled quantum cascade lasers was extended down to 1.8 THz in 2012, compared to 2.89 THz in 2007.

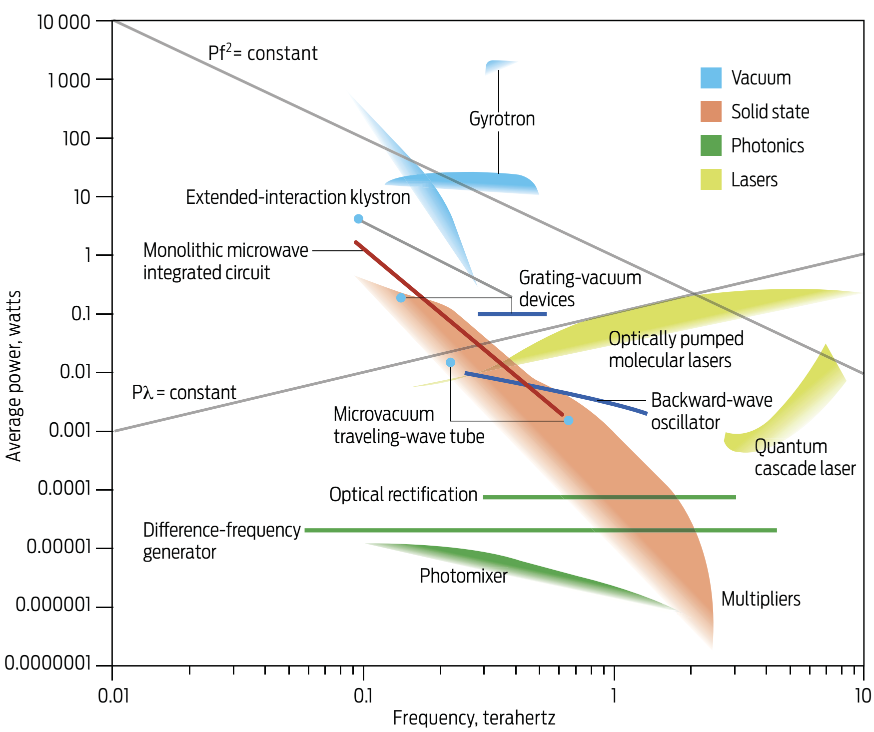
With an eye toward use outside the laboratory, researchers have been enhancing their sources in other ways, too, including improved packaging for photonic devices and lasers and higher-temperature operation for quantum cascade lasers. Given the amount of effort and interest in the field, there will certainly be more advances and improvements to come. (For more on the current state of technology, I suggest consulting the *IEEE Transactions on Terahertz Science and Technology* and similar journals.)

That said, my main points still hold: While terahertz molecular spectroscopy has continuing scientific uses in radio astronomy and space remote sensing, some of the well-publicized mainstream proposals for terahertz technology continue to strain credulity. In addition, despite recent progress in cracking the terahertz nut, it is still exceedingly difficult to efficiently produce a useful level of power from a compact terahertz device. I strongly feel that any application touted as using terahertz radiation should be thoroughly validated and vetted against alternative approaches. Does it really use terahertz frequencies, or is some other portion of the electromagnetic spectrum involved? Is the application really practical, or does it require such rarefied conditions that it may never function reliably in the real world? Are there competing technologies that work just as well or better?

There is still a great deal that we don't know about working at terahertz frequencies. I do think we should keep vigorously pursuing the basic science and technology. For starters, we need to develop accurate and robust computational models for analyzing device design and operation at terahertz frequencies. Such models will be key to future advances in the field. We also need a better understanding of material properties at terahertz frequencies, as well as general terahertz phenomenology.

Ultimately, we may need to apply out-of-the-box thinking to create designs and approaches that marry new device physics with unconventional techniques. In other areas of electronics, we've overcome enormous challenges and beat improbable odds, and countless past predictions have been subsequently shattered by continued technological evolution. Of course, as with any emerging pursuit, Darwinian selection will have its say on the ultimate survivors. ❑

*NOTE: The views presented in this article are solely those of the author.*




**SOURCE SAMPLER:** Compact terahertz sources exhibit low power and conversion efficiencies of much less than 1 percent. And in nearly every case, as the frequency rises into the terahertz range, the source's output power plummets. Here, the Pf² = constant line is the power-frequency slope you'd expect to see in a more mature RF device, while the Pλ = constant line is the expected slope for some commercial lasers.

# *How I* Quantified *Myself*

*Can self-measurement gadgets help us live healthier and better lives?*

ONE WARM NIGHT LAST FEBRUARY, I lay down to bed feeling like a lab mouse. A heat- and motion-sensing armband gauged my energy expenditure, another activity tracker clipped to my waistband recorded movement, a blood-pressure cuff connected to my iPad squeezed my right arm, and a brainwave-sensing headband would soon monitor my sleep. A scale linked by Bluetooth to an app on my iPad sat on the bathroom floor. With consistent use, these devices would provide a numeric picture of my general health and behaviors. They would give me intimate knowledge of my physical self, with all the information displayed neatly in graphs and charts.

Not too many years ago, you had to go to medical specialists to get this kind of biological data. Now, whether your problem is migraines or mood swings, you can keep track of your ailment with a consumer device that costs around US $100. As these health-and-wellness gadgets proliferate, a "quantified self" movement is gaining strength: It's attracting athletes, fitness buffs, data lovers, hypochondriacs, and people just trying to lose some weight.

*by* EMILY WALTZ

ALL PHOTOGRAPHY: DAVID BEAN/THE VISUAL RESERVE

Many of these early adopters wear their health trackers around the clock and consider them the next must-have tech accessories. After all, our smartphones are already our constant companions, and we think nothing of stopping a conversation to Google-check our facts. It seems natural that we'll soon add mobile health devices to our attire and let the biometric stat-checking ensue.

Or will we? As a journalist, I wondered whether these devices would catch on. One way to judge that was obvious: Try out the technology myself. My mission, then, was to test the most popular health-monitoring gadgets on the market and see what they really offered.

My first impression was that self-quantifying is just another example of technology stretching the limits of narcissism—the kind of thing a compulsive oversharer on Facebook would like. But I had been looking for a solution to sleep problems that cropped up when my son was born a year ago and, without a better idea, figured that analyzing myself using hard numbers and graphs couldn't hurt. So as I plunged into this assignment, I was hoping to answer the question: Can these devices really enable us to change our behavior? Will they help us eat, sleep, and move better? Or are they just new toys?

When I became a lab mouse in February, here's what I looked like in numbers. Sleep: 6 hours, 35 minutes; energy burned per day: 2306 kilocalories (9648 kilojoules); kilocalories consumed per day: 2269; moderate activity per day: 2 hours, 38 minutes; vigorous activity per week: 56 minutes; blood pressure: 102/65; resting heart rate: 66 beats per minute; weight: 55 kilograms (122 pounds); body mass index (BMI): 18.5.

Six and a half hours of fragmented sleep is abysmal for me. I used to go to bed at 11:00 p.m. and wake up refreshed 8 or 9 hours later. That changed when my son was born and for months needed feeding two or three times a night. My husband and I slogged through that ordeal as all new parents do, catching daytime naps and trading off nighttime duties. My husband went right back to sleep after attending to our son, but I couldn't. The anxiety of knowing I had to get up again in a few hours kept me awake longer and longer as time went on. Eventually, I stopped being able to get back to sleep at all. Even after my son started sleeping through the night, I continued to lie awake for hours and never felt rested during the day.

**MOM'S MEASUREMENTS:** Waltz's son checks out her BodyMedia activity tracker.

February's stats suggested that sleep deprivation was affecting my health. I weighed less than I did before I was pregnant, and if I lost another pound it would put my BMI in the "underweight" category. I wasn't getting nearly as much cardio exercise as I used to, partly because I was too tired to push myself at the gym. One day a few months earlier I had nearly collapsed from exhaustion during a tennis match. I already knew I wasn't well, and quantifying how badly I was doing fully confirmed my instincts.

THE ZEO Sleep Manager is as sleek as a Velcro-and-plastic headband can be, but there's nothing about it that says "bedtime." Nevertheless, nearly every night for two months I slipped it on, positioning the plastic enclosure so its sensors would rest against my forehead.

The Zeo can determine when you're in rapid-eye-movement (REM) sleep, light sleep, deep sleep, or awake. The headband wirelessly sends readings throughout the night to your nearby iPad or iPhone, and in the morning the Zeo app gives you a color-coded graph showing how you slept. There's also a bedside model that transmits the signal from the headband to a base station where you can view the data.

The headband's three sensors work by detecting electrical activity in the skin of the forehead. Microvolt-level changes arise from three different biological mechanisms, starting with brain-cell activity, which the Zeo detects by electroencephalography. The sensors also pick up the electric pulses that cause contractions of the frontalis muscle, which stretches across the forehead and moves the eyebrows. Finally, the sensors detect eye movements: Because each eye functions like a dipole with a positive and a negative side, the eye's movements cause changes in an electric field that can be tracked in the skin. All this electrical activity is combined into one digital signal that shows both the frequency and duration of the various voltage changes.

The information is then fed into a processor within the headband that determines your stage of sleep based on the signal's electrical features. To develop their signal-processing algorithms, company researchers strapped Zeo units as well as lab-grade sleep monitors onto volunteers and recorded their slumber. A professional sleep scorer determined each volunteer's sleep stages based on the data from the lab-grade monitor. Researchers then "trained" their algorithms to match the signals coming from the Zeo's sensors to the sleep stages determined by the professional scorer.

# *Self-Quantifying* Tools

Reporter Emily Waltz used the five gadgets shown here to record and analyze her biometric data

## 1 ZEO SLEEP MANAGER PRO: MOBILE *$100*

A sensor headband measures electrical signals to track sleep stages and calculate "sleep quality." The customer uses a mobile app and online tools for sleep analysis.

## 2 FITBIT *$100*

A small device with an accelerometer and altimeter, the Fitbit tracks motion, calculates calories burned, and displays real-time stats. The customer uses a mobile app or online tools to enter information about diet and to monitor progress toward goals.

## 3 BODYMEDIA FIT CORE ARMBAND *$150*

This armband uses an accelerometer and several skin sensors to track motion, skin temperature, and perspiration, producing a very accurate calculation of calories burned. The customer uses a mobile app or online program to enter information about diet and to monitor progress toward goals.

## 4 iHEALTH BLOOD PRESSURE MONITORING SYSTEM *$100*

The blood pressure cuff is attached to a dock, where the customer puts her iPhone or iPad to view data and monitor changes over time.

## 5 iHEALTH DIGITAL SCALE *$70*

The scale uses Bluetooth to send weight data to a mobile app, where customers can set goals and track their progress.

So what's it like to use the thing? Despite some maddening glitches—I had to contact customer service three times to resolve bad connections between the headband and my iPad—the Zeo seems accurate. I tested it by jotting down the times I was awake overnight and checking them in the morning. A 2011 study published in the *Journal of Sleep Research* compared the Zeo with lab-grade sleep measurement tools and concluded that the Zeo does pretty well. "It's not the gold standard, but it's reliable enough," says James Maas, a retired professor of psychology at Cornell University and coauthor of *Sleep for Success* (AuthorHouse, 2011).

My time with the Zeo gave me plenty of information—but no relief. Zeo awards a "ZQ" sleep-quality score from 0 to 120, with 120 being the best sleep. On average, my ZQ was 66 (pretty shabby), and it got slightly worse over two months. The sleep graphs were both unnerving and addictive. REM sleep, when vivid dreaming takes place, is supposed to occur every 90 minutes and is thought to be critical for the consolidation of memories. A well-rested person will drop into REM sleep four or five times a night, with each REM period longer than the last. My REM-sleep graph told a different tale. I was getting only three or four REM periods, with later intervals so disrupted by awakenings that they were just as short as the early ones. On my graph, tall red spikes representing awakenings sliced up what should have been solid blocks of green-line REM sleep. Seeing just how poorly I was sleeping in black and white—or rather in red and green—convinced me I had to find the culprit.

To look for answers, I turned to the rest of my gadgets.

Gregory Welk, director of the Nutrition and Wellness Research Center at Iowa State University, has tested the accuracy of this new generation of wellness devices. In 2011, Welk strapped eight activity trackers and one lab-grade monitor onto each of 51 volunteers. For 71 minutes the volunteers ran on treadmills, swept floors, biked, and walked outside with heavy backpacks while the gizmos measured their energy expenditure. The most accurate commercial unit, Welk found, was the BodyMedia Fit, an armband whose data deviated from the lab-grade monitor's results by less than 1 percent. A distant second, at 11 percent off, was the Fitbit, a thumb-size device that clips onto your waistband.


## *Life*, Quantified

**Graphs from BodyMedia [top] and Fitbit [middle] show Waltz's activity on a February weekday; the activity spikes represent a vigorous tennis game at midday and a walk in the afternoon. The graph from Zeo [bottom] depicts a typically terrible night of sleep for Waltz, with frequent awakenings interrupting crucial REM sleep.**

BodyMedia's armband is distinguished by the sophistication of its sensors and algorithms. Most activity monitors are simple pedometers or accelerometers that sense motion. BodyMedia has additional physiologic sensors that pull information from your skin, including its temperature and electrical conductance, which varies with how much you sweat. The data from these skin sensors, along with measurements of ambient temperature, allow the device to determine the rate of heat-energy transfer, which in turn lets the unit calculate the extra effort you expend when you're running up a gradual incline or carrying something heavy.

The armband's software crunches about 5000 data points per minute. It first employs statistics-based algorithms to classify the activity the user is likely doing, such as walking, running, or biking. The software takes into account the user's weight, age, and gender. Finally it applies an intensity factor—how hard the user is working—based on data from the motion, heat, and sweat sensors, and it assigns each activity an energy-expenditure value. As with Zeo, BodyMedia's algorithms were tuned by collecting data from volunteers.

Fitbit, by contrast, contains only an accelerometer, a pedometer, and an altimeter. It can tell how many stairs you've climbed, but it has no idea if you're also toting a 1-year-old and a bag of groceries. I wore both BodyMedia and Fitbit during my tenure as a lab animal and did some side-by-side comparisons. During one particular week in February, BodyMedia estimated I burned 2248 kilocalories a day on average, whereas Fitbit came up with 2012. Knowing that BodyMedia is more accurate, I found myself using that data.

When I connected my BodyMedia armband to my computer through a USB cable, my stats popped up through the company's website. There's lots of information: a pie chart and four timelines that show energy burned per minute, vigorous activity versus moderate activity, steps per hour, and a crude estimation of sleep. BodyMedia's website tallies up your averages over days or weeks, and it keeps your history so you can look back through previous days. In a moment of geeky nostalgia, I clicked through my graphs for February and March and was able to spot the night I went to the symphony (a couple of hours with almost no movement). I also found the day I backed my car into my husband's—an event marked by my jumping out of the car and vigorously waving my arms (short spikes on the graph).

BodyMedia's meal-logging function allows you to input what you ate that day, and the program calculates your kilocalories consumed. But typing in the food information is painfully tedious and probably futile. "These devices do a good job measuring output, but not input," says James Hill, director of the Center for Human Nutrition at the University of Colorado. "Our research has shown that people are not within 60 percent of what they actually eat. It's not that people are lying. It's that it's very, very hard." BodyMedia has a database with thousands of foods, yet what I was looking for never seemed to be listed. So I would manually copy numbers from nutrition labels or input the weight of every raw ingredient in a meal in an attempt to get an accurate count.

After two months I had tons of data, but it was spread across three websites and three iPad apps. I needed a way to collect and analyze it all in one place. Health-management companies U.S. Preventive Medicine and Qualcomm Life have developed an app called Macaw that will do just that, but it wasn't yet set up for my devices. So I did something low tech: I made a spreadsheet. I knew that exercise, alcohol, caffeine, big late dinners, and blood pressure are all linked to sleep quality, so I compared those numbers with each night of sleep data. Right away I ruled out blood pressure. The iHealth blood pressure monitor, which connects to an iPad or iPhone and stores your history through an app, said mine stayed low, around 102/65. That has been my blood pressure since long before my sleep problems developed.

In my spreadsheet, some correlations emerged. On days I did vigorous exercise like tennis or jogging, precious deep sleep increased 12 percent on average. Nights that I drank an alcoholic beverage or two, my time awake increased 48 percent and my REM sleep decreased 7 percent. And on nights when I ate more than my average number of kilocalories at dinner I was awake 51 percent more than usual—although that last figure is skewed by one particularly sleepless night.

IT'S KNOWN that feedback—seeing our own biological data in front of us—can affect our behavior. Several years ago David Levitsky, a nutritionist at Cornell, set up an experiment to see whether college freshmen could avoid the weight gain typical among first-year students. Levitsky separated students into two groups: one that weighed themselves every morning for 12 weeks and a control group that didn't. At the end of the 12 weeks, the students in the control group gained an average of 3 kg (7 pounds), but the students who weighed themselves every day collectively gained no weight. Feedback helped them dodge the dreaded freshman bulge.

Whether objective data can motivate people to make more dramatic lifestyle changes is unclear, say public health specialists. Joseph Kvedar, head of the Center for Connected Health at Harvard, is a proponent of health trackers. But he has found that only a small portion of the population, around 10 percent, will change their behavior based on tracker information alone. That 10 percent is composed of people inherently interested in data, like fitness buffs and "quantified selfers," the newly recognized class of nerdy people who revel in using technology to track their daily lives. Everyone else needs an additional motivator, he says, like coaching, social networking, games, or rewards.

Some device makers have picked up on that. Zeo offers a seven-step coaching program, and Fitbit offers an online community where you can compete with and trash talk your friends. Fitbitters have sorted themselves into groups like Walking at Work Treadmill Desk Users and my favorite: Crime Fighter Fitbit Users.

But even with these added motivators, the value of these devices to the general public remains unresolved. Hill at the University of Colorado, who is also cofounder of the National Weight Control Registry, says he has not seen any research suggesting that activity monitors like BodyMedia and Fitbit can help the average person lose weight. "We have to give people a reason to change and to exercise more and eat less, and I don't think information or data is enough," Hill says.

By the end of my experiment, I'd realized that mere data probably isn't enough to motivate me either. The stats made it clear that less alcohol and more exercise would improve my sleep. But lazing about the house with my husband, my son, and a glass of wine is my favorite thing to do, and I suspect that no amount of data will make me change my ways. Obsessing over my health data, however, was a much easier habit to kick. After two months of quantifying and analyzing, it felt blissful to unstrap all my monitors, forget about my daily stats, and just fall asleep. ❏

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# Tapping the Power of 100 SUNS

## CONCENTRATED SOLAR POWER WILL KEEP FUTURE ARMIES ON THE MARCH

BY RICHARD STEVENSON

ILLUSTRATION BY DANIEL HERTZBERG



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Napoleon's dictum no longer applies: These days, an army marches not so much on its stomach as on its batteries. Without them, soldiers can't see in the dark, work their radios, or determine their positions. But even the best storage batteries—accounting for one-fifth of the load in a typical infantryman's 45-kilogram pack—can't last the week or so that field soldiers require. The same problem is coming to afflict the rest of us, as we become ever more dependent on our smartphones and GPS navigation.

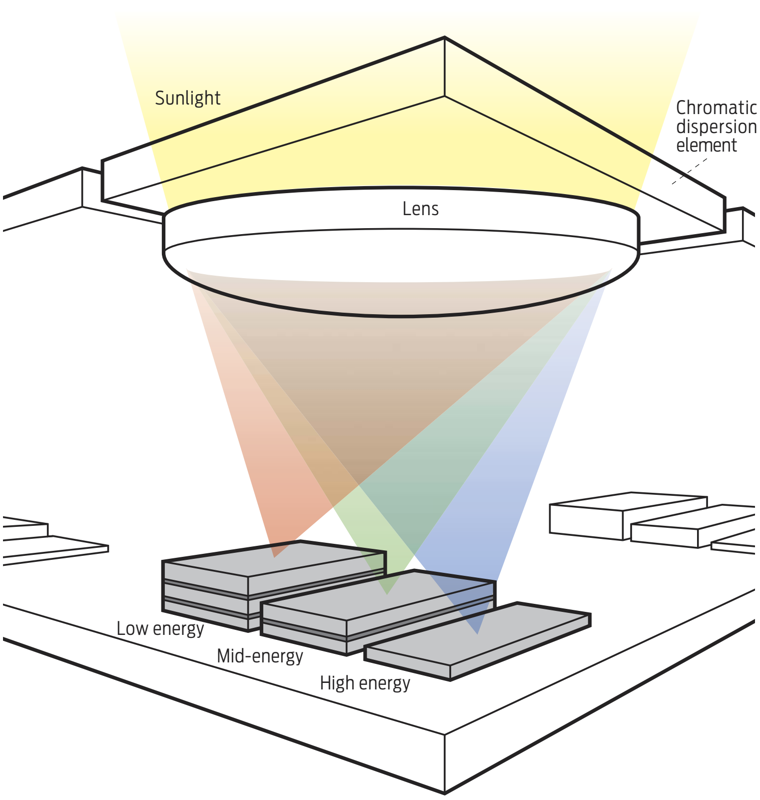
While we wait for better batteries we must find new ways to recharge the ones we have when we're far from a wall socket. What we need is a really good, portable photovoltaic system, one that can take in a huge gulp of sunlight and convert most of it into electricity. Such an advance could also help drive down the cost of solar electricity in sunny climes around the world and prevent great quantities of carbon emissions.

The most promising effort to create such superefficient photovoltaics began in 2005, when Doug Kirkpatrick, a veteran of the optics industry, kick-started the Very High Efficiency Solar Cell (VHESC) program for the U.S. Defense Advanced Research Projects Agency (DARPA). He wanted a way to build modules from solar cells that would convert a full 50 percent of the solar energy they receive into direct current. That's a jaw-dropping number when you consider that in 2005 the best laboratory devices were still shy of 40 percent efficiency and were improving by less than one percentage point per year.

KIRKPATRICK CONSIDERED the needs of the end user—the soldier. He noted that each electrical gizmo offered a different-size area for placing solar cells. This would make it possible to put more cells on bigger gadgets and use them to charge up other gizmos, such as flashlights, which have very little real estate. But that was a risky strategy, because the failure of one piece of equipment would put the others out of commission, too. Therefore, Kirkpatrick decreed that each piece of gear would have its own solar power, limiting the solar module's area to 10 square centimeters and setting cell efficiency at a minimum of 50 percent. The only other key specification for the module was power, which had to be at least 0.5 watts to recharge the batteries of the more common gadgets in an acceptable time.

The program started on the wrong foot by encouraging researchers to build on DARPA's existing programs to use biological processes to build solar cells. However, the agency abandoned that tack when two electrical engineers, then at the University of Delaware, wrote a white paper outlining a new way of using existing photovoltaic cells. Christiana Honsberg, now at Arizona State University, and Allen Barnett, now at the University of New South Wales, in Australia, argued that the best approach would be to concentrate sunlight, break it into its constituent colors, and project each color onto the kind of solar cell best suited to it. This meant placing the cells side by side instead of the conventional way, in a vertical stack. Their paper went down very well, and DARPA invited the Delaware duo to a meeting where they could pitch their idea alongside 10 others. "A lot of people there were saying that we can't do 50 percent, but we could do 33 percent," says Kirkpatrick. "We were not interested."

Because the Delaware team wasn't banking on the success of a particular material but rather on a way of exploiting a diversity of materials, there could be many different paths to success. That



was another reason DARPA put Honsberg and Barnett in charge of VHESC, which has become one of the largest solar-energy research programs ever. Initially backed by US $53 million, this effort, which commenced in September 2005, involves a consortium that at one point numbered 21 institutions, including BP Solar, Corning, and DuPont, and such universities as Georgia Tech, Harvard, MIT, Purdue, the University of California, Santa Barbara, and the University of Rochester.

THERE'S NO BETTER way to appreciate the merits of Honsberg and Barnett's approach than by considering how far short of the 50 percent target you fall using conventional tricks. It all comes down to an optimization problem, rather like that of a coffee-shop manager who has to decide how much to charge. If you set the price high, you make a good amount on each cup but sell few of them. If you set it low, you'll have a slim margin but a high volume. You need to find the sweet spot, the price that maximizes the product of the margin and the volume—that is, your profit. It's a similar story with solar cells, though here the variables are current and voltage, whose product, of course, is power.

At the heart of every photovoltaic cell is a pair of semiconductor layers. One layer has more negatively charged electrons than needed to form the material's crystalline bonds; thus it's known as *n*-type. The other, a *p*-type material, has a deficiency of such bond-forming electrons, creating what are known as holes. In a small region around which the layers meet—the *p-n* junction—the excess electrons move to fill in the deficiencies. This flow of electrons and holes leaves the *p*-type and *n*-type regions with negative and positive charges, respectively, creating an electric field.

When the cell absorbs photons, it creates pairs of electrons and holes. Then there is a net movement of holes in one direction and electrons in the other, due to both the electric field itself and to diffusion—the tendency of charge carriers to move to where their concentration is lower. An electric current is thus created in the circuit attached to the cell.

Solar-cell designers might be tempted to pick a semiconductor that best absorbs light of short wavelengths, like gallium nitride. Those photons carry the most energy and thus produce the highest voltage. Trouble is, there aren't many of them in sunlight, so the output current will be meager. Alternatively, designers can build cells from mercury cadmium telluride, a material that can absorb the solar spectrum all the way from the high-energy photons in the ultraviolet range to the low-energy photons in the short-wave infrared. Such a cell can indeed generate a lot of current, but its voltage—and hence its output power—is very low. So like the coffee-shop owner, solar-cell designers need to find a good compromise.

Theoretically, a semiconductor that absorbs light at infrared wavelengths greater than 910 nanometers will come closest to the sweet spot where power is maximized. Gallium arsenide fills the bill, and back in June 2005 researchers at Radboud University Nijmegen, in the Netherlands, were using this material to claim a single-cell efficiency record of 26.1 percent. Today, Alta Devices of Santa Clara, Calif., holds the record with a 28.2 percent cell. That's still a long way from Kirkpatrick's 50 percent target.

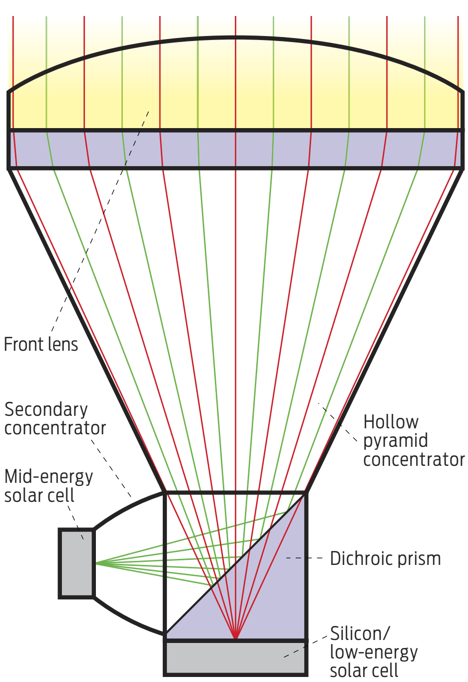
To close the gap requires a diversified strategy. Instead of using one material, a solar-cell maker can build cells from several. It's rather like offering coffee in three grades—a deluxe brand, a bargain brand, and a house brand—so as to hit profit-maximizing sweet spots for the rich customers, the poor ones, and everyone in between. The practical limit—for use in photocells, at least—is three different materials, given the traditional way of stacking them up.

To capture photons of relatively low energy, cell makers most often use a layer of germanium. For photons of intermediate energy, they include a gallium arsenide layer, and for high-energy photons, they create a third layer made up of indium gallium phosphide. The voltages simply add.

In theory, this strategy would work even better if you added more layers. But in practice, the material quality of the device tends to deteriorate, although some companies, such as Stanford University spin-off Solar Junction, have been working on approaches that promise to produce up to six stacked junctions.

The efficiency of triple-junction solar cells has been slowly creeping up. When the VHESC program kicked off in 2005, Spectrolab (a Boeing subsidiary in Sylmar, Calif.) led the way with a device boasting 32 percent efficiency, which the company had developed to power satellites. Now the Japanese firm Sharp holds the crown, with a device operating at 36.9 percent efficiency. It uses indium gallium arsenide, rather than germanium, for the bottom junction.

THE OTHER BIG FACTOR governing the financial success of any coffee shop is advertising. Good signage will pull in more traffic and should lead to more sales. In the case of solar cells, that means replacing a large triple-junction device with a lens or mirror that captures sunlight over




**FUNNELING COLOR:** The DARPA design concentrates sunlight and splits it into "buckets" optimized to absorb at particular frequency ranges. The initial concept, not yet realized, was to split light into three ranges. High-energy photons would go to a single cell, while two or three cells stacked together would harness the power from mid-energy and low-energy cells, respectively. As of today, researchers have not been able to produce a good enough cell for the high-energy photons, so the prototype design has just two buckets—a "green" one for higher frequencies and a "red" one for lower ones.

*ILLUSTRATION: JAMES PROVOST*



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an area just as great and focuses it on a photovoltaic chip that's much smaller and far cheaper to produce. Just as important as the reduction in cost is the increase in the efficiency and output power of the cell. When light is concentrated by a factor of 20, it doesn't merely create 20 times as many photons—it also boosts the output voltage, though it takes rather a bit of math to explain why this is the case.

In 2005, Spectrolab led the way with this approach, producing 39 percent efficiency with a triple-junction cell under the equivalent of the light coming from 236 suns. This bar has been raised many times. In 2011, Solar Junction claimed the most recent record of 43.5 percent cell efficiency at the equivalent of 400 suns, and this June, Sharp matched this figure with a cell operating at an undisclosed concentration.

To hit these figures, the cells must be mounted on systems that track the sun's position in the sky with tremendous precision. The smallest of such systems are several meters high and wide, which makes them suitable for solar farms but not as attachments to a soldier's gear. If concentration is to be used in portable solar systems, the factor of magnification must be far more modest.

**HIGH MAGNIFICATION:** Focusing sunlight on photovoltaic cells not only reduces the chip costs of the system but also boosts efficiency. That's because the more intense the light gets, the higher the voltage and the output power become. *PHOTO: SOLFOCUS*

Forty-three percent is pretty good, but it's not the desired 50. Further progress required a radically different approach, the one that Honsberg and Barnett had suggested to DARPA five years earlier. Rather than stack cells vertically, you tile them laterally, then split sunlight into several energy bands and focus each of them on different tiles.

Switching from a multijunction stack to a side-by-side array increases the maximum theoretical efficiency. That's because in a stacked system each layer is normally connected in series and thus has to produce the same amount of current. Designers can adjust layer thicknesses and other parameters to try to meet this requirement, but that's hard to do perfectly because the solar spectrum varies throughout the day—it's redder in the morning and late afternoon, bluer at midday. So a triple-junction cell's current is often limited to whatever the least productive layer can produce.

Also, stacked cells are limited by the way the stacks must be put together. To form these devices, crystalline layers are deposited atom by atom, and the spacing of the atoms in each layer must be very similar to avoid crystal imperfections. This limits the number of material combinations—and therefore the range of absorption wavelengths—that can be used in a multijunction cell. By avoiding stacks, Honsberg and Barnett's approach allows materials with vastly different atomic spacing to be used alongside one another without any compromise in quality.

Calculations show that without concentrated sunlight, efficiency should rise from 51.5 to 55.6 percent when you shift from three junctions to four. And moving to five or six junctions should raise efficiency to 58 percent and 59.6 percent. Real-world gains would of course be lower, but still, upping the concentration should assure good results. Barnett and Honsberg estimate that for a six-junction cell operating at 20 suns you get an efficiency of 54.3 percent, and at 100 suns, 55.6 percent. With much more concentration than that the cell might overheat, and it would be difficult to point the mirrors precisely.

Barnett and his colleagues initially developed tracking-free solar modules using concentrations of 20 suns. A mobile user could manually point the cells toward the sun.

ALTHOUGH IN THEORY it should improve efficiency, splitting the solar spectrum into six portions and focusing each of them onto a separate cell is actually taking things too far, because substantial losses result from steering that many beams of light. "Ideally, we like to separate them into three 'buckets'—high energy, mid-energy, and low energy," explains Barnett. Each bucket contains up to three cells, which means it's also a stack, but one that isn't connected in series. That way, you don't have to worry about matching the current. Stacks are required because it's the only way to get to the five or six junctions you need to achieve 50 percent efficiency.

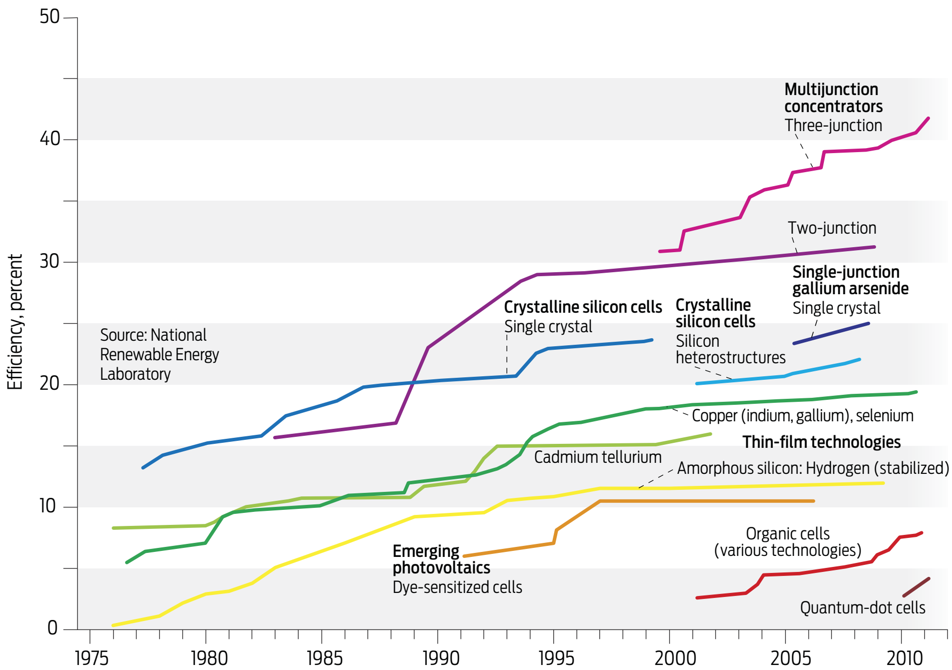
Deciding on the best way to get the sunlight into these buckets is tricky. At a meeting in 2006 at the University of Rochester, in New York, Kirkpatrick proposed to do it by using coatings that consist of finely built-up layers with different refractive indices that together create the desired interference patterns, much like those seen on the surface of a thin film of oil. Such dichroic designs let a range of wavelengths through while reflecting others with nearly perfect efficiency. This strategy would allow you to send the reflected light into one bucket and transmit light elsewhere, either onto cells or through another dichroic film for further spectral splitting. So far, designs have used only two buckets because the performance of the high-energy bucket isn't yet good enough to bother including it.

"Everybody was saying, 'No, no, no, that cannot work. You're wrong,' " Kirkpatrick says. The naysayers' skepticism reflected their background: They were aware only of incredibly precise dichroic coatings used in lasers. Kirkpatrick, however, knew that dichroics are also used in ceiling lamps in Europe to prevent filaments from overheating and thus failing prematurely.

Kirkpatrick demonstrated the capability of dichroic coatings by arranging for some of them to be made by Fiberstars (now Energy Focus) of Solon, Ohio. This firm joined the VHESC program shortly after the Rochester conference.

THE INITIAL DESIGN concept for the module—one that was never built—featured an optical element to split the sunlight into three spectral buckets and a lens the size of a thumbnail to focus it onto the low-energy, mid-energy, and high-energy cells. The modules were tiled, forming an array.

The choice for the mid-energy bucket was rather obvious: an indium gallium phosphide cell in front with a gallium arsenide cell behind. Together they captured wavelengths from the




**50 PERCENT, HO:** The efficiency of photovoltaic cells has continued to rise for decades, though particular designs may well have reached their practical limits. The highest efficiencies result from stacking three junctions on top of one another and using lenses or mirrors to concentrate the sunlight several hundredfold. *ILLUSTRATION: JAMES PROVOST*

near infrared to the green part of the spectrum, where the high-energy bucket began. But it was harder to fill the low-energy bucket, which stretched from the short infrared to the near infrared, and the high-energy bucket, which stretched from the green through the ultraviolet. Silicon works well in the infrared and can be partnered with germanium-based compounds, but it works even better when paired with indium gallium arsenide phosphide and indium gallium arsenide, because this combination generates some of its electricity at a higher voltage. There are very few good candidates for the high-energy bucket. Materials based on gallium nitride are the most promising, but they are dogged by problems such as dislocations in the crystal lattice.

Because of the difficulties with the high-energy bucket, the VHESC program has so far developed optical modules with merely low-energy cells, together with mid-energy variants that also capture some high-energy photons, although not as efficiently. In 2007, researchers measured the performance of cells made from indium gallium phosphide, gallium arsenide, silicon, indium gallium arsenide phosphide, and indium gallium arsenide, then calculated the contribution that each would deliver to a five-junction cell operating at 20 suns. They concluded that such a device could have a 42.9 percent efficiency, well ahead of the 40.7 percent record then held by a Spectrolab cell operating at a concentration of 240 suns.

Since then the program has defined its target differently, aiming not for a cell efficiency of 50 percent but rather for a module efficiency of 40 percent. This makes sense: Modules are always less efficient than cells, partly because imperfections prevent their optics from directing all the incident sunlight on the cell. And it's the output power of the modules that matters. The 40 percent target is still plenty tough, given that the best commercial triple-junction photovoltaic modules have efficiencies of just over 30 percent when operating at concentrations of several hundred suns.

By 2008 the consortium had set a new benchmark for efficiency with cells that collect light with one lens and then split the spectrum with a dichroic mirror onto tandem cells, one absorbing ultraviolet and visible light, the other absorbing infrared light. Operating at 20 suns, the device upped the record for module-wide efficiency from 32.6 percent to 36.7 percent when tested independently at the National Renewable Energy Laboratory (NREL). One hit 39.5 percent efficiency in tests at the University of Delaware. Differences in the values reflect disparities in the measurement of the aperture above the focusing lens, misalignment of the cells, and variations in individual cells.

A road map to the 40 percent efficiency mark and beyond followed. Options include turning to more highly reflective coatings on the focusing lens; enshrouding the optics in silicone to reduce internal reflections; adding antireflection coatings to the individual cells; and improving the optical alignment of the module as a whole. The team recently implemented some of these ideas, increasing the efficiency of the modules measured at NREL to 38.5 percent.

"We moved away from silicon to hit the big number," admits Barnett, who is not a fan of records but acknowledges the good publicity they bring. More headline-grabbing success is now within reach, because Barnett believes that a recently fabricated, high-quality gallium phosphide cell could be inserted in front of the mirror, increasing module efficiency beyond 40 percent.

FOR THE TIME BEING, though, the researchers are concentrating less on efficiency and more on economics, trying to beat the cost per watt that all-silicon cells now provide. According to Dan Laubacher, a research fellow at DuPont, one of a handful of firms responsible for building the first prototype modules, costs can be trimmed by using silicon germanium cells for the low-energy bucket alongside cheaper dichroic coatings that sacrifice little in terms of performance.

The VHESC program is clearly on its way to providing a portable, affordable source of solar power. Soldiers will be the first to reap the benefits, but not the last. With such modules in hand, it'll be possible to carry the makings of a solar farm on a few trucks and set it up quickly. The result? A lot of electricity, with a relatively small footprint—not just for field soldiers but also for explorers, off-the-grid environmentalists, and isolated rural communities. It would shine wherever the sun does. ❑

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# GENERATION SMART-PHONE

## The smartphone's role as constant companion, helper, coach, and guardian has only just begun

BY DAN SIEWIOREK

**IT'S THE YEAR 2020** and newlyweds Tom and Sara are expecting their first child. Along with selecting the latest high-tech stroller, picking out a crib, and decorating the nursery, they download the "NewBorn" application suite to their universal communicator; they're using what we'll call a SmartPhone 20.0. Before the due date, they take the phone on a tour of the house, letting the phone's sensors and machine-learning algorithms create light and sound "fingerprints" for each room.

When they settle Tom Jr. down for his first nap at home, they place the SmartPhone 20.0 in his crib. Understanding that the crib is where the baby sleeps, the SmartPhone activates its sudden infant death syndrome (SIDS) application and uses its built-in microphone, accelerometers, and other sensors to monitor little Tommy's heartbeat and respiration. The "Baby Position" app analyzes the live video stream to ensure that Tommy does not flip over onto his stomach—a position that the medical journals still report contributes to SIDS. Of course, best practices in child rearing seem to change quickly, but Tom and Sara aren't too worried about that because the NewBorn application suite updates itself with the latest medical findings. To lull Tommy to sleep, the SmartPhone 20.0 plays music, testing out a variety of selections and learning by observation which music is most soothing for this particular infant.

PHOTO: DAN SAELINGER; STYLIST: MARIA-STEFANIA VAVYLOPOULOU



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# A Lifetime of Apps

## The smartphone of the future will be a constant companion, coach, collaborator, and advisor

As a toddler, Tommy is very observant and has learned the combination on the gate to the swimming pool area. One day, while his parents have their backs turned, he starts working the lock. His SmartPhone "Guardian" app recognizes what he is doing, sounds an alarm, disables the lock, and plays a video demonstrating what could happen if Tommy fell into the pool with no one else around. Not happy at being thwarted, Tommy throws a tantrum, and the Guardian app, noting his parents' arrival, briefs them on the situation and suggests a time-out.

WHILE THIS SCENARIO IS, of course, science fiction, many of the technologies I'm describing are here today in research labs or even in app stores. So the reality of a SmartPhone 20.0, along with its envisioned NewBorn suite, are not far off.

Geo-fencing, for example, is already a standard part of the iPhone operating system. Several smartphone apps can use GPS to identify the user's location and bring up targeted advertising. Research focusing on improving location accuracy indoors, as well as software that "fingerprints" ambient light and sound, will soon make these apps able to accurately identify rooms in a house. Today, wearable SIDS monitors detect a baby's breathing motion and vibrate when it stops, to stimulate the baby to take another breath—for example, the Halo, from the South African company Snuza. Researchers at the Technical University of Munich and others are testing emotion recognition from audio.

But the SmartPhone 20.0 won't be just a high-tech baby monitor. Rather, the device or smart mobile devices like it will serve as nanny, nurse, or golf caddy—the perfect assistant for people of all ages. If you think that people can't seem to make a move without consulting their phones today, well, you ain't seen nothing yet.

Let's age Tommy to 3 years old. Tom and Sara take him skiing for the first time. Tommy's SmartPhone, now version 23.0, downloads the "Virtual Skiing Coach," which uses accelerometers sewn into Tommy's clothing to sense his posture and then offer suggestions for maintaining balance; when it foresees an impending collision, it quickly blurts out instructions on how to stop. We already have basic sensor-based virtual coaches. For example, the InForm Exercise Coach for knee osteoarthritis uses accelerometers and gyroscopes to track motion during rehabilitation exercises and correct errors. Such coaches would enable therapists to remotely monitor home-based exercise, making it easier for seniors to remain at home as they age and reducing health-care costs. These virtual coaches learn, so the longer people use them, the better they work.

At age 5, with the SmartPhone 25.0 education apps, Tommy has become a curious and eager learner. He looks forward to his first day at kindergarten. He meets Alice, who can neither hear nor speak, but because of her SmartPhone, she is able to easily participate in class. Alice greets Tommy by signing, and her SmartPhone plays a translation provided by the American Sign Language (ASL) app. Tommy responds, and Alice's speech-recognition app provides her with real-time captioning. Tommy shares his favorite song with Alice, sending it from his SmartPhone to hers, which translates the music to vibrators in a vest she wears.

Back in 1997, Thad Starner of Georgia Tech put a camera in the bill of a baseball cap to enable a computer to interpret a user's ASL gestures and display the results on a smartphone; no such product has yet been released commercially. But some ASL apps already exist: For example, the SmartSign from Georgia Tech, designed for hearing parents of deaf children, allows them to call up a video of a sign by speaking the


JAMES PROVOST

In the crib, the smartphone will **MONITOR** breathing and sleeping position.

Outside, the smartphone will **SET BOUNDARIES** through geo-fencing.

On the ski slope, the tennis court, and the golf course, the smartphone will be a **VIRTUAL COACH**.

As a **LANGUAGE TRANSLATOR**, the smartphone will be able to handle even sign languages.

**INDOOR MAPPING** of office buildings, malls, universities, and other complexes will be commonplace.

With a smartphone as an **ASSISTANT**, you'll never forget another name or face.

Teens will learn safer driving with a **SMARTPHONE ADVISOR**.

As a **VIRTUAL WATCHDOG**, the smartphone of the future will warn of potentially dangerous situations.

A smartphone-generated **VIDEO RECORD** of the day's events will help people remember them.

**HEALTH-MONITORING APPS** will prompt users to test themselves and send the results directly to doctors.

It will get easier to measure vital signs with **SMARTPHONE ATTACHMENTS**.

**ADVICE** will be passed down through generations—and kids will be able to turn to virtual grandparents for advice.

English word. The VibeAttire vest, which lets wearers feel music through vibrating motors sewn into the fabric, debuted at the 2010 International Consumer Electronics Show, or CES.

One day, Tommy is walking home from school, and the SmartPhone 27.0 Guardian app notices that a stranger has started a conversation with him and is coaxing Tommy to get into a van. The Guardian app whispers in Tommy's ear not to talk to the stranger and tells him to run to a nearby house, one the app has already verified as a local kid-safe house and confirmed that someone is home. The Guardian app takes a picture of the stranger and the license plate of his van and forwards the information to the police.

First Person Vision, introduced at the 2011 CES, uses video taken by wearable cameras and smartphones to identify gestures, actions, and faces in real time. It's not much of a stretch to envision it alerting users to threats.

FOR TOMMY'S 16TH BIRTHDAY, his parents download the "Driving Instructor" app. Of course, by 2036 cars have many safety features but still require the driver to take over in emergency situations, so a driver's license is still required. Under the tutelage of the app, Tommy becomes an excellent driver; his parents trust that they'll be alerted if he starts driving recklessly.



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These kinds of driver-monitoring tools are now in the lab. For example, the DriveCap project at the Quality of Life Technology Center, in Pittsburgh, run by Carnegie Mellon University and the University of Pittsburgh, uses in-car sensors to track driver behavior (accelerometers can detect erratic maneuvers and sudden changes in braking and acceleration) and the driver's cognitive load—that is, how attentive, tired, or overwhelmed the driver is—by focusing a camera on the eyes.

Years later, Tom Jr.'s SmartPhone (upgraded, of course, many times over the years) continues to be a trusted companion. On a business trip, the "Administrative Assistant" app reminds Tom of people's names and their connections to him; this is an easy-to-imagine extension of First Person Vision. Tom has an appointment in a large building complex, which has a confusing maze of corridors and bridges between buildings. Tom's SmartPhone snaps pictures for comparison to an archive of pictures of different parts of a building; that's something the First Person Vision app already does. By locating his position on a floor plan and knowing his destination, the "Building Navigation" app can efficiently guide him to his meeting. Applications like this already exist; the simplest are based on indoor maps developed by Google Places for Business.

On one trip, Tom twists his ankle while jogging. His SmartPhone directs him to the nearest emergency room; iPhone 4s users are already familiar with the Siri app's ability to do this kind of location finding. Later the SmartPhone recognizes that Tom is using his crutches incorrectly and gives him some pointers. While a "crutches coach" is not currently on the market, similar coaches have been demonstrated in the field. People who use manual wheelchairs are susceptible to repetitive-use injuries to their wrists and shoulder rotator cuffs. Researchers at Carnegie Mellon and the University of Pittsburgh have tested accelerometers in a wristwatch-like bracelet that classifies the arm movements and encourages those patterns that generate the least stress on the wrist and shoulder. Powered wheelchairs are being used to test more sophisticated built-in sensors to help users with spinal cord injuries avoid developing pressure sores by making sure they shift positions frequently; these devices have also been tested at the two Pittsburgh universities.

Tom wants to give his son, Thomas III, some of the tips he learned from his father on how to swing a baseball bat. So Tom uses a virtual coaching tool kit to develop his own baseball batting app. The app uses one set of sensors to recognize the type of pitch and another set, worn on the body, to analyze the batter's reaction. Tom doesn't stop there; he builds several coaching apps, including some for camping skills, gardening, household repairs, and automobile maintenance.

Tool kits already exist for simplifying the development of applications that augment reality—for example, the ARToolKit, an open-source project supported by the University of Washington; the University of Canterbury, in New Zealand; and ARToolworks, in Seattle. To pass along his father's life lessons, Tom records video of his father answering a variety of questions. In years to come, Tom's son will ask questions, which the SmartPhone's speech recognizer will match with an automatically generated index of the video clips, letting the grandson have simulated conversations with his grandfather.

Researchers at Carnegie Mellon have already used such synthetic interviews to enable people to converse with historic figures like Albert Einstein or Charles Darwin (played by actors) and with actual teenage breast-cancer survivors.

As Tom ages and his cognitive capacity decreases, he becomes less able to make critical decisions as he is driving. In particular, his decreased night vision makes it difficult to judge the speed of oncoming traffic. His SmartPhone "Driver Capability" app notices his hesitation and instructs the car's navigation system to use only intersections with left turn signals or to plan right-turn routes after dark. As Tom exhibits characteristics of early-onset Alzheimer's, he takes advantage of MemeXerciser, developed years ago in Pittsburgh, which collects snapshots and audio clips from a camera and microphone worn as a pendant. After an event, such as a trip to the zoo, with the aid of a video-editing tool kit, a caregiver can create an audio/video summary of the event, which Tom can replay at his leisure. Studies at Carnegie Mellon's Human-Computer Interaction Institute have demonstrated that MemeXerciser helps improve recall, not only of a particular event but also of activities that have not been recorded.

Even later, Tom's declining health requires ever more monitoring by his doctor. Fortunately, Tom's SmartPhone Health app allows his doctor to request routine self-monitoring tests using sensors built into the phone. The app administers these tests to Tom according to a schedule set by the doctor, who can review test results and order additional tests if necessary. The Health app also monitors Tom's activities and notifies the nurse in the independent living complex where he now resides if there are any anomalies.

Today, "health kiosks" that perform these functions are already in use in workplaces and senior living centers. United Healthcare, for example, offers them to its clients. It's not much of a stretch to imagine those functions moving to the smartphone. Already, new applications like VitalClip, an iPhone accessory soon to go into a private beta test, allow users to measure vital signs by touching a finger to a sensor.

Tom's SmartPhone has captured his eventful life through video and audio, automatically divided into segments and indexed for textual search through speech-to-text conversions. Virtual coaches and synthetic interviews capture his hard-won wisdom and archive it for posterity. Later his son, and then his grandchildren, can tap that wisdom with Tom as one of his family's virtual companions, guardians, and coaches.

The apps that help Tom throughout his imaginary life are all straightforward extrapolations from what exists today. But technology isn't always bound to a straight path. In the future, the SmartPhone and smart communicators like it will decrease in size until sensing and computing is simply part of everyday objects, integrated into the outer "skins" of devices, woven into clothing, and embedded into countertops. This integrated technology will be situationally aware, understanding the user's intent and jumping in to help without a touch or a voice command. The Tommys of the future will be protected by helmets and uniforms that anticipate potential concussion-causing collisions and quickly react with counterforces that minimize bruising of the brain. Their footballs will signal "first down" from the bottom of the pile of players—no human judgment necessary. Their kitchens will figure out what meal is being made as ingredients are pulled from the refrigerator and step-by-step preparation instructions are displayed on the countertop. All this technology will have a zero carbon footprint, as it scavenges energy from radio waves in the environment and biodegrades when it is discarded. And we can see this future reflected in today's smartphones. ❑

**POST YOUR COMMENTS** *online at* http://spectrum.ieee.org/smartphone0912



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c/o Toya Jordan, School of Electrical and Computer Engineering.
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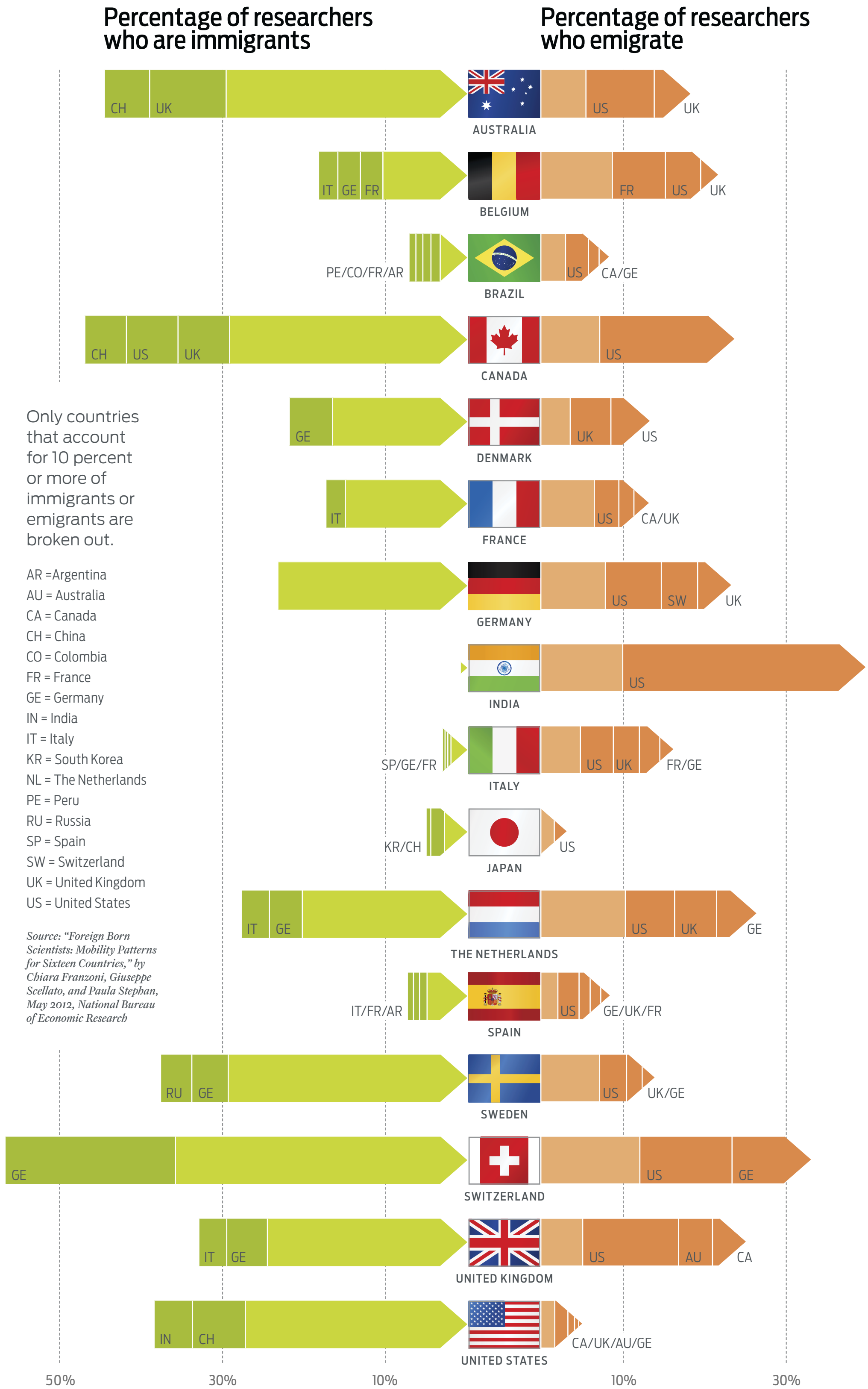
# the data

## The Global Brain Trade

A survey reveals the worldwide migration patterns of researchers

WHICH countries have the most foreign scientists, and which ones suffer from the worst brain drain? To answer these questions, researchers at the National Bureau of Economic Research, in Massachusetts, conducted a Web-based survey of over 17 000 published scientists in 16 countries. (China wasn't surveyed: The researchers tried but were unsuccessful in administering the survey to scientists there.) While the United States is, unsurprisingly, a popular destination for scientists from around the world, Switzerland actually has the highest percentage of immigrant scientists. On the other side of the coin, Japan is the most insular country surveyed, exchanging relatively little scientific talent with the rest of the world.

—*Ritchie S. King*




Only countries that account for 10 percent or more of immigrants or emigrants are broken out.

AR = Argentina
AU = Australia
CA = Canada
CH = China
CO = Colombia
FR = France
GE = Germany
IN = India
IT = Italy
KR = South Korea
NL = The Netherlands
PE = Peru
RU = Russia
SP = Spain
SW = Switzerland
UK = United Kingdom
US = United States

*Source: "Foreign Born Scientists: Mobility Patterns for Sixteen Countries," by Chiara Franzoni, Giuseppe Scellato, and Paula Stephan, May 2012, National Bureau of Economic Research*



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