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FOR THE TECHNOLOGY INSIDER | 05.13

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The little Danish island that could
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THE NEW TECH START-UPS
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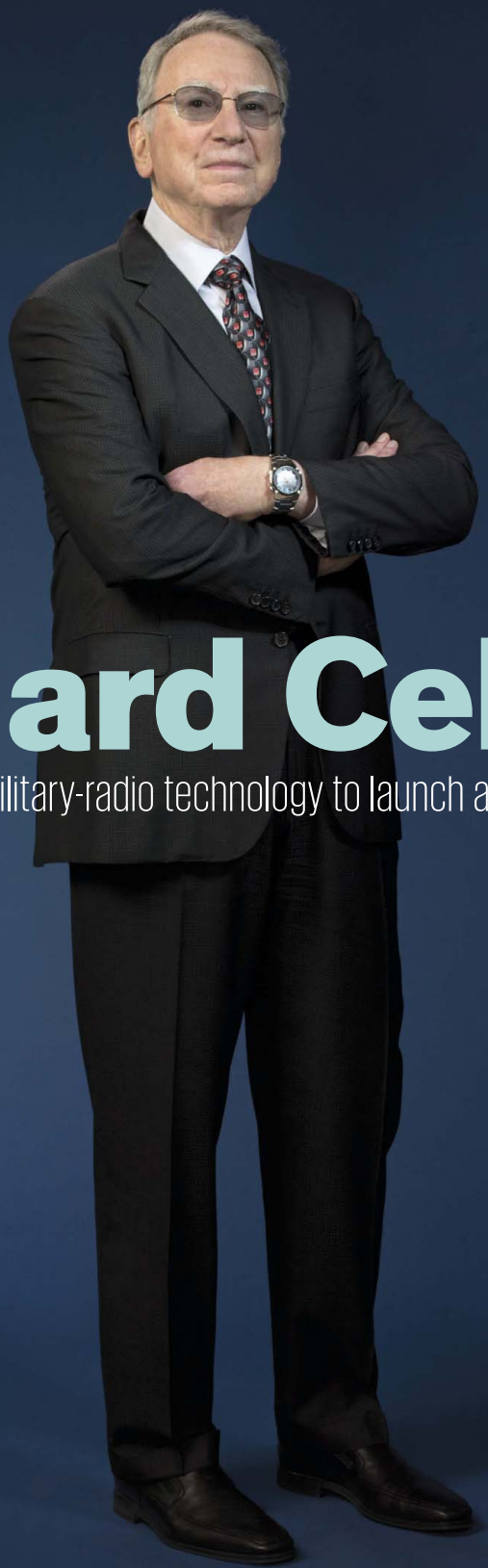

Hard Cell

How Irwin Jacobs used a military-radio technology to launch a wireless revolution P. 48

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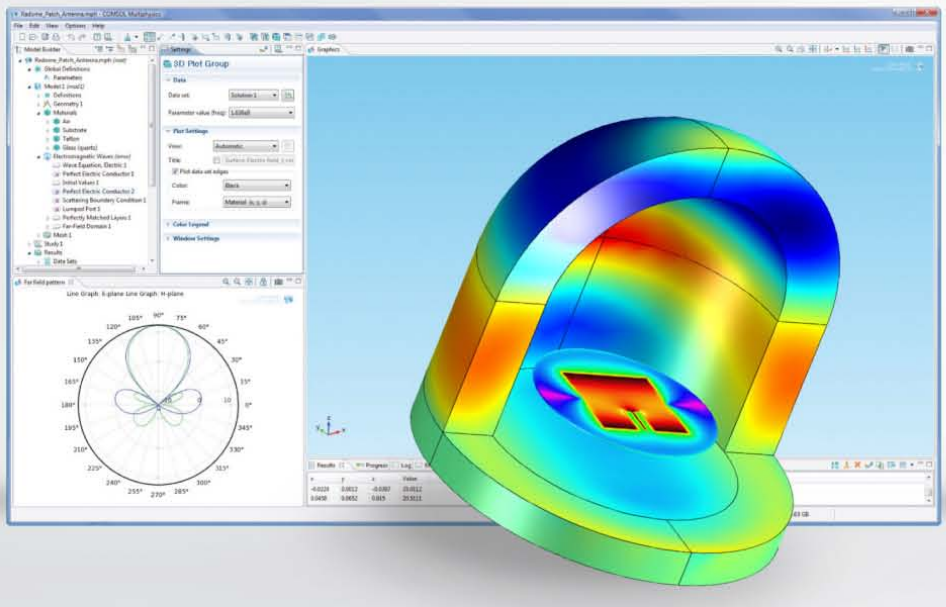
PATCH ANTENNA: A radome minimizes losses and improves radiation characteristics of a patch antenna through its design. Such devices are light, and easy to manufacture and integrate with other electronics components for wireless network or GPS applications.



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EUROPE'S FUTURE GRID

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Germany Jump-starts the Supergrid

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Tiny Danish Island Shows the Way

By Jean Kumagai

Greater use of wind and solar has grid operators everywhere scrambling to tame these unpredictable sources. *IEEE Spectrum* looks at two bright solutions: Germany's high-voltage DC plans and a smarter, greener grid in Denmark.

JOCHEN SCHLENKER/GETTY IMAGES

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When Spectrum Auctions Fail

Economists believe auctions make the most efficient use of radio spectrum. For fixed microwave, though, competitive bidding has proved a lousy approach. **By Mitchell Lazarus**

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The Troubled Life of Patent No. 6,456,841

How a simple cellphone patent got caught up in the intellectual-property war over smartphones.
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Qualcomm cofounder Irwin M. Jacobs, the 2013 IEEE Medal of Honor recipient, revolutionized cellular communications with code division multiple access.
By Tekla S. Perry

ON THE COVER Photograph for *IEEE Spectrum* by Gregg Segal

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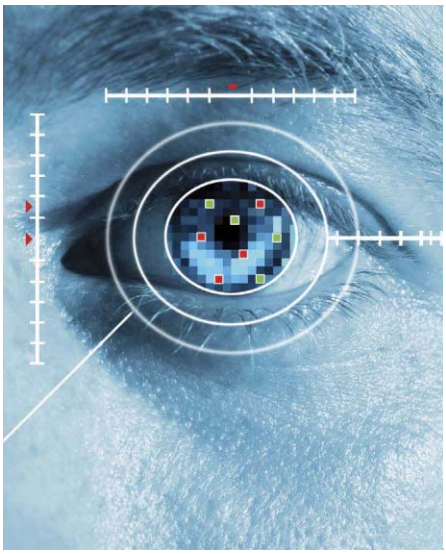

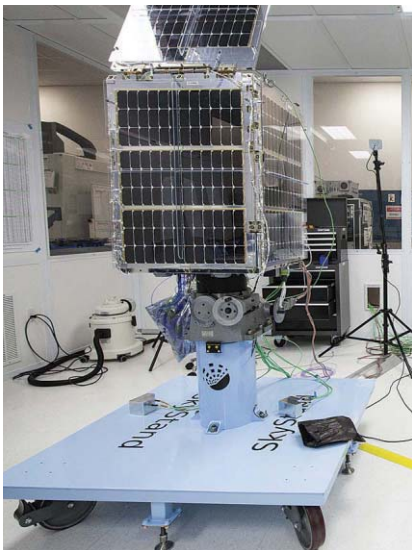

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Taking Tech to Market
Skybox Imaging is the latest company we've profiled in our ongoing series covering start-ups at the forefront of commercializing technology. Skybox is hoping to create a revolution in satellite imagery by building a low-cost constellation of spacecraft. Read more at http://spectrum.ieee.org/at-work/innovation

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3-D PRINTING GOES GREEN IEEE member Joshua Pearce is working on a tool called Recycle Bot, which can turn milk jugs and other trash into 3-D printing material. The bot requires only one-tenth of the energy normally needed to produce a 3-D filament.

LEARN A NEW LANGUAGE FOR LESS Being bilingual can be a great career booster. That's why IEEE is now offering members a discounted rate for Rosetta Stone, the world leader in language-learning software.

CONFERENCE COVERS UNDERSEA EXPLORATION Engineers will meet in Rio de Janeiro this July to discuss state-of-the-art and emerging techniques for using acoustics to investigate the water column, seafloor, and more. The conference is sponsored by the IEEE Oceanic Engineering Society.

FROM LEFT: TRACY LORNA/ISTOCKPHOTO; DISCOVERY BAY GAMES; MATT McDONALD

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High Anxiety

Shortly before Jean Kumagai arrived on the Danish island of Bornholm to report on a new smart-grid project [see "The Smartest, Greenest Grid"], one of her contacts e-mailed a proposed itinerary. It was packed solid with interviews, she says, "but a little light on excitement." Interviews are the stuff of journalism, of course, but she didn't relish the idea of flying 6000 kilometers to sit in conference rooms and stare at PowerPoint slides.

So it was with an odd mix of relief and terror that she found herself, four days later, perched 60 meters in the air, clinging for dear life to a metal strut while the wind whipped around her. That unnerving experience came thanks to power engineer Mark Moseholt, who works for the Bornholm electricity utility Østkraft Net.

After a full afternoon that included a lunch of smoked herring, a visit to a smart-grid demonstration house, and a tour of Østkraft's main power plant, Moseholt suggested they take a drive across the island. It was a gorgeous fall day, and the country roads wound past picturesque farms and tiny villages and right through Bornholm's native forest. Turning down an unmarked dirt road, they arrived at their destination: three giant wind turbines plunked down in the middle of a field.

Moseholt pointed out a repair truck. "You're in luck," he said. "They're working, so we can peek inside." When one of the technicians offered to show her the turbine's generator, Kumagai quickly donned a safety harness, scrambled into the cramped metal cage that passes for an elevator, and took a slow, jerky ride to the top.

Popping open the roof hatch, she gazed appreciatively at the patchwork quilt of farmland. Then she noticed 1) the massive 80-meter-long blades just a meter or so away, 2) the roof's smooth downward slope, and 3) the absence of any railing between her and the blades. Her mind quickly raced through several gruesome scenarios.

Technician Ole Enggaard chuckled at her look of panic. "You maybe won't believe me," he said, "but it's nice to have lunch up here on a summer day." ■

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PHOTOGRAPH BY **Mark Moseholt**

CONTRIBUTORS_

Peter Fairley

Paris-based contributing editor Fairley traveled to Stuttgart last November to report on Germany's bold plan to build high-voltage DC lines to send renewable energy where it's needed most ["Germany Jump-starts the Supergrid," p. 32]. The weather was bitter cold and very dark, he says, which made it "chillingly clear" that the boom in solar power wouldn't make up for the coming closure of the region's nuclear plants—at least not year-round. "Fixing the grid will keep all of Germany on track," he says.

Tam Harbert

A freelance journalist based in Washington, D.C., Harbert recounts in this issue the convoluted legal machinations of a single U.S. patent ["The Troubled Life of Patent No. 6,456,841," p. 44]. "Despite the debate about so-called patent trolls, many companies trade patents behind the scenes with those very trolls," she notes. "Everyone's goal is the same: to make as much money as they can from their patents." She wishes she could do something similarly lucrative with her copyrighted works.

Mitchell Lazarus

A former electrical engineer, Lazarus is now a partner in the Washington, D.C., law firm Fletcher, Heald & Hildreth. He helps the Fixed Wireless Communications Coalition and others navigate Federal Communications Commission rules. In "When Spectrum Auctions Fail" [p. 28], he describes the history and technology of point-to-point microwave communications and a current challenge: whether regulators should auction the spectrum or let engineers avoid interference on their own.

Robert W. Lucky

Lucky ["Sensuous Electronics," p. 26] says he's always been fascinated with electronics. As a child, while listening to the radio at night, he would watch the dancing orange lights coming from the filaments in the vacuum tubes and wonder how the voice of the Lone Ranger came out of them. He went on to work for many years at Bell Labs, became an IEEE Fellow, and earned 11 patents along the way. He says he can still remember the smell of a newly opened box from Heathkit.

Gregg Segal

A regular contributor to *IEEE Spectrum*, Segal has photographed Irwin M. Jacobs, recipient of the 2013 IEEE Medal of Honor [cover and p. 48], on three occasions. Segal's exhibit "State of the Union," a series featuring Civil War enactors at now-modernized battle locations, comes in June to the O. Winston Link Museum, in Roanoke, Va. In October, the Blue Sky Gallery, in Portland, Ore., will display his "None of the Above," a collection of portraits that explore stereotypes of voters' political identities.

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PHOTO-ILLUSTRATIONS BY Gluekit

KARMA MEANS PAYBACK: The U.S. government will likely never recover the money it lent Fisker.

Fisker Automotive: Fraught With Failure

Does the U.S. Department of Energy have the guts to tolerate defaults on its loans?

WHILE DRIVING a new and very expensive car around Manhattan, it's disconcerting to see the electronic instrument cluster fade to black, then to be told to pull over, put the car to sleep, wait a few minutes, and then restart it.

Worse still is when the manufacturer's representative chirps, "We rely on our early customers to identify issues like this for us."

That's something you'd never hear from General Motors, Toyota, or Volkswagen. But it's emblematic of the challenged development process of the US $106 000 Fisker Karma, a range-extended electric luxury sport sedan.

Venture capitalists risk their own money backing such firms; should the government do so, too, using taxpayers' money? That's a question not just for Washington but for any government anywhere that might be tempted to bail out a green-tinted job-making concern. And the temptation is always high for concerns that make cars, central as they are to a country's sense of self.

Look past the Karma's low, sleek design and you'll see the least efficient plug-in electric vehicle, one with so little room inside that the Environmental Protection Agency calls it a subcompact, despite a footprint equaling that of a full-size BMW 7 Series sedan. And the early cars were riddled with defects. Several hundred of them had their battery packs recalled, and at least two caught fire due to an overheating fan. Sixteen more burned after immersion in seawater during Superstorm Sandy.

Fisker Automotive is expected to declare bankruptcy any day now. It's failed time and again to meet deadlines under the terms of the low-interest loans it got under the U.S. Department of Energy's Advanced Technology Vehicle Manufacturing Loan Program, in 2009.

The ATVM program lent out $9 billion of $25 billion authorized. Two-thirds went to Ford, largely to roll out a fuel-efficient line of engines; Nissan used $1.4 billion to help it build its Leaf electric car, and the batteries that power it, in Tennessee.

But all the opprobrium was focused on smaller loans authorized for two high-profile venture-backed start-ups: $465 million to Tesla Motors and $529 million to Fisker Automotive. Both companies were "losers," sneered Republican presidential candidate Mitt Romney, during the 2012 presidential election debates. Tesla has now seemingly become a functioning carmaker, albeit a small one, but Fisker's failure proves Romney at least half right.

And therein lies the challenge: Failure comes with the territory. Seasoned venture capitalists know that of any ten start-ups they fund, perhaps five or six may fail completely, another two or three may be sold at a loss, and one or two will be successful. If just one of those successes is a biggie, the VCs will make money.

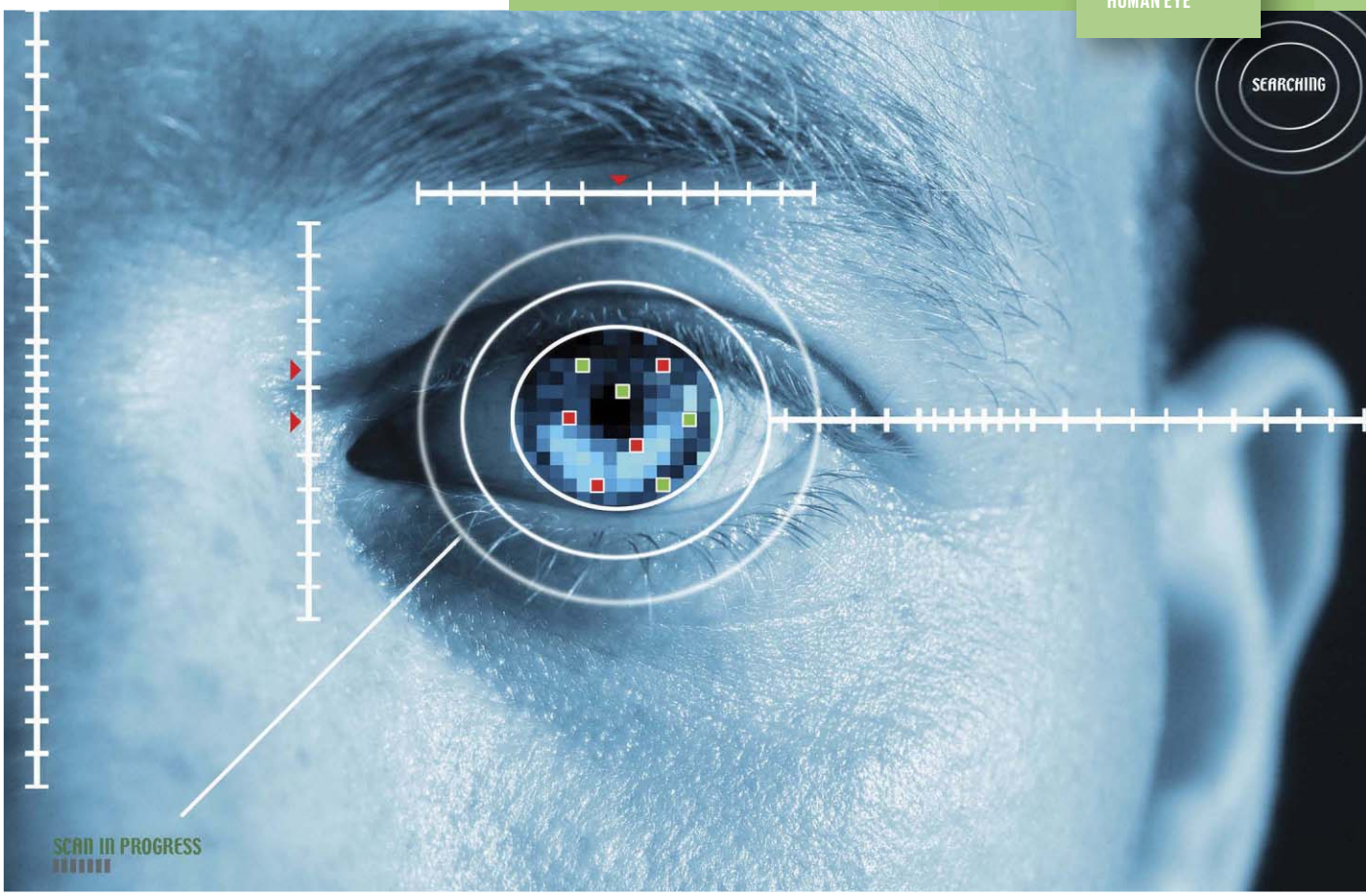
Government funding is different, because failure—or acknowledgement of failure—is politically unacceptable. Unless politicians are prepared to acknowledge up front that loan programs to businesses may have losers as well as winners, perhaps they should resolve to fund basic science and other worthy endeavors that aren't subjected to a profit-and-loss analysis, and just let companies fend for themselves—or at least the controversial companies. Nobody has uttered a peep of protest against the loans made to Ford and Nissan. —JOHN VOELCKER

John Voelcker is editor of *Green Car Reports* and a senior editor at High Gear Media. He covers fuel-efficient and alternative auto technologies for both consumer and industry outlets.

FABRICE COFFRINI/AFP/GETTY IMAGES

NEWS

900 DEGREES PER SECOND: PEAK ANGULAR SPEED OF THE HUMAN EYE



TRACY LORNA/ISTOCKPHOTO

RISE OF THE EYE PHONES

Gaze-tracking software is bringing hands-free control to phones and tablets

GO AHEAD, wake up your smartphone. No, don't touch it! Just look at it. Wait for a second...and...yes! It recognizes you. You don't even need to key in a pass code. Your phone identifies the unique way your eyes flicker. See? What app do you want to open? News? Okay, stare at the icon. Want to scroll through an article? Look down. Pause a video? Look away.

The day when eye tracking becomes a common feature in mobile gadgets may not be far off. The technology got a lot of buzz this March when Samsung demonstrated finger-free scrolling and video control on its flagship phone, the Galaxy S4, during the product's launch in New York City. The same week, LG Electronics announced it would include similar capabilities in its newest smartphone, the Optimus G Pro.

But while the South Korean giants may be trailblazers in bringing gaze-based interfacing to the mobile market, analysts and researchers say their products only scratch the surface of what's possible. The Galaxy S4, for instance, knows when to start or stop a video simply by discerning the presence of a user's face through its front-facing camera. And it scrolls text by sensing the tilts of the user's wrist.

Other innovators are working to build systems that not only detect face orientation but also follow the subtle motions of the head and eyes, allowing for more sophisticated applications. Israeli start-up »

Umoove, for example, is developing head- and eye-tracking software that the company says will be able to work on any mobile platform. Last month, it shared its tool kit with a select group of app developers, including game and e-book designers. Umoove says it expects to release a commercial version of the kit for Apple's iOS and Google's Android later this year.

Eye-tracking systems for desktop computers have been around for decades—for instance, to conduct laboratory experiments and to help disabled people control their machines. But these systems often require bulky external hardware and complex algorithms that demand ample processing power. So there are huge challenges when trying to adapt the technology for mobile devices.

The first hurdle is overcoming instability. "You have to separate between the movements of the device and the movements of the user," says Umoove CTO Yitzi Kempinski. His company's software solves this problem, he says, by pulling data from a smartphone's various sensors, including its gyroscope, accelerometer, and compass. The system then combines the results with image data to filter out unwanted information.

Then there's the problem of computing resources. "Eye tracking needs to be something that can run almost invisibly in the background of any application," Kempinski says. Three years ago, when Umoove began pursuing mobile eye tracking, its engineers thought they could borrow many of the algorithms used in PC-based systems. They ran their first program on a Nokia smartphone, Kempinski says, because it was one of the only models with a front-facing camera. "Within about 3 seconds, the phone crashed," he recalls. "That's when we realized, okay, we're really going to have to start from scratch."

In traditional image tracking, a system searches a large portion of each frame to identify relevant features, such as irises or eyelids. It then models how those features shift between frames. To save processing power, Umoove's software follows a different set of rules. For instance, it uses information extracted from previous frames, such as the angle of the user's head or the acceleration of a blink, to predict where to look for facial targets in the next frame. This anticipation minimizes the amount of computation needed to scan each image. When run on a Galaxy S III, Umoove's system uses less than 2 percent of the phone's CPU power, Kempinski says.

Other researchers are skeptical that today's smartphone cameras alone can support refined eye tracking. "I'd be really surprised if someone could do accurate pointing or perform similar actions reliably for a wide range of users and conditions," says Ralf Biedert, a senior interaction researcher at Tobii Technology. The Swedish company is commercializing a consumer-grade eye tracker that would plug into a computer's USB port. The candy-bar-size device projects infrared light and follows a user's gaze by capturing the eyes' reflections with a pair of cameras.

Biedert and others agree that whatever the underlying system, eye tracking has the potential to transform the way consumers interact with their devices. The technology is already used in some cars to warn drivers when they are dozing off. It could also enable chefs to browse recipes while cooking and inform authors where readers lose interest in a text. Even simple tasks such as reading or browsing "will be more natural and more convenient," says Robert Jacob, an expert on computer interfaces at Tufts University, in Medford, Mass. "You don't have to interrupt your flow of thought," he explains, which often happens when you must manually point to something your eye has already found.

Widespread adoption of eye-tracking technology could also invite some unwanted consequences, cautions John Villasenor, a technology and policy expert at the Brookings Institution and the University of California, Los Angeles. "The big concern is privacy," he says. Your phone could collect data on your eye movements, such as which Google results you skimmed, which advertisements you lingered at, and whether your pupils dilated when you read about certain subjects. That information could easily pass into the hands of advertisers or law enforcers. While you are intently watching your device, Villasenor says, "your device, perhaps unbeknownst to you, could be watching you."

—ARIEL BLEICHER

A SOLAR MIRAGE IN THE MIDDLE EAST?

The oil-rich monarchs' ambitions for solar power will be tough to achieve

Solar power in the Middle East seems simultaneously logical (sun-scorched deserts everywhere) and illogical (all that oil!). That contradiction lay just under the surface in March as United Arab Emirates president Sheikh Khalifa bin Zayed Al Nahyan flipped the ceremonial switch to ramp up the new Shams 1 solar thermal power plant toward its 100-megawatt capacity. The U.A.E. is at the head of the renewable energy pack in the region, but several of the "Gulf monarchies," all major contributors to the world's oil supplies, are starting to set goals to cut back on consuming the hydrocarbons they produce in favor of sustainable, climate-friendly energy sources. Are they really going to leave some of that black gold in the ground forever? Or are projects like the US $600 million Shams 1 just shiny distractions in a plan to push oil profits farther into the future?

Abu Dhabi, the biggest and most oil-rich of the seven semiautonomous emirates in the U.A.E., has a goal of getting 7 percent of its electricity from renewable sources by 2020. Saudi Arabia, the world's largest oil producer, is even more ambitious. The Saudi government hopes to just about double its installed electricity capacity by building 54 gigawatts of renewable energy (as well as 17.6 GW of nuclear power) by 2032, of which 41 GW will come from the sun. Qatar is also turning to renewables, with a plan on the table to get 10 percent of the electricity and energy used in water desalination from solar by 2018. Kuwait, too, has ambitions for 10 percent renewables by 2020.

The environmental rhetoric that surrounds these plans and targets can be impressive. But at the Shams 1 dedication, the talk was also about extending the number of years that the U.A.E. can keep pumping oil. "In the near term, hydrocarbons will continue to be a vital commodity and source of energy, espe-

BEN JOB/REUTERS

A SUNNY DELIGHT: Celebrants at the official opening of the 100-megawatt Shams 1 solar power plant in Abu Dhabi in March.

cially with global energy demand expected to double by 2050," says Bader Al Lamki, director of clean energy for Masdar, the U.A.E. company behind Shams 1 and other renewables projects. "The U.A.E.'s investment in renewable energy, although [it] will help extend the lifetime of our hydrocarbon reserves, is geared at ensuring the longevity of the overall economic, social, and environmental benefits...of our nation and the world."

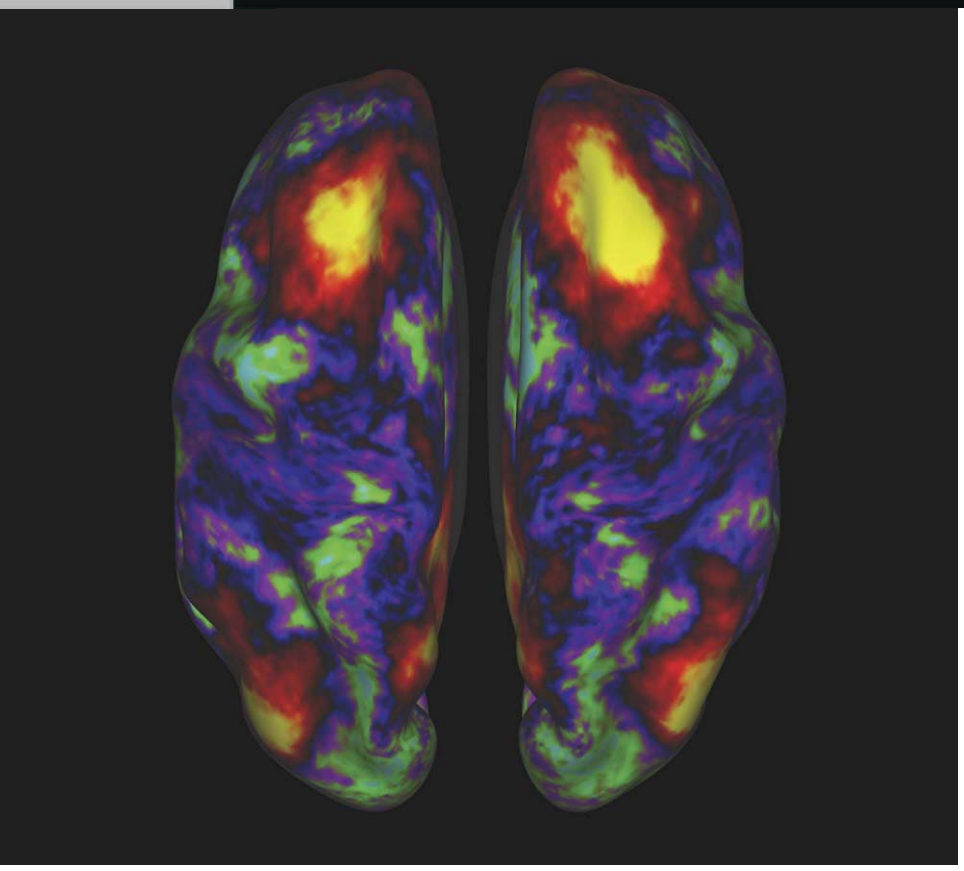
Outsized and rapidly growing domestic consumption in the U.A.E., Saudi Arabia, and other countries in the region is pushing the drive for nuclear and renewable energy, but only so that the oil-based economies can continue to thrive in the future, says Bernard Haykel, a professor of Near Eastern studies at Princeton University who leads a program on oil and energy in the Middle East.

Laura El-Katiri, a research fellow at the Oxford Institute for Energy Studies, in England, agrees, but she doesn't expect it to extend the oil years by much. "The Gulf states... are exceptionally dependent on hydrocarbons, primarily oil and natural gas, so the decision to introduce a small share of renewables will not turn around this balance fundamentally," she says. "Renewable energy technology also poses its own challenges in the region, including in the technical and regulatory arenas, which means no renewable energy revolution should be expected in the region overnight."

At present, the chances of the U.A.E. meeting its 7 percent renewables goal seem slim. Even at today's peak demand, meeting that goal would require another 15 solar plants on the scale of Shams 1, and the U.A.E.'s demand has been growing so dramatically in recent years that it has become a net importer of natural gas. What's more, there are difficulties involved in desert construction, including dust, high winds, and transmission requirements.

At root, it's what lies under the desert that will hold back a renewable revolution above it. Saudi Arabia has more than 264 billion barrels of proven crude oil reserves. The U.A.E. and Kuwait each sit on about 100 billion barrels, and Qatar has just over 25 billion of its own. A few shiny mirrors in the Abu Dhabi desert may delay the burning of some of that oil for a few years, but without major political and economic shifts, it probably won't stay buried for long.

—DAVE LEVITAN



LIGHTBULB MOMENT: This color-coded map, created by researchers at the Human Connectome Project, illustrates relative levels of functional connectivity between points in the brain's cerebral cortex.

A WIRING DIAGRAM OF THE BRAIN

Advances in medical imaging allow the Human Connectome Project to map neural connections

In early March, an unusual 2 terabytes of data hit the Web: the first batch of images from a massively ambitious brain-mapping effort called the Human Connectome Project. Thousands of images showed the brains of 68 healthy volunteers, with different regions glowing in bright jewel tones. These data, freely available for download via the project's website, give neuroscientists unprecedented insights into which parts of the brain act in concert to do something as seemingly simple as recognizing a face.

The project leaders say their work is enabled by very recent advances in both brain-scanning hardware and image-processing software. "It simply wouldn't have been feasible five or six years ago to provide this amount and quality of data, and the ability to work with the data," says David Van Essen, one of the project's principal investigators and head of the anatomy and neurobiology department at the Washington University School of Medicine, in St. Louis.

Based on a growing understanding that the mechanisms of perception and cognition involve networks of neurons that sprawl across multiple regions of the brain, researchers have begun mapping those neural circuits. While the Human Connectome Project looks at connections between brain regions, a US $100 million project, announced in April and called the BRAIN Initiative, will attempt to zoom in on the connectivity of small clusters of neurons.

> The $40 million project will scan the brains of 1200 adults using three different types of advanced MRI.

But it's the five-year Human Connectome Project that's delivering the data now. The $40 million project funds two consortia; the larger, international group led by Van Essen and Kamil Ugurbil of the University of Minnesota will eventually scan the brains of 1200 adults, a group of twins and their siblings. The goal, says Van Essen, is "not just to infer what typical brain connectivity is like but also how it varies across participants, and how that relates to their different intellectual, cognitive, and emotional capabilities and attributes."

To provide multiple perspectives on each brain, the researchers employ a number of cutting-edge imaging methods. They start with magnetic resonance imaging (MRI) scans to provide basic structural images of the brain, using both a 3-tesla machine and a next-generation 7-T scanner. Both provide extremely high-resolution images of the convoluted folds of the cerebral cortex.

Next, a series of functional MRI (fMRI) scans, which detect blood flow throughout the brain, show brain activity for subjects both at rest and engaged in seven different tasks (including language, working memory, and gambling exercises). The fMRI is souped-up as well: Ugurbil pioneered a technique called multiband imaging that takes snapshots of eight slices of the brain at a time instead of just one.

To complement the data on basic structure and blood flow within the brain, each participant is also scanned using a technique called diffusion MRI, which tracks the movement of water molecules within brain fibers. Because water diffuses more rapidly along the length of the fibers that connect neurons than »

DAVID VAN ESSEN FOR THE WU-MINN HCP CONSORTIUM

across them, this technique allows researchers to directly trace connections between sections of the brain. The Connectome team had Siemens customize its top-of-the-line MRI machine to let them alter its magnetic field strength more rapidly and dramatically, which produces clearer images.

Each imaging modality has its limitations, so combining them gives neuroscientists their best view yet of what goes on inside a human brain. First, however, all that neuroimaging data needs to be purged of noise and artifacts, and it needs to be organized into a useful database. Dan Marcus, director of the Neuroinformatics Research Group at the Washington University School of Medicine, developed the image-processing software that automatically cleans up the images and precisely aligns the scans so that a single "brainordinate" refers to the same point on a diffusion MRI and fMRI scan. That processing is computationally intensive, says Marcus: "For each subject, that code takes about 24 hours to run on our supercomputer."

Finally, the team adapted open-source image analysis tools to allow researchers to query the database in sophisticated ways. For example, a user can examine a brain simply through its diffusion images or overlay that data on a set of fMRI results.

Some neuroscientists think that all this data will be of limited use. Karl Friston, scientific director of the Wellcome Trust Centre for Neuroimaging, at University College London, applauds the project's ambition, but he criticizes it for providing a resource "without asking what questions these data and models speak to." He'd prefer to see money spent on hypothesis-directed brain scans, which can investigate "how a particular connection changes with experimental intervention or disease."

But the Connectome team thinks the open-ended nature of the data set is an asset, not a weakness. They're hoping to provoke research questions they never anticipated, and in fields that they know nothing about. "You don't have to be a neuroscientist to access the data," says Marcus. "If you're an engineer or a physicist and want to get into this, you can."

—ELIZA STRICKLAND

NEWS

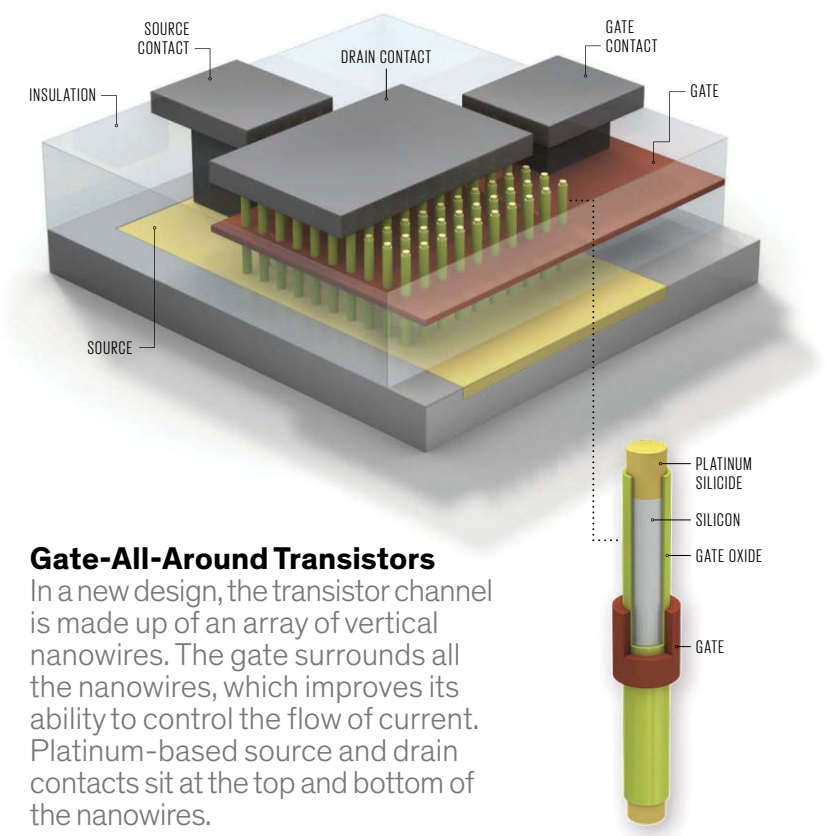
RING AROUND THE NANOWIRE

Researchers are perfecting ways to produce gate-all-around devices

THE END OF Moore's Law has been predicted again and again. And again and again, new technologies, most recently FinFETs, have dispelled these fears. Engineers may already have come up with the technology that will fend off the next set of naysayers: nanowire FETs (field-effect transistors).

In these nanodevices, current flows through the nanowire or is pinched off under the control of the voltage on the gate electrode, which surrounds the nanowire. Hence, nanowire FETs' other name: "gate-all-around" transistors. However, because of their small size, single nanowires can't carry enough current to make an efficient transistor.

The solution, recent research shows, is to make a transistor that consists of a small forest of nanowires that are under the control of the same gate and so act as a single transistor. For example, researchers at Hokkaido University and from the Japan Science and Technology Agency reported last year in *Nature* a gate-all-around nanowire transistor consisting of 10 vertical indium gallium arsenide nanowires grown on a silicon substrate. Although the device's electrical properties were good, the gate length—a critical dimension—was 200 nanometers, much too large for the tiny transistors needed to power the microprocessors of the 2020s.



Gate-All-Around Transistors
In a new design, the transistor channel is made up of an array of vertical nanowires. The gate surrounds all the nanowires, which improves its ability to control the flow of current. Platinum-based source and drain contacts sit at the top and bottom of the nanowires.

ILLUSTRATION BY Emily Cooper

BLADDER-BOT Vanderbilt University engineers have invented a 5.5-millimeter-wide robot designed to snake through the urethra to find and remove bladder tumors.

Now two researchers working in France, Guilhem Larrieu of the Laboratory for Analysis and Architecture of Systems, in Toulouse, and Xiang-Lei Han of the Institute for Electronics, Microelectronics, and Nanotechnology, in Lille, report the creation of a nanowire transistor that could be scaled down to do the job. It consists of an array of 225 doped-silicon nanowires, each 30 nm wide and 200 nm tall, vertically linking the two platinum contact planes that form the source and drain of the transistor. Besides their narrowness, what's new is the gate: A single 14-nm-thick chromium layer surrounds each nanowire midway up its length.

That thickness, the gate length, is the key. "The advantage of an all-around gate allows the creation of shorter gates, without loss of control on the current through the channel," explains Larrieu. "We demonstrated the first vertical nanowire transistor with such a short gate." An all-around gate will be a must if gate lengths are to get smaller than 10 nm, he says. In that scheme, "the size of the gate depends only on the thickness of the deposited layer; there is no complicated lithography involved," he adds.

The nanowires were of an unusual construction. Unlike with most vertical nanowire transistor prototypes, in which the nanowires are grown upward from a substrate, the French duo created their nanowires by starting out with a block of doped silicon and then etching away material to leave nanopillars. In between the pillars, they deposited an insulating layer to about half the pillars' height. Then they deposited the 14 nm of chromium and filled the remaining space with another insulating layer. "We tried to make the process completely compatible with current technology used in electronics. No new machines will have to be invented," says Larrieu. The researchers have plans to try to go below 10-nm gate length, and also to use indium gallium arsenide nanowires because of the better electron mobility.

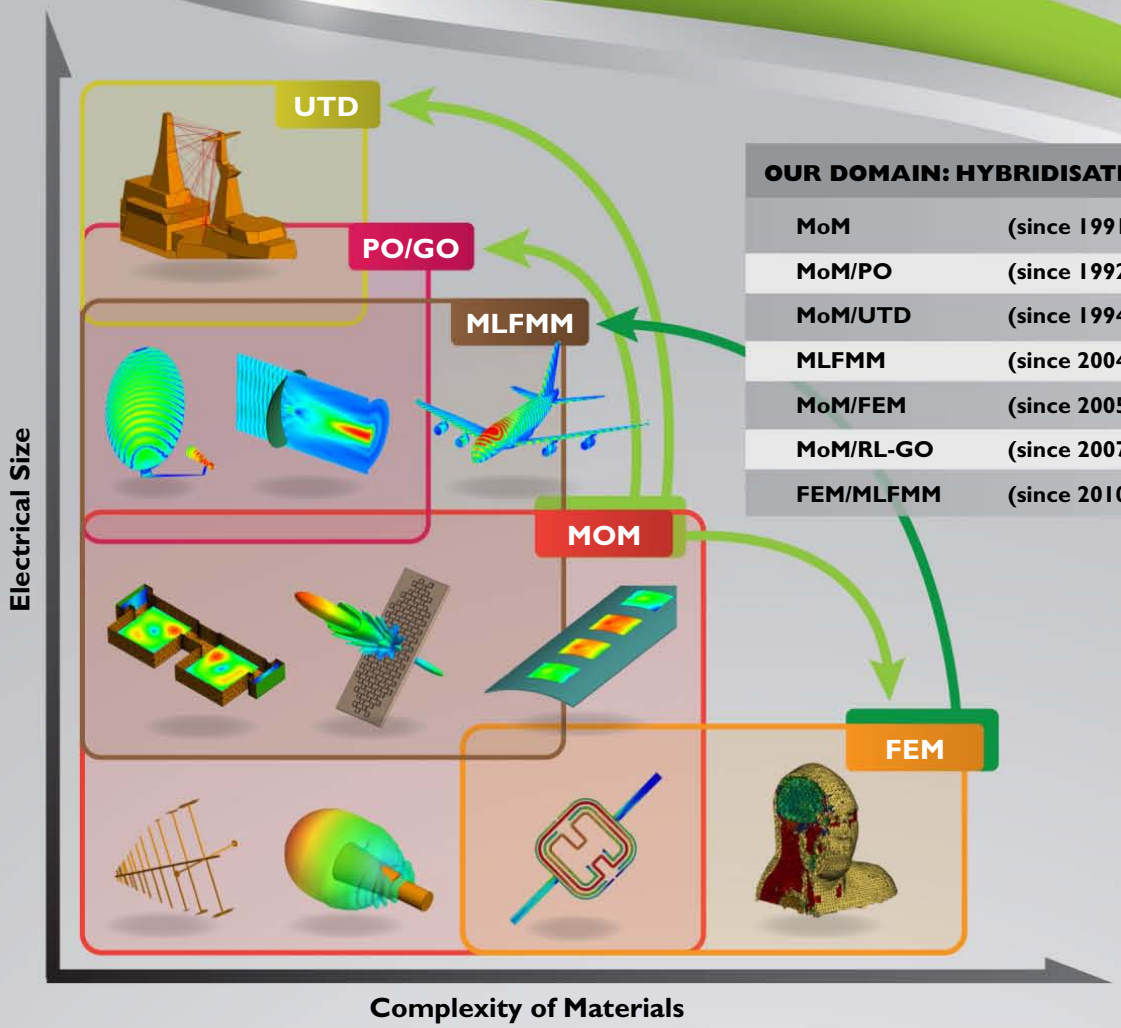
Kelin Kuhn, director of advanced device technology at Intel's Hillsboro, Ore., location, agrees that all-around gate structures have some key advantages. Of all the CMOS-style advanced devices, they're generally expected to provide the best gate control for very short channels, she says.

Davide Sacchetto, a researcher at the École Polytechnique Fédérale de Lausanne, agrees: "The fabrication of the gate is interesting, and you get a small gate length." However, the advantage is lost if the nanowires are too long–200 nm in this case–and the channel is only a small part of the total length of the nanowire, he says. "Even a difference of 5 nm would make a huge difference in the drain current."

According to Judy Hoyt, a researcher at the Microsystems Technology Laboratories at MIT, gate-all-around technology is now under study at a number of university labs worldwide. But as the nanowire transistors are more complex than the FinFETs, will this effort allow Moore's Law to live longer and fit even more transistors on a chip? "The jury is still out," says Hoyt. It depends on what the fabrication process and the structure will be, she says. "You really have to get the physics right, and that is what all these efforts are based on."

–ALEXANDER HELLEMANS

JOE HOWELL/VANDERBILT UNIVERSITY



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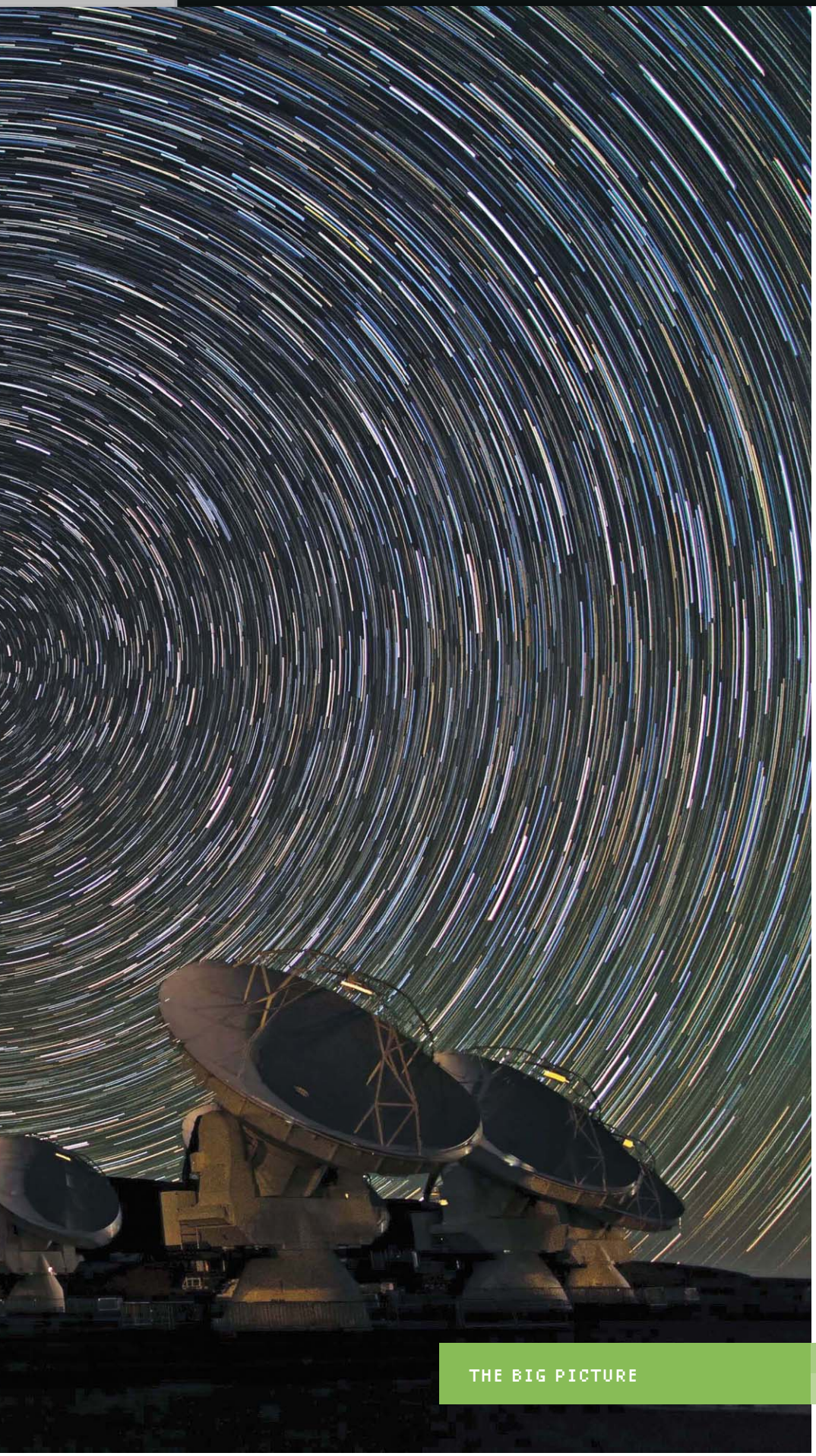


STAR SEARCH

WHEN VINCENT VAN Gogh set out in 1889 to depict his window view of Saint-Rémy-de-Provence in southern France, the result, the renowned painting *The Starry Night*, brilliantly captured a single moment in time. But with the 13 March inauguration of the Atacama Large Millimeter/Submillimeter Array, or ALMA, located on the 5000-meter-high Llano de Chajnantor plateau in Chile's Atacama Desert, scientists and engineers now have the ability to see back to the beginning of time itself. ALMA currently comprises 50 (out of an eventual 66) high-precision antennas that collectively are so powerful and sensitive that they can yield images 10 times as sharp as those resolved by the Hubble Space Telescope.

RESOURCES

BY 1982, 400 000 *PAC-MAN* MACHINES HAD BEEN SOLD. BY THE END OF 2012, *ANGRY BIRDS* AND ITS SEQUELS HAD BEEN DOWNLOADED MORE THAN 1 BILLION TIMES.

DUO GAMER

A BLUETOOTH CONTROLLER MAKES THE IPAD A BETTER PLATFORM FOR HARDCORE GAMING

DISCOVERY BAY GAMES

In 2008, casual and social games began rapidly developing into a multibillion-dollar global industry, an unexpected consequence of Apple's new App Store and Facebook's introduction of a new platform for third-party developers. Games like *Angry Birds* and *FarmVille* became cultural icons in a way not seen since the days of *Space Invaders* and *Pac-Man*. ● The games also helped send the market for video consoles into decline. Why buy a US $200 console that plugs into a TV when all the hot games your friends are playing are available on your phone or a website? Nor does it help that the current generation of consoles is based on seven-year-old technology [see "*Defiance*: The First Video-Game Television Show," *IEEE Spectrum*, February 2013] even as smartphone and tablet manufacturers narrow the graphics performance gap between that of their devices and current consoles. ● But Web browsers and mobile devices leave much to be desired when it comes to games like first-person shooters or simulations, due to the absence of the button-and-joystick festooned controllers that have been standard console peripherals since the mid-1980s. ● So it's not surprising that companies like start-up Ouya and established player Sony have made controllers key parts of their marketing strategy for a new wave of consoles [see "Profile: Ouya," *Spectrum*, November 2012]. Indeed, when Sony announced in February that it would be launching the PlayStation 4 later this year, the only element of the system it was willing to show was the controller. ● Consequently, the $40 Duo Gamer, from Discovery Bay Games, is something of a fly in the ointment for any would-be revival of the console market. Connecting to an iPad wirelessly via Bluetooth, this game pad has most of the bells and whistles found on a traditional one—dual joysticks, a directional thumb pad, four general-purpose buttons, and left and right trigger buttons.

That's not quite as many as you find on an Xbox 360 or PlayStation controller, but it's enough for most games. The game pad fits nicely in the hand and takes only a few moments to set up, and it comes with a stand to support the iPad during play.

The Duo Gamer's biggest drawback is the small number of titles it currently works with, all from the games developer Gameloft. Discovery Bay struck a similar single-developer deal a couple of years ago with its successful Atari Arcade joystick controller. The difference, however, is that Atari made available a huge back catalog of beloved games for both its coin-operated arcade machines and home console, while Gameloft has only about half a dozen titles that work with Duo Gamer.

How well does the Duo Gamer justify the $40 investment? I played a car-racing game and a first-person shooter from among Gameloft's titles, first with the iPad's touch-screen interface and then with the game pad. The game pad certainly improves the experience. Not only are the games more fun to play, but you're also not constantly covering up parts of the action with your fingers. And it's much less fatiguing to play a fast-paced game with the controller.

If the Duo Gamer—or a similar controller from another manufacturer, such as the Kickstarter-funded PhoneJoy—becomes broadly available to mobile-game developers, we could see the last good reason to own a console evaporate.

—STEPHEN CASS

A version of this article appeared online in March.

REMOTE CONTROL: With the iPad mounted on a stand rather than held in the hand, playing games is more like using a console with a TV screen.

RIDE BY WIRE

BUILD A PUSH-BUTTON-CONTROLLED ELECTRONIC BICYCLE SHIFTER ON THE CHEAP

WHEN I WAS A TEENAGER, I WENT FROM A BICYCLE WITH A 3-speed gear hub to a 10-speed with front and rear derailleurs. The wider range of gearing was empowering, but the derailleur shifting was sometimes a bit finicky, something that's still the case even as I've gotten better bikes over the years. My road bike (a 1980s-era 12-speed) always seems to need its shifter friction tweaked. And my 21-speed mountain bike—which I converted to a human-electric hybrid a few years ago [see "The Hybrid E-Bike," *IEEE Spectrum*, September 2009]—has always had trouble with the indexed shifter for its rear derailleur, perhaps a consequence of the time it spent rusting on an outdoor scrap heap before I rescued it. • One solution would be to buy better mechanical components, of course. But instead I decided to experiment with electronic shifting. Bicycle designers have been dabbling with electronic shifting for more than two decades, and in 2009 the Japanese company Shimano started selling its Ultegra Di2 electronic system. Problem is, a Di2 shifting kit costs nearly US $1900. Ouch.

LEFT: DISCOVERY BAY GAMES; RIGHT: DAVID SCHNEIDER

GEARING UP

I wanted a cheaper way to find out whether the advantages of electronic shifting would be worth the fuss of keeping a battery charged. The solution was to cobble together an electronically operated rear derailleur myself, following the example of Preston Fall, a bicycle mechanic from Oregon who has provided detailed instructions on his website, DIYshift.com. He's not the only person to design a home-brew electronic bicycle shifter, but his approach and guidance looked much better than anything else on the Web.

Fall's strategy is to modify a standard rear derailleur, removing the spring and replacing one side of the derailleur's parallelogram-like cage with a bracket that holds a radio-control servo. Rotating the servo arm changes the cage's geometry, which in turn moves the chain.

For this project, Fall recommends a metal-geared servo (a Hitec HS-225MG) and a popular derailleur, the X5 from SRAM. The first item was very easy to find ($26 from Servocity.com). Getting the second was trickier, because, as Fall warns, SRAM recently altered the design of this product in a way that could make his hack unworkable. So I acquired a new old-stock X5 derailleur from a seller on eBay (for $38).

I made some tweaks to Fall's recipe for mechanically altering the derailleur to make it a little more robust on my bike. I also didn't worry about power consumption. Fall was understandably concerned about depleting his system's modestly sized battery, so he designed the electronics to cut power to the servo after each shift. I was working on an electric bike, which has a meaty battery for its traction motor. So the added energy demands of keeping the servo continuously powered (a few hundred milliamperes during a shift and a few tens of milliamperes between shifts) were inconsequential.

Keeping the servo continuously powered made the electronics a little simpler, eliminating the need for a MOSFET to switch the power on and off. But the biggest advantage is that with the servo always powered, the derailleur won't accidentally move to a different gear. Fall's arrangement avoids accidental shifts by leaving enough friction in the system to prevent vibration from moving things, but not enough to thwart the servo when shifting. That seems a real balancing act to me. So I adjusted my derailleur to have as little friction as possible, leaving it to the servo to hold it in position. A powered servo moves only when commanded and will resist outside forces applied to it, thanks to a built-in feedback circuit.

Handlebar buttons [top] signal an Arduino microcontroller, tucked in with my electric bicycle's main batteries [middle], to shift gears via a servo. A voltage regulator mounted to a heat-sink plate provides power to the Arduino and the servo mounted in the rear derailleur's cage [bottom].

DAVID SCHNEIDER (3)

As Fall did, I used an Arduino microcontroller to control the system. But I decided it would be easier to write my own code than to figure out his, so I created two Arduino programs. The first is for setup, which moves the servo one degree at a time, reporting its position to an attached laptop running a serial monitor. I used this to measure where the servo arm should be for each gear while I was cranking the pedals with my free hand. I then hard-coded those values into the second program, which shifts one gear up or down on command.

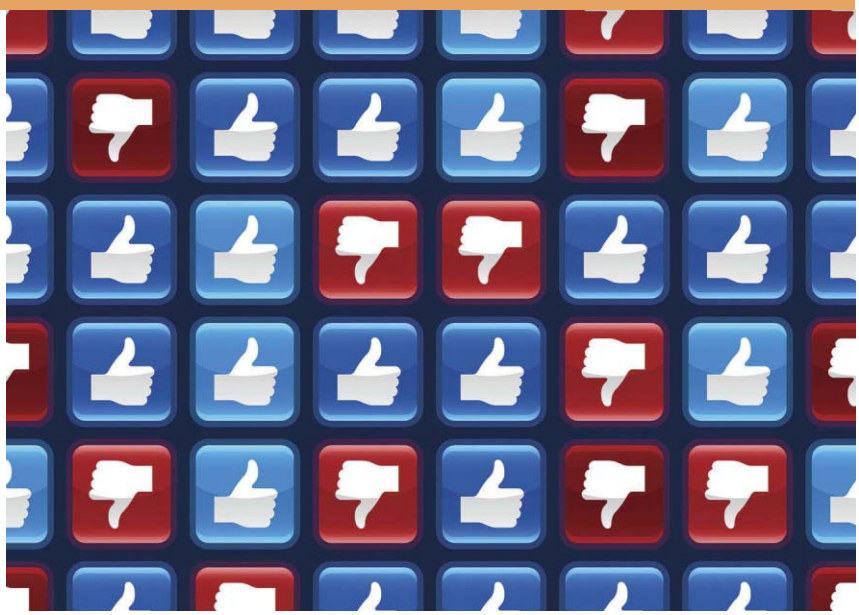
Another difference is that Fall's shifter buttons are nicely integrated into the brake levers. Mine are merely lashed to the handlebars with cable ties. Perhaps I'll attempt something more elegant later, if I decide to move to electronic shifting permanently.

So far, shifting this way seems very pleasant—tapping buttons is effortless, and the chain hits its targeted sprocket reliably. The system also offers flexibility, should I one day want to change the 7-speed cassette on the rear wheel to one with more gear choices. That would merely require updating the code, whereas with a mechanical system you'd need to install a new indexed shifter on the handlebars. I may try to electrify the bike's front derailleur next, although with bigger jumps between chain rings here, this may prove challenging to do without stripping servo gears, as Fall warns on his website. In the meantime, my hybrid electric bike remains very much a hybrid, not just for propulsion but also in the shifting department.

—DAVID SCHNEIDER

Q&A: TREVOR PINCH

ONLINE USER REVIEWS ARE DISPLACING PROFESSIONAL CRITICISM. CAN WE TRUST THEM?



REVIEWS BY THE USERS OF POPULAR e-commerce sites such as Amazon.com can often be the determining factor in whether a sale is made. A professor of science and technology studies in Cornell University's sociology department, Trevor Pinch, has been probing the reliability of these reviews. He talked with Steven Cherry about them for *IEEE Spectrum*'s podcast series, "Techwise Conversations."

STEVEN CHERRY: The theory is that there's a sort of wisdom of the crowds. Prejudices, favorable and unfavorable, tend to balance out. How are people gaming the system?
TREVOR PINCH: We did a survey of [the most frequent] reviewers, and we found that many of them are plied with free stuff. They're not genuine customers in the sense that they've purchased the item. And that's what I object to. It won't necessarily lead them to be biased in their account of the object or the book, but they're not genuine customers. That's one way it can be gamed positively. It can be gamed negatively with one-star reviews and so-called sock puppets—people who set up fake e-mails to attack a book.

SC: There was another manipulation that you described in the paper by an author who created what he called the "Amazon Hour." What was that?
TP: That's a lovely story. This person sent out e-mail messages telling everyone to buy the book at [a specific time], and it got such a big spike that he got to be the No. 1 selling book on Amazon for a very short time, like half an hour. But he could always say he had been the No. 1 seller on Amazon.

SC: You started down this road when you discovered plagiarism in the Amazon reviews of one of your own books. How big a problem is plagiarism?
TP: I discovered, quite by accident, that one of the reader reviews was copied under a false e-mail address from another book on a similar topic. My coauthor, Shay David, is an information-science Ph.D. student at Cornell. He was able to write a plagiarism algorithm to search for this more systematically. We looked through 50 000 reviews of CDs and books, and we found 1 percent copied text. There's been another study at Cornell by the college of information tech on a much bigger data set, and they've found consistently this figure of about 1 percent copied text amongst these reviews.

SC: Do you think that the problems you've found will eventually get sorted out?
TP: I think one way this will happen is to do as some of the travel sites have done, where you can only write a hotel review if you've actually stayed in the hotel and paid for the hotel room. It's rather like the Genuine Purchase badge that Amazon has introduced that shows that you've actually bought that item that you're reviewing.

These questions and answers have been edited and condensed. To read or listen to the full interview, visit http://spectrum.ieee.org/pinch0513.

TREVOR PINCH

ISTOCKPHOTO

PHOTO-ILLUSTRATION BY Gluekit

RESOURCES_PROFILE

LIMOR FRIED: CHANNEL YOUR INNER MAKER

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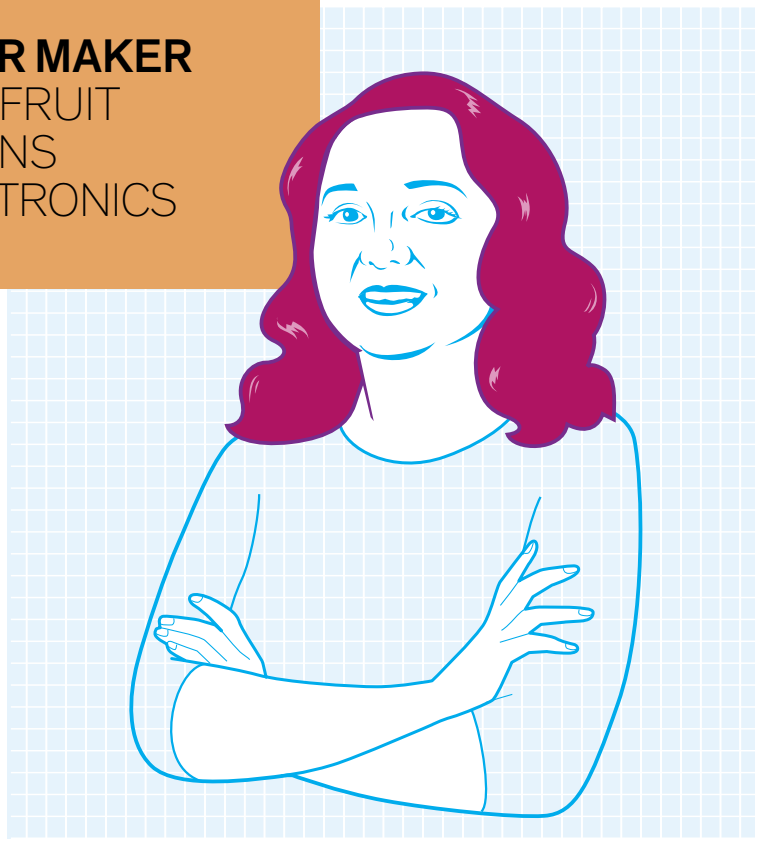

LIMOR FRIED HAS BEEN BUSY. Last year her company, Adafruit Industries, had its best year ever, selling US $10 million in DIY electronics kits and components. In October it moved into an 1100-square-meter manufacturing and warehouse space in lower Manhattan. Two months later, Fried appeared on the cover of *Entrepreneur* magazine as its Entrepreneur of the Year. And in February she grilled President Obama, via Google Hangout, on what his administration was doing to support inventors and tech entrepreneurs and to encourage girls to study science, math, and engineering.

Fried didn't set out to become a successful CEO or a de facto spokeswoman for the loose-knit maker community of technically inclined do-it-yourselfers. But now that she is, she's making the most of it. And if her shock-your-granny hair and facial piercings challenge people's image of engineers, well, so much the better.

Shortly before getting her master's in electrical engineering from MIT's Media Lab eight years ago, Fried founded Adafruit. The company was an organic outgrowth of chronicling her own DIY projects online, which, she discovered, found an eager audience. "People loved the tutorials, and there was nothing else like it at the time," says Fried, who's known to her fans as Ladyada (a nod to Ada Lovelace, who's been called the world's first computer programmer).

Since then, Fried has ridden the crest of the techno-DIY revolution, building Adafruit into a leading open-source electronics company. Even as others have jumped on the maker bandwagon, Adafruit stands out for its well-designed and well-made kits and unparalleled customer support. Need to spec a battery? Don't know how to solder? Want to sew electronics into your pants? Adafruit's got an online tutorial for that.

"It's not just 'Here's your data sheet, good luck,'" Fried says. "We always give people pointers and maybe some code to get them up and running." Engineers on staff field customer calls and e-mails; online forums nurture an active community of users. "We want to show that you don't need years of higher education in electrical engineering to build something fun and cool," she says.

Lately she and her team are out to prove that even the preschool set can appreciate the beauty of the electron. At press time, the company was getting ready to roll out a new Web TV series called "Circuit Playground." Each 10-minute episode features a Muppet-style robot called the Adabot "that's curious about itself and what's inside its body," Fried says. Other cast members include Billie the Blue LED, "who sings the blues because she needs more power to start up than a red LED," and Cappy the Capacitor, who smooths over any friction between the other characters "in the same way a capacitor smooths out ripple voltage and lets devices connect together," she explains.

There's also an upcoming Circuit Playground game for the iPhone and iPad. It's mainly color coding and pattern matching, Fried says, because designing actual electronics involves "a lot of pattern matching—remembering which parts to use when." No kids' show would be complete without a merchandizing tie-in, so there's also a line of Circuit Playground plushies. And once tykes have mastered the game, watched the show, played with the toys, and are ready to start their first hacks, they can move on to the Circuit Playground reference app.

Fried is convinced that introducing electronics early on will lead to more young people choosing science and engineering careers down the road. Because if the last eight years have taught her one thing, it's that "everyone has an engineer or a maker inside them."

—JEAN KUMAGAI

ILLUSTRATION BY Jason Lee

SENSUOUS ELECTRONICS

THE ENTREPRENEUR HAD FINISHED talking about the software and processing algorithms for a new camera he was marketing, and as he came down from the stage he left the camera on the podium—perhaps forgotten, but perhaps suggesting that it wasn't expensive enough to worry about. • I was contemplating those processing algorithms when a woman who had been sitting behind me pushed by, heading up the aisle. As she passed by, I heard her urgently muttering to herself, "I have to touch it." • It seemed a curious urge. All the magic was in the software and algorithms; the hardware was simply a lens, a sensor, and a few chips. Yet I understood exactly what she was saying. I felt the same way myself. • Why, I asked myself, did I have this need to touch? I started to think about the look and feel of electronic gadgets instead of their functionality. Meanwhile, another speaker was showing a small intelligent thermostat that promised to learn your heating habits and usage. She said it had been designed to be "pretty and fun." Indeed, it had a certain unadorned beauty, simply a circular face with a small touch screen. It seemed the hardware equivalent of the Google home page—minimal and clean. When I remarked on this, someone told me that the insides of the thermostat were equally beautiful. Looking again up at the stage, I was surprised to recognize the truth of this observation. The uncovered circuit board inside resembled a work of art, having the clean geometric lines of a Mondrian painting, compressed to a minimal size and with no appearance of clutter. It exuded a powerful latent functionality.

This artistic design contrasted with what I have seen of disassembled laptops, smartphones, and other electronic gadgets, all of which look as though a bunch of random electronics had been thrown into a compactor. When I take one of these gadgets apart, my overwhelming feeling is that I will never be able to put it together again—all the parts are going to spring out into the room and will never be found again. No sense in designing for inner beauty when all the labels warn of the dire consequences of opening the product.

I remembered disassembling old radios back when I was a child. Most of the space was taken by the vacuum tubes on top of the chassis. Underneath was a rats' nest of wiring, full of dust, careless solder, lumpy capacitors dripping wax, and blackened resistors. I recall also the distinctive smell of overheated components. Nothing there resembled beauty, but there is nevertheless a nostalgia in the remembrance. Integrated circuits and printed circuit boards have done away with all that mess, and now I find a kind of beauty in motherboards. But by the time they are stuffed almost carelessly into a box with cables, power supply, drives, and I/O, it all looks like a kludge ready for the junk pile.

Electrical engineering today is mostly a lot of math and physics, and sometimes we forget about the physicality and appearance of electronic design, the urge to see, touch, feel, and smell. The importance of this aesthetic dimension is evident in Apple stores. They are always very crowded, but it is a different kind of crowd, where the hubbub is muted and the focus is intently on the gadgets themselves. I study the concentration of the shoppers, but perhaps they study me, because I also am affected by the magnetism of those gadgets. Somehow they have become jewelry, while their poor cousins across the street in another store have become orphans, in spite of what may be equal functionality.

But excuse me now, because I must go and touch them. ■

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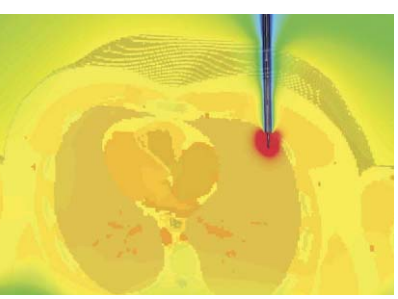

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WHEN SPECTRUM AUCTIONS FAIL

For some microwave links, cooperation beats competition as a way to share the air

By **Mitchell Lazarus** / Illustration by **Dan Page**

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MOST PEOPLE THINK

that the atomic bombings of Hiroshima and Nagasaki in 1945 ended U.S. involvement in the Pacific theater of World War II. In fact, the state of war with Japan persisted, in a technical sense, until September 1951, when the formal peace treaty was signed. "Making peace is like repairing the many strands of an intercontinental cable," President Truman said at the time. "Each strand must be spliced separately and patiently, until the full flow of communication has been restored."

Thanks to some then-new technology, more than 30 million U.S. viewers witnessed Truman compare peacemaking with cable mending during the very first TV broadcast aired from coast to coast. Electrical engineers watching the event might have appreciated the irony: You see, the new technique for linking far-flung TV stations had just made lengthy cables obsolete. Engineers at AT&T instead used a network of microwave transmitters to beam TV signals from point to point across the country.

This system let TV viewers all over the United States watch presidential speeches, documentaries, sporting events, and, of course, a lot of silly sitcoms; "I Love Lucy," for example, was broadcast nationally just a month later. "Lucy" swiftly became entrenched, as did the microwave systems. Now you see the antennas everywhere: sideways-facing dishes and flat disks hanging on the sides of radio masts, water towers, and tall buildings.

These antennas don't carry as much television programming nowadays. But they do carry phone calls and Internet data packets, handle cellphone traffic to and from local cell towers, transmit calls for assistance to firefighters and police, help balance the electric grid, coordinate railroad trains, regulate pressure and flow in oil and natural-gas pipelines, and convey vast amounts of ordinary business data.

The industry refers to these communications channels as fixed microwave, to distinguish them from the many other wireless applications that also use frequencies in the microwave bands, including everyday cellphones and Wi-Fi networking gear. Fixed-microwave links have multiplied over the years, with engineers continually devising ways to meet increasing demands. Now, however, the tradition of letting those engineers work together to squeeze in links is under assault. More and more, government regulators in the United States and the United Kingdom have been awarding licenses for fixed-microwave communications to the highest bidder, auctioning off the spectrum as they have done for many other wireless services.

Basic physics, economics, and real-world experience all suggest this is a bad idea. Left unchallenged, it could needlessly impede a vital and successful mode of radio communications.

To understand the problem, first consider how this form of radio works. Today's microwave links are a by-product of radar, first invented in the 1930s and vastly improved under the pressures of World War II. Radio transmitters before that time—mainly AM broadcast, maritime, and early attempts at mobile communications—sent out signals more or less equally in all directions. The most urgent task of wartime radar, finding the distance and direction of incoming aircraft, called for

something different: a narrow beam. So the development of radar yielded, among other things, antennas capable of concentrating radio-frequency energy in one direction.

Engineers soon realized that radar-style antennas would allow for a new kind of radio communication, one that was ideal for exchanging signals between fixed locations, not over a wide area. Telephone companies, to take an early example, had to move large numbers of calls from one switching office to another. For that, point-to-point transmission using a focused beam offered important advantages.

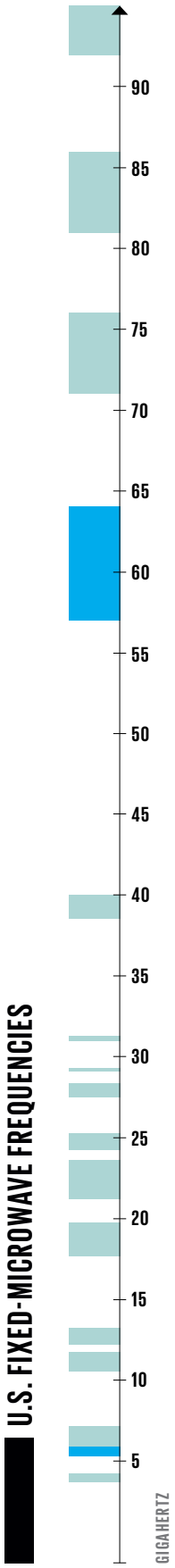
With a larger fraction of the transmitter power aimed at the intended receiver, fewer watts cover more kilometers. A similarly directional antenna on the receiving end, pointed back at the transmitter, further magnifies the incoming signal and makes the receiver relatively insensitive to interference coming from other directions. Also, covert eavesdropping becomes difficult because it requires positioning a receiver within the relatively narrow transmitted beam.

Less significant in those early days, but of great importance as the radio spectrum became more crowded, was the ability of several point-to-point links in the same area to share the same frequency. They can easily do that, so long as different transmissions do not impinge on the same receiving antenna from the same direction.

The early adopters of this technology were Bell Canada and AT&T, which in the 1950s built continent-spanning microwave systems to carry telephone calls and Teletype messages in addition to television programming. Frequency-division multiplexing allowed for up to 5400 telephone channels on each microwave radio channel, with as many as 10 radio channels combined on one antenna. Towers could be up to 70 kilometers apart. Those early systems used analog modulation. Now, of course, all new systems are digital, which makes them much more efficient and reliable.

What hasn't changed much is the shape of the antennas: Typically, they're still parabolic dish antennas, similar to those found in World War II radar installations. Radio waves diffract to a small extent around the edges of these antennas, so some energy unavoidably radiates off the desired axis. Increasing the size of the antenna diminishes the stray radiation and improves focusing power. In this context, the relevant measure of size is not the centimeter but rather the wavelength of the radio signal involved. Good performance requires an antenna roughly 20 to 40 wavelengths in diameter. So higher frequencies (shorter wavelengths) allow an antenna of the same physical size to produce a tighter beam.

Wartime radar used frequencies in the tens or hundreds of megahertz, very low by modern standards. That upper limit on frequency was set by the performance of 1940s-era vacuum tubes. As a result, some of the early antennas were tens of meters across, and even then they weren't all that effective in forming beams. But improvements in vacuum tubes came quickly, followed by bigger improvements in transistors, permitting point-to-point microwave to move to ever-higher operating frequencies.



Today, commercial use extends up to 95 gigahertz, where the corresponding wavelength is only 3 millimeters. And as frequencies have increased, antennas have shrunk. Whereas a typical microwave antenna in the 1950s was the size of a one-car garage, some antennas today are no bigger than a dinner plate.

Besides tight beams and small antennas, higher frequencies also allow for wider radio bandwidths, giving greater carrying capacity, typically measured in bits per second. The older microwave bands, around 2 GHz and below, had radio bandwidths of only a few hundred kilohertz. Typical modulation schemes can convey about 5 bits of information per second per hertz of bandwidth, so the maximum data payload at those frequencies was just a few megabits per second. At the other extreme, in the 92- to 95-GHz region, links can handle tens of gigabits per second. That's enough to supply broadband Internet service to thousands of customers.

Higher frequencies provide narrower beams, which, all else being equal, need less clearance over obstructions, so you can get by with shorter supporting structures. The narrower beams are also less susceptible to multipath interference, which arises when the same transmitted signal reaches the receiver both directly and also by reflection, say, from the surface of a body of water, or by refraction, as it passes through atmospheric layers with different densities. The reflected or refracted copy, arriving a little later, can partially or even completely cancel out the direct signal.

But higher frequencies are suitable only for shorter distances. Whereas a 2-GHz link might extend over 100 km, links above 70 GHz are usually limited to less than 1 km. One reason is that at a given distance from the transmitting antenna, the loss in signal strength goes up with the square of the frequency, because of what's called free-space attenuation. This isn't actually a frequency-dependent attenuation: The loss comes about because each element of the receiving antenna is less effective at higher frequencies. Typically, this effect largely cancels out the greater signal strength gained from a more tightly focused beam.

Another impediment to propagation is something known as rain fade, the weakening of a signal due to dispersal by raindrops or ice | CONTINUED ON PAGE 52

FIXED-MICROWAVE frequencies below 3.7 gigahertz have largely been reassigned to other services and are not shown here. The frequencies available for fixed microwave above 3.7 GHz include two unlicensed bands [blue] and many more licensed bands [blue-green].

PHOTOGRAPH BY Stephen Studd/Getty Images

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Europe's Future Grid

Germany Jump-starts the Supergrid

New developments in high-voltage DC electronics could herald an epic shift in energy delivery

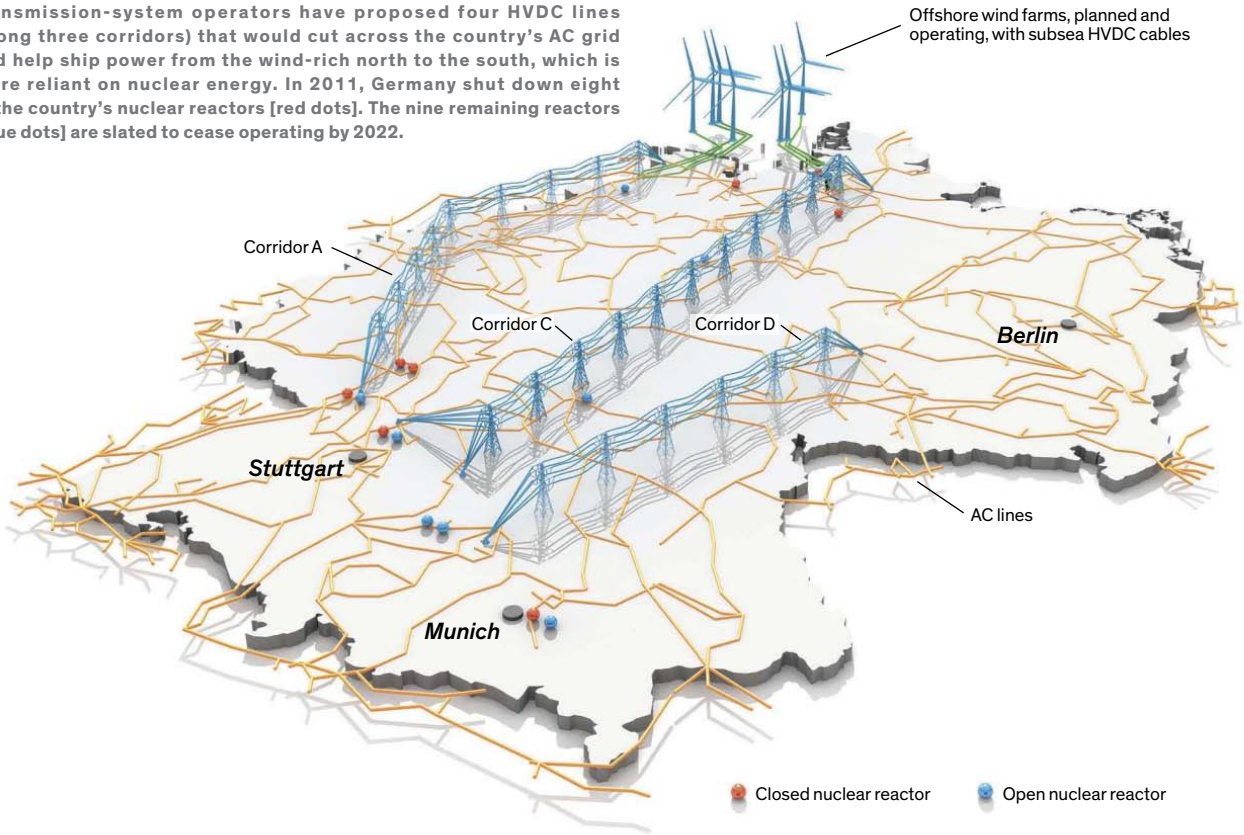
By Peter Fairley

STUTTGART IS ONE OF THE LAST PLACES you'd expect to find in a power pinch. This south German city's massive automotive plants run 24-7 without a hiccup, efficiency measures have held industrial power consumption flat, and solar panels flash from atop its major buildings. But now all that is at risk. The country's accelerated shift from nuclear power and fossil fuels to renewable resources, such as wind and solar, has exposed a huge gap in its transmission capacity. If they are to survive, Stuttgart's factories—and power consumers across southern Germany—will need to import a lot more power from the north, and Germany's grid is already at capacity.

To fill the gap, Germany is considering an aggressive plan that would push high-voltage direct current, or HVDC, from its conventional position on the periphery of AC grids to a central role. The primary reason is simple: For the first time, HVDC seems cheaper than patching up the AC grid. But Germany's transmission planners also have another motivation: They want to provide as much performance and reliability as they can to an AC grid that's already strained by excess wind power. For that, they're considering implementing power electronics that are capable of doing something that's never before been done on a commercial line: stop DC current in milliseconds flat.

As *IEEE Spectrum* went to press in early April, the €10 billion project was still being debated by the German parliament, but planning for the first HVDC line was already well under way. The project would start with the southern half of a 1000-megawatt, 660-kilometer line called Corridor A, to be strung from the North Sea port of Emden—a connection point for offshore wind farms under construction around Germany's Borkum Island. It would end at an AC grid hub near the nuclear power station at Philippsburg, which lies 70 km northwest of Stuttgart.

CUTTING ACROSS THE GRID: Germany's transmission-system operators have proposed four HVDC lines (along three corridors) that would cut across the country's AC grid and help ship power from the wind-rich north to the south, which is more reliant on nuclear energy. In 2011, Germany shut down eight of the country's nuclear reactors [red dots]. The nine remaining reactors [blue dots] are slated to cease operating by 2022.



If Germany moves forward with such HVDC lines, it could help pave the way for something much bigger, a "supergrid" of interconnected DC lines capable of transporting electricity on a continental scale, ferrying energy from North Sea turbines, dams in Scandinavia, or Mediterranean solar farms to wherever demand is greatest at that moment. The European Commission is counting on this sort of flexibility to meet its goal of an 80 percent renewable power supply by 2050. Corridor A could be the first step.

THE IDEA FOR HVDC LINES started to gain traction two years ago, when the Fukushima nuclear accident in Japan led German chancellor Angela Merkel to shut down 8 of her country's 17 nuclear reactors and revive plans to phase out the rest of them by 2022. Although this will eliminate just 16 percent of the country's annual electricity generation, the share comes to nearly half in the southern states of Bavaria and Baden-Württemberg, of which Stuttgart is the capital. Stuttgart will have to make up part of the loss by drawing on distant sources of wind power and fossil-fueled power plants. All told, some 10 gigawatts of power will need to be moved from northern to southern Germany once the last nuclear plant is closed. And the grid simply isn't up to the challenge.

Renewable energy is already getting dumped because of it. In 2010, for example, German wind farms let some 127 gigawatt-hours of energy, enough to supply more than 30 000 German households for a year, fly on by. There was no grid capacity to deliver that power. The grid is so stressed that Bundesnetzagentur (BNetzA), Germany's federal networks regulator, recently departed from typically dry language in its annual report to warn that the accelerated shift from nuclear to renewables has "brought the transmission systems to the brink."

Like many German cities, Stuttgart has a complex energy portfolio. The city generates one-eighth of its own electricity and gets most of the rest from elsewhere in Baden-Württemberg. Solar panels are the fastest-growing supplier in both the city and the state, thanks to premium prices set by the federal government. PV alone could account for as much as 18 percent of the energy produced in Baden-Württemberg by 2020.

Little of that power will arrive in the winter, however, and none overnight. At the same time, solar generation is flattening peak power prices, undermining the profitability of natural gas and coal power plants. The Düsseldorf-based power company E.ON blamed the weakened market last November when it mothballed two natural-gas plants and shelved plans for a state-of-the-art coal plant; all happen to be in the south.

Using less coal and natural gas is a key plank in Germany's response to climate change. But the pace of change is unsettling for BNetzA, which oversees the power grid and counts on fossil-fuel plants that deliver power on demand to maintain its stability. BNetzA is so concerned that for the past two winters it has paid owners of several older gas-fired power plants in southern Germany and Austria to keep their plants on standby.

In principle, wind power in the south could take up some of the slack—but not much. Winds are generally slower in the south. Turbine construction to exploit what wind is available requires clearings and roads, and

SOURCE: WWW.ENTSOE.EU

MAP BY Bryan Christie Design

Germany's celebrated Black Forest is defended tooth and nail by local communities. Expanding the south's power storage capabilities with extra pumped storage has also met with resistance from environmental groups, which argue that building new hydropower reservoirs would destroy habitats.

Add it all up and there appears to be no ready means of meeting the south's needs other than bringing more power from the north. That would include a sizable amount of wind power, which already accounts for 8 percent of the country's electricity consumption and is expected to nearly double by 2022.

Germany's transmission system operators (TSOs), which operate the regional grids, have been eyeing major upgrades in the AC grid since 2005. That's when the German Energy Agency published an analysis showing that variable renewable energy flows were already at risk of overloading the country's grid. Whereas conventional power plants generated power close to where it was needed, the grid was increasingly moving renewable energy from wherever it was in surplus to whatever regions could use it. To add capacity, the agency called for a modest 5 percent expansion: 850 km of new ultrahigh-voltage AC lines, to be completed by 2015.

The plans didn't stay modest. In 2010, the agency found that the country would need an additional 3600 km of new AC lines by 2020 to handle the growth in wind and solar power. That's a daunting number given that stiff local opposition has stymied construction of all but 214 of the 850 km called for in 2005. The ballooning estimates are only partly due to the accelerating shift to renewable power. They are also exacerbated by the physics of AC grids. Germany's grids, like most worldwide, are essentially single circuits, formed by a mesh of interconnected high-voltage lines. Electricity flows freely across the grid following a path of least resistance, one that shifts from moment to moment as power plants across the country (and Europe) ramp up and down and as millions of homes, businesses, and factories use appliances and machines.

Getting more power from point A to point B in an AC grid often requires building more than just one line to ensure that wandering power flows do not overload the grid's weakest paths. Although some newer technologies can help nudge AC electricity down particular lines [see "Flexible AC Transmission: The FACTS Machine," *Spectrum*, January 2011], they're expensive to implement on large scales.

HVDC offers a comparatively elegant solution. Thanks to power electronics placed at either end, a single HVDC line can act as a high-capacity electrical wormhole, pulling electricity from close to its point of generation and reinjecting it into the AC grid hundreds or thousands of kilometers away. The direction and magnitude of the power transmitted on a line can be precisely controlled, something that's impossible to do for an AC line within the grid's wide-open circuit. The power electronics needed to make this happen can push the cost of a single HVDC line well above that of an AC line. But when Germany's TSOs totaled up all the costs, they found that a DC system would be a less expensive way to enable the country's shift toward renewables, primarily because fewer lines have to be built or upgraded.

NORTH WIND: Turbine construction is on the rise off Germany's North Sea coast. The Bard Offshore 1 wind farm will boast 80 turbines, one of which [top] is located alongside an HVDC converter platform. Foundations [bottom] have been laid for 30 turbines for the Riffgat farm. Much of the electricity generated by these farms will eventually be carried by Corridor A.

TOP: BARD ENGINEERING; BOTTOM: EWE

ONE FACTOR that has made HVDC particularly attractive is improvements to electronic converters—the units at either end of the line that transform AC current into DC current, and vice versa. Classic HVDC lines use converters built from thyristors, which are efficient but limited in their capabilities. Those converters rely on the AC system to support their operation. As a result, classic HVDC is typically chosen nowadays for long-haul lines moving loads of stable power, such as hydropower, that is relatively easy for the AC network to absorb.

In the late 1990s, Swiss-Swedish engineering giant ABB commercialized more sophisticated and compact converters, built from high-frequency silicon insulated-gate bipolar transistors (IGBTs). These "voltage source converters" (VSCs) control their own voltage and can thus help stabilize the AC grid around them. In an HVDC line using these advanced converters, hundreds of IGBTs connected in series fire synchronously to channel power from the AC line and rectify it into steady current for the DC line. The converter at the downstream end of the line performs a similar process to convert the current back into AC. At the same time these IGBT-based converters can watch for and correct voltage dips or surges on the AC lines. That has made them popular in applications such as linking offshore wind farms where shifting power levels require dynamic regulation of voltage at the AC connection point.

These capabilities ignited hope that HVDC could escape its niche status and challenge AC transmission for jobs at the heart of power grids. But the IGBT-based converters still had three hurdles to overcome before they could challenge AC technology. One was a

capacity ceiling of a few hundred megawatts. Another was switching losses of about 1.5 to 2 percent of transmitted power per converter, which made them costly to use. For a line carrying power from a thousand offshore wind turbines, such converters would throw away the output of 15 to 20 of those multimillion-dollar machines.

In 2010, Siemens commercialized a novel IGBT converter that cleared those two hurdles. These so-called modular multilevel converters gang together several hundred miniconverters, or "submodules," to push the overall converter capacity from a few hundred megawatts to 1000 megawatts or more—the scale that Germany's TSOs are looking for. Each submodule fires only when it's needed to contribute to the conversion to or from a variable AC wave, cutting switching losses to just 1 percent per converter.

Rising power and efficiency have made the technology particularly attractive to Germany's TSOs, which have pushed modular multilevel converters to the top of their list. But to get the performance and stability they want for Corridor A, they say they'll need to overcome VSC technology's ultimate Achilles' heel: its inability to break DC current.

To avoid complex route planning and minimize opposition, the TSOs have sketched a route that would build the HVDC line down existing AC corridors, using the very same towers—a first for VSC-based lines. A long, exposed DC line is a large target for lightning, tree strikes, and other disruptions. Given the central role that Corridor A and three other planned DC lines will play in an already strained grid, the TSOs are hunting for an advanced HVDC converter that can tolerate or quickly recover from faults.

What's needed is advanced HVDC equipment that's capable of stopping the flow of high-voltage DC current so that a line can be quickly reset and rebooted. This isn't a problem with AC lines—even ultrahigh-voltage ones—because the voltage zeroes out every time the current reverses direction: 100 times per second on Europe's 50-hertz grids. Any one of those zero points is a natural spot to interrupt the circuit without creating a damaging arc. Direct current, however, just keeps pumping. Stopping it quickly and at high voltage is like slamming a gate in front of a speeding truck. "In DC, you always have full energy. If you tried to break a DC line with a mechanical breaker... it would just burn up the switchgear," says Claes Rytoft, chief technical officer for ABB's power systems division.

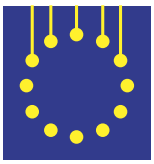
Today's modular multilevel HVDC converters can't help, because of a design quirk that actually feeds DC faults. Those converters are assembled from submodules that contain a pair of IGBTs, a pair of diodes, and a DC capacitor. The diodes are the problem component during DC faults. In normal operation, they dynamically reconfigure the submodule circuitry to handle the alternating positive and negative voltage coming from the AC grid. During a DC fault, however, current arcs over the diodes and connects the submodules' positive and negative terminals, creating internal short-circuits.

Existing HVDC lines with IGBT-based converters get around their breaking problem by relying on the AC grid to shut the converters down. To clear a fault on a DC line, a speedy AC breaker upstream can cut off the current in less than 100 milliseconds. This sounds fast, but it's only a small step toward restarting the line. The system must wait half a second to close the AC breaker after the fault is cleared, says ABB's Rytoft, in order to reset the converters. And it can take up to 2 seconds for the converters to return to full power, he adds. While this works fine when HVDC lines are handling a few hundred megawatts, a line like Corridor A would shunt a tsunami of excess energy into the AC grid. And with the HVDC converter shut off, it could offer the AC grid no help in handling the disturbance.

IGBT POWER: Existing IGBT-based HVDC units, like ABB's HVDC Light system [left] and Siemens's modular multilevel converters [right] cannot break DC current on their own.

THE MOST STRAIGHTFORWARD solution is to redesign the AC-DC converter submodules to function as breakers. One design fix that would work is already applied in some lower-power DC units: doubling the number of IGBTs to create a "full-bridge submodule." The full-bridge's two extra IGBTs give the circuit more flexibility, enabling it to repurpose its capacitor to fight a fault. In normal operation the capacitor acts primarily as a short-term energy buffer. But during faults on the DC line, the full-bridge's extra switches can reconfigure the circuits

LEFT: HALVOR MOLLAND/ABB; RIGHT: SIEMENS



so that the voltage across the capacitor, and thus the submodule, opposes the voltage on the DC line, resulting in zero current flow. In February, the French power equipment supplier Alstom demonstrated a converter incorporating full-bridge submodules that extinguished DC currents exceeding 3000 amperes in less than 2.5 milliseconds—up to 40 times as fast as an AC breaker. And the converter never turns off, so it can stabilize the AC grid and is ready to pump DC at full power once a fault is cleared.

But the penalty that comes with this speed boost may be substantial. Because full-bridge submodules use twice as many IGBTs as those in existing modular converters, they are less efficient, returning losses from each converter of as much as 1.7 percent. "It is a trade-off between losses and security of supply," acknowledges Thomas Ahndorf, senior manager for system analysis at Stuttgart-based TransnetBW, the TSO for Germany's southern grid.

Ahndorf says he will pay the full-bridge's efficiency penalty if he must, but he may not have to. HVDC innovators are racing to demonstrate smarter options. Alstom's approach is to limit losses by substituting only some of the multilevel converter's 2-IGBT submodules with full-bridge submodules. And in November, ABB demonstrated an entirely novel solution to efficient HVDC breaking: a stand-alone breaker that would sit on the HVDC line and be used along with the standard, two-IGBT converter. It couples a mechanical switch with two electronic breakers. In normal operation, electricity passes through the mechanical switch and the smaller of the two breakers. When the system detects a fault, the smaller breaker has just enough heft to start the breaking sequence, applying voltage to its IGBT gates to raise its resistance. That briefly shunts DC power through the larger breaker, which contains enough IGBTs to break the current. When the current switches over, the mechanical breaker is triggered, physically disconnecting the default path. Then the larger breaker cuts off the alternate path, squelching the DC current. According to ABB's Rytoft, it's all over in less than 5 milliseconds—much faster than the blink of an eye. And, says Rytoft, operating the larger current-stopping circuit solely during faults all but eliminates the efficiency penalty.

Power engineering heavyweight Siemens, meanwhile, is collaborating on a third option with Rainer Marquardt, chair for power electronics and controls at the University of Federal Defense, in Munich, and inventor of the modular multilevel converter. Marquardt's scheme is to connect two of the submodules that he invented for Siemens's VSC converters with a fifth IGBT. This "double submodule" can reorient capacitors to stop DC current, just as a full-bridge module does. But because only three of the five IGBTs are conducting current at any given moment, it loses one-third less power than a full-bridge converter. This solution might be considerably cheaper than ABB's stand-alone breaker, as it can function as both a converter and a breaker. Marquardt estimates that installing a separate breaker such as ABB's next to each converter on an HVDC line could increase its component costs by up to 50 percent, while his design could be comparable in cost and footprint to today's VSC converters.

ALL OF THE HVDC INNOVATORS are poised to move fast. Alstom plans to test its design at higher current within months. Siemens has not revealed its plans for Marquardt's design, but Marquardt says it won't be hard to implement, because his new submodules are essentially a drop-in replacement for those Siemens already sells. And ABB is seeking a utility partner to test its system, which it plans to have ready for a first commercial application for 2017.

That might be just in time for Corridor A, which is already in the public consultation phase and is set to begin carrying power in 2017. TransnetBW's Ahndorf says the corridor is on a "very tough schedule," but keeping it is critical if all the grid extensions are to be constructed by 2022. "We have to learn. We have no time to lose," he says.

HVDC innovators are already looking ahead to what they see as the technology's natural conclusion: HVDC grids that can optimize the flow of power between countries and across continents. "Most experts in this field have long said that it is very doubtful that this would be realistic," Marquardt says. They have more confidence now, he says, since such supergrids are likely to need both advanced converters and stand-alone breakers, units that the German TSOs are helping to drive forward.

Supergrid backers say the need for HVDC grids, meanwhile, is already evident in the increasingly unmanageable cross-border flows on AC grids. The Czech Republic is installing phase-shifting transformers at its border with Germany, for example, to keep its neighbor's renewable energy from looping through the Czech grid, which is at its carrying limit. Such rogue flows are a growing phenomenon across continental Europe, says Sébastien Lepy, head of grid development studies for RTE, France's TSO, which is also eyeing more central HVDC lines.

In principle, a European supergrid would make it easy to coordinate a range of far-flung sources of renewable energy, and it could be cheaper than revamping each country's grid one by one. Large-scale grid schemes are already being seriously studied. A three-year project called E-Highway 2050, for example, is creating a modular scheme for linking up HVDC lines such as Corridor A to form a European supergrid. And the German Commission for Electrical, Electronic & Information Technologies is drafting technical standards for HVDC grids.

But some TSOs are skeptical that supergrids are urgently needed. "Point-to-point is a very good result. You don't need a DC grid yet," says Ahndorf, who is a member of the German electrotechnical commission's HVDC grids working group. The benefits, he says, are still unclear. For now, German transmission planners like Ahndorf are just trying to get the first HVDC lines built. They're keenly aware that the clock is ticking. The plan will need to be approved, financed, and then built, one line at a time. Years could slip away in negotiations with opponents of each line.

And the stakes are high. Projections by the Berlin-based energy think tank Agora Energiewende suggest developers can bump up the generating capacity of renewable installations to 130 GW by 2022 from the roughly 75 GW in place at the close of last year. Without the ability to carry that power where it's needed, that would be a hollow victory for the green energy movement. ■

POST YOUR COMMENTS online at http://spectrum.ieee.org/germangrid0513

PHOTOGRAPHY BY Nicky Bonne

Europe's Future Grid

The Smartest, Greenest Grid

What a little Danish island is showing the world about the future of energy

By Jean Kumagai

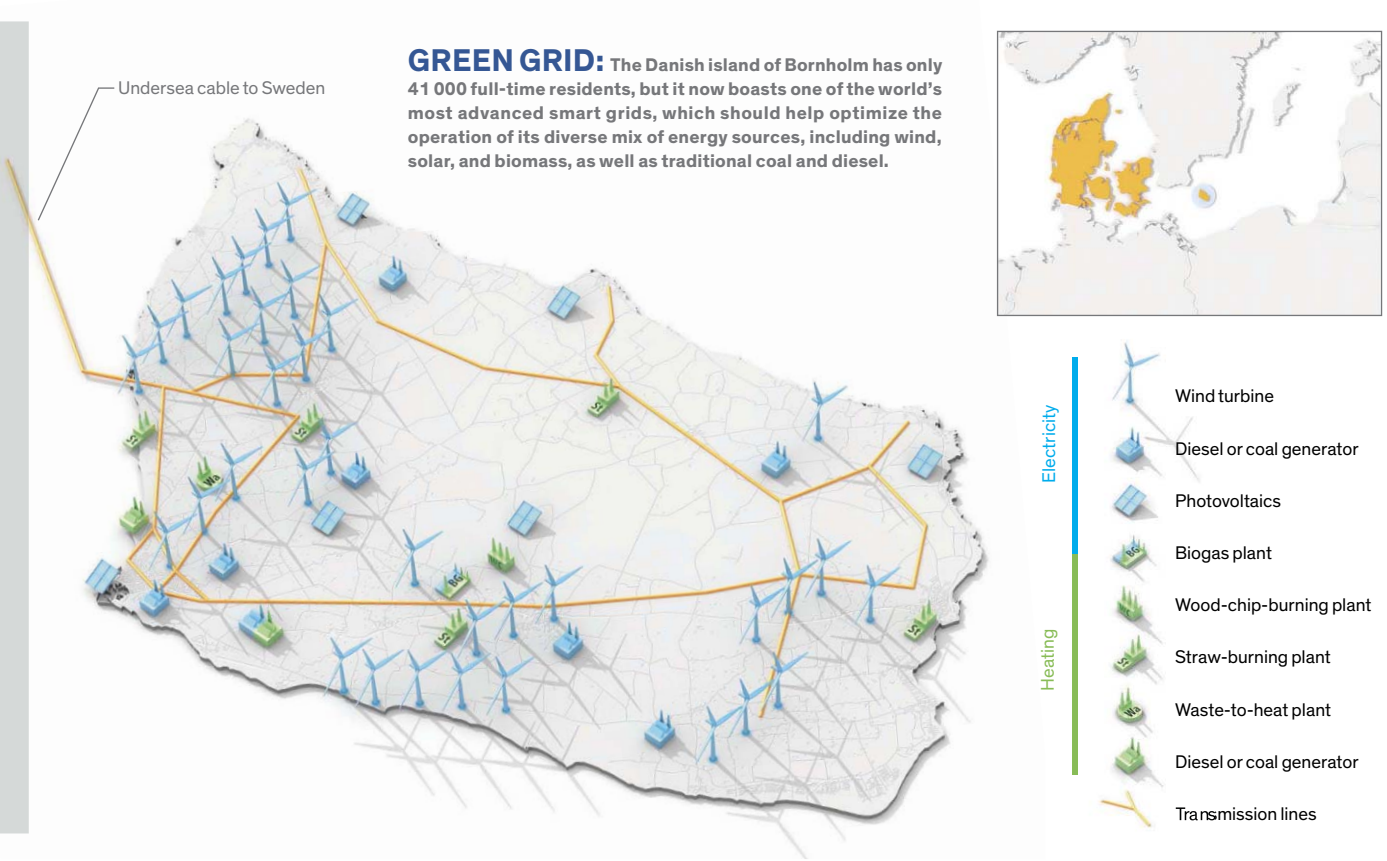
ON CHRISTMAS NIGHT, Maja Bendtsen and her husband were curled up on the couch watching TV in their cozy house on the Danish island of Bornholm. Suddenly the house lost power. "The lights flickered briefly and then everything went black," Bendtsen recalls.

Peeking out the window, they saw that the whole neighborhood was dark. A few quick phone calls confirmed that all of Bornholm was without power. Bendtsen, an engineer with the island's utility, Østkraft Net, mentally ruled out the obvious culprits: It wasn't a particularly busy night, as Christmas festivities had wrapped up with the midday meal, nor was the weather particularly cold or stormy.

She thought of one thing, though, and it made her heart sink. She phoned the Østkraft control room, where the chief engineer confirmed her suspicion: A ship dragging its anchor in the narrow Baltic Sea channel between Bornholm and Sweden had severed the 60-kilovolt, 70-megawatt undersea power cable that is the island's only external source of electricity. It would take a repair crew more than six weeks to pinpoint the damage, haul the cable to the water's surface, and fix it.

Incredibly, this was the fourth such mishap in 10 years. "We're getting accustomed to it, almost," Bendtsen says. By "accustomed" she doesn't mean "resigned." During the last decade, Østkraft has built up an impressive array of renewable sources like wind, solar, and biomass, which can now supply about three-quarters of the island's demand. In the process, Bornholm has transformed itself into a kind of living laboratory for testing new energy ideas.

Now it is taking the ultimate step, by deploying one of the world's most advanced smart grids, called the EcoGrid EU. It's a four-year, €21 million (US $27 million) project, funded in part by the European Union, that aims



GREEN GRID: The Danish island of Bornholm has only 41 000 full-time residents, but it now boasts one of the world's most advanced smart grids, which should help optimize the operation of its diverse mix of energy sources, including wind, solar, and biomass, as well as traditional coal and diesel.

to demonstrate how electricity will be produced, distributed, and consumed in the future. While any smart grid today can track in excruciating detail electricity supply, demand, and other information, Bornholm's is one of the first in which individual household consumption can respond to real-time price changes in the electricity market. By doing that, the grid's customers are helping to balance the sometimes big and sudden swings in supply that inevitably accompany the use of wind and solar power.

And as Bornholm goes, so goes Denmark and the rest of Europe. The European Commission's 20/20/20 Plan, for instance, states that by the year 2020, greenhouse gas emissions will be cut by 20 percent, while renewable energy usage and energy efficiency will both rise by 20 percent. Last year, the Danish parliament approved an even more ambitious target: to have renewables supply 35 percent of the country's total energy needs—not just electricity but also heating and transportation—by 2020, and an incredible 100 percent by 2050. Can those targets actually be reached?

That's what the EcoGrid project aims to find out. The choice of Bornholm, with its 41 000 full-time residents, to host it was no accident. Although the island's beauty draws hundreds of thousands of tourists every year, it's not just a vacation destination. Commercial fishing, dairy farming, and arts and crafts all buttress the economy and give Østkraft a representative mixture of commercial, industrial, and residential customers, as well as schools, a hospital, an airport, and an international seaport.

"We're like a microcosm of Danish society," Bendtsen says. "We are in many senses a picture of the future power system in Denmark." And by studying how a high-tech grid can help this little island cope with the challenges of renewable energy, EcoGrid's organizers hope to discover larger lessons for the wider world.

BORNHOLM HAS LONG held a special place in the Danish psyche. According to local legend, when God got to the end of his creation he still had bits of paradise left over, and so he threw them all down in the Baltic Sea and created Bornholm. In medieval times, another tale goes, Danish kings hid their mistresses away in the island's large forest. Today, Europeans flock to Bornholm in the summer for its beautiful sandy beaches, sunny (for Denmark) weather, and, yes, that forest.

For Jacob Østergaard, though, the most attractive thing about Bornholm isn't the beaches or the sun: It's that pesky undersea cable, or, more important, what that cable allows him as a power engineer to do. Østergaard, a professor of electrical engineering at the Technical University of Denmark (DTU), in Lyngby, is involved in a number of electricity projects on Bornholm, including EcoGrid. The cable can be switched off at will, he explains, putting the Bornholm grid into what's known in electricity circles as "island" mode. And that's interesting, he says, because the wealth of wind power makes the Bornholm grid challenging to operate and

LOST AT SEA: Bornholm's only link to the Nordic grid is via a three-phase undersea cable, which has broken four times in the last 10 years.

MAP BY Bryan Christie Design

FUELING THE FUTURE: The main power plant on Bornholm [top] burns wood chips in addition to coal and diesel. A 2-megawatt biogas plant [right] converts manure and other organic waste into electricity and heat. Meanwhile, researchers at the Technical University of Denmark, outside Copenhagen, monitor the island's grid in real time [left].

BOTTOM LEFT: TECHNICAL UNIVERSITY OF DENMARK (DTU)

fascinating to study. Last year, he and his colleagues even built a duplicate of the Østkraft control room on the DTU campus to monitor the Bornholm grid in real time.

On a windy day, Bornholm's turbines can supply up to 30 MW of power, or more than half of the island's peak load of 55 MW. But the wind blows as it will, and that variability and unpredictability can wreak havoc on the grid's stability. If the wind abruptly dies, for instance, electricity supply could dip way below demand, causing the grid's nominal 50-hertz frequency to likewise plummet. A dip or a spike of just over a tenth of a hertz is cause for alarm, Østergaard says, and if it drifts out of kilter even further—to, say, 47 Hz—it can trigger a blackout.

Something close to that happened on 17 September 2009, when the sea cable was shut down for maintenance. To keep the grid balanced, the wind turbines were also initially shut down. At 11:25 a.m., all was calm, with the grid frequency steadily hovering just north of 50 Hz. Then, at 11:26 a.m., six of the turbines were turned on, and over the next several minutes their share of the island's power supply rose to 15 percent.

But as the wind output grew erratic, so did the grid frequency, spiking more than a tenth of a hertz several times and dropping sharply to 49.8 Hz just before noon. Østkraft engineers and DTU researchers were closely monitoring the situation and quickly stepped in, ramping up the output of the island's conventional generators and dialing back the proportion of wind to 10 percent, at which point the frequency returned to normal.

Dozens of experiments before and since have confirmed that there's an upper limit of about 15 percent on the amount of wind power that Bornholm's grid can absorb when in island mode. And to greater or lesser degrees, all power grids that have a substantial amount of wind and solar do the same thing, falling back on traditional "peak" generators to compensate for gaps in renewable output. Some grid operators also store electricity in pumped hydro or compressed-air installations or in industrial-grade batteries, but the latter aren't yet economical, and the former can be used only in certain locations.

But what if, instead of boosting generation when demand is high, you just cut back demand? Answering that basic question is at the heart of the EcoGrid.

THE GOAL OF THE SMART GRID isn't to demonstrate that Bornholm can be energy independent, notes Bendtsen, sitting in one of the light-filled offices at Østkraft's sleek headquarters just outside the main town of Rønne. The island is independent already:

NEW ENERGY IDEAS: Martin Kok-Hansen [left] was one of the first homeowners to sign up for the EcoGrid smart grid. He's already decided to swap his halogen lights for more efficient bulbs. A demonstration house equipped with rooftop photovoltaics [center] and smart-grid devices lets people see how these technologies work. Bottle coolers [right] outfitted with special controllers respond to changes in grid frequency by automatically turning off or on.

At present it has about 50 MW of domestic capacity, from a mix of conventional coal and diesel generators, three dozen wind turbines that dot the countryside like giant pinwheels, rooftop photovoltaics, a biogas plant, and several wood-chip- and straw-fired plants. As a result, the Christmas night blackout lasted only a few hours, the time it took to bring the domestic plants online.

But producing electricity that way is expensive, and so the cable to Sweden lets the island buy electricity from the Nordic grid when it's cheap and sell when the price is high. Ordinarily, trading in electricity markets is done at the level of utilities and the like. EcoGrid is letting individual households and smaller businesses also become market players.

The idea is to shift the consumption of electricity to periods of the day and night when electricity demand and prices are low, Bendtsen explains. You could do that by simply sending people a text message whenever prices change. But that would quickly get tiresome.

"And if we let people interact directly with the market, their behavior will, of course, change," says Østergaard. "Everyone will want to charge their electric vehicles when the price is low, for example. If too many people do that, you create congestion in the weakest parts of the grid."

Instead, EcoGrid's people have installed smart grid controllers in about 1200 households and a hundred businesses, and since April the controllers have been receiving a continuous stream of data based on the 5-minute price for electricity in the Nordic electricity market, which covers Denmark, Finland, Norway, and Sweden. The controllers wirelessly communicate with designated appliances, and algorithms determine whether to turn each one on or off, based on factors like the time of day, the weather, and current, past, and future market prices.

At first, the project's organizers envisioned regulating a whole suite of household machines—dishwashers, washing machines, refrigerators, TVs, lights. It turns out, though, that although such smart appliances have been on the market for years, there's still no standard protocol for automating them. So your dishwasher might speak ZigBee while your freezer converses in KNX, and they can't easily understand each other.

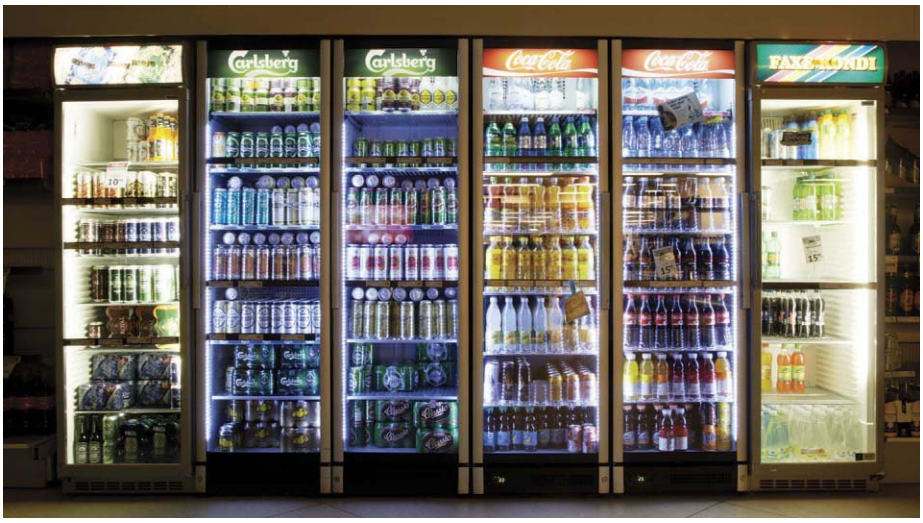
Standards clearly would help, says Bendtsen. "Imagine that you go to a white goods store to buy a new dishwasher," she says. "You have to consider not just what size and what color and how much energy and water does it use but which language does it speak. Fine if you're an engineer, but we need some sort of standard so that ordinary people don't have to think about all these things themselves."

In the meantime, the EcoGrid is keeping things simple and dealing primarily with households that have electric heating systems and heat pumps. In 700 of those households, the heating system is directly controlled using algorithms developed at IBM's research lab in Zurich. A thermal model of each household has been created, based on factors like electricity usage patterns and the size of the windows and walls, explains Dieter Gantenbein, smart grid project leader at IBM Research-Zurich.

"If you leave the window open a lot to let your cat in and out, then your parameters will be different from somebody who keeps the windows closed," he says. From the thermal model, he adds, "we can determine the electrical flexibility of this house—we have a planned strategy on how to throttle the heat pump up or down. The goal is that the owners do not see any reduction in their quality of life." About 100 businesses on Bornholm are being similarly equipped.

Another 500 or so households are being treated as a single electricity-consuming unit; Siemens's Denmark subsidiary is coordinating that part of the smart grid. The remainder of the 1900 households enrolled in the project—about a tenth of the island—are just getting smart meters, which provide them with fine-grained information about their electricity consumption and market prices but don't control their usage in any way.

Interestingly, EcoGrid participants aren't being told to expect a drop in their electricity bills. That's partly a way to manage expectations, but it's also just being realistic: Numerous studies in Denmark and other countries have shown that the incremental savings people get from



being more energy efficient usually aren't enough to change their behavior. That said, Gantenbein notes, there's been no lack of volunteers on Bornholm.

"Danes take preservation of the environment close to their hearts," he says. "It's like a sport. They heat carefully, they close doors, they use different technologies, and by being engaged, they are very enthusiastic to participate in such an ambitious pilot."

MARTIN KOK-HANSEN is just such an enthusiast. He and his family live in a one-story brick house on the northern edge of Rønne, and he was among the first on Bornholm to sign up for the smart grid. The real estate agent says he decided to participate for the same reason he traded in his Jeep Grand Cherokee for a Volkswagen Golf a few years back. "In the future, we won't have that much power," he says. "And my son is probably going to have kids as well. Where are they going to get all the power from?"

There's now a Landis+Gyr smart meter on the wall of Kok-Hansen's garage, a small relay and reader in the laundry room that turns the electric heater on and off, and a digital thermostat in the living room; all three of these units communicate wirelessly with a "gateway" controller and router that in turn connect via the Internet to the utility company. The gateway and most of the other hardware, as well as the household communication and end-user Web services, were designed by a company called GreenWave Reality, based in Irvine, Calif.

Like other participants, Kok-Hansen can set limits on how warm or cool his house gets. "If it's 21 °C in here and they need the power, they can switch off the heat and let it fall to 18 °C," he says. That's two or three degrees cooler than normal, but he thinks he can cope. "Maybe you put on a sweater for a while."

Standing in his recently remodeled kitchen, laptop perched on the black granite countertop, he logs into his account on the Østkraft website. He can see, in near real time, how much electricity he's using. It's been illuminating, to say the least.

"Right now I'm using 1200 watts," he says, pointing to a graph onscreen. "But when you turn this one on"—he walks over to a wall switch and flicks on the recessed halogen lights overhead—"you see that the usage goes way up." Sure enough, within a few seconds, the graphed value nearly doubles. That's because each halogen bulb is 50 watts, and the kitchen has 16 of them. At current rates, 1 kilowatt-hour runs about 2 Danish kroner, or 35 cents. So keeping those lights on just 4 hours a day is costing him $500 a year, he figures. He plans to swap them out soon for compact fluorescents or LEDs.

"I definitely will change those," he says. "This is a whole new lifestyle."

THE SUPERBEST SUPERMARKET just off the main square in Rønne is packed on a Saturday afternoon. A young man stops at a refrigerator, pulls out a few bottles of beer, and puts them in his cart. He doesn't bother to read the explanatory sticker plastered across the refrigerator's glass front, nor does he glance up at the shoebox-size device sitting atop the cooler. And so he may have no inkling that this refrigerator, and about 200 other units like it on Bornholm, is special: Like the EcoGrid's heat pumps, the bottle coolers are helping to balance the grid.

Two years ago, researchers at DTU modified each cooler so that it directly monitors grid frequency, explains Østergaard. In a series of experiments, his group has shown that the coolers can be programmed to turn themselves off when the frequency drops by more than a tenth, and then automatically turn back on when the frequency stabilizes. "If it's just a small frequency variation, then you just have a small number of coolers respond," he explains. "But if there's a large variation, then all of them will react."

The concept of using coolers, pumps, and other appliances in this way has been kicking around for a while, Østergaard says, but only in the last decade or so has it become economically feasible. "These days, every cooler has a thermostat with a microcontroller and processor, so you can just program it to do this," he notes. Whereas the heating systems hooked up to the EcoGrid are reacting to market prices, which are an indirect measure of power supply and demand, the Bornholm bottle coolers are detecting conditions on the grid itself.

Østergaard says both approaches are useful: "It's important to balance the grid on all time scales, from seconds and minutes to days and years." And by using information technology to strategically roll back demand, rather than ramping up supply, the smart grid can create a more efficient network. "Moving bits and bytes is less expensive than moving amperes," he says.

As to whether Denmark and the rest of Europe will meet their lofty energy goals, Østergaard's not saying. "It's good to have goals," he allows. "I don't know if we will succeed. But without projects like this, there is no chance at all." ■

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THE TROUBLED LIFE OF PATENT NO. 6,456,841

TRACING THE TORTURED LEGAL TRAIL OF A SIMPLE SMARTPHONE PATENT

BY TAM HARBERT • ILLUSTRATION BY MCKIBILLO

TAKESHI TOMIMORI, an engineer at Mitsubishi Electric Corp., in Tokyo, had an idea. What if you could alert a cellphone user of incoming messages by displaying an icon on the screen? He worked out the details for what Mitsubishi's lawyers called, in their 1999 filing, a "Mobile Communication Apparatus Notifying User of Reproduction Waiting Information Effectively." Three years and three months later, the U.S. Patent and Trademark Office awarded Tomimori and his employer Patent No. 6,456,841. Let's call it Icon, for short.

For nine years, Icon had a very quiet life—understandable, given that the cellphone wasn't yet the ubiquitous gadget it is today. But think about Tomimori's idea: Doesn't it sound a little like the tiny numbers that show up on an iPhone's text, e-mail, and social media icons when there are new messages?

Steven S. Rubin, a lawyer with Moritt Hock & Hamroff, says the Mitsubishi patent is actually more relevant to older cellphones. "This is going back to the flip-phone days, when a phone didn't display anything until we opened it," he says. Despite that key difference, in 2011 certain parties in the tech industry suddenly took an interest.

By then, the smartphone patent wars had reached a fever pitch. That year, Apple sued Samsung Electronics for smartphone-related patent and trademark infringement, and Samsung countersued. Apple and Motorola Mobility were embroiled in a similar globe-spanning legal battle; after Google bought Motorola Mobility for US $12.5 billion, the struggle became Apple v. Google. And when Google sought to buy Nortel Networks Corp.'s 6000-plus mobile-telecom patents, a consortium of Apple, EMC, Ericsson, Microsoft, Research In Motion, and Sony paid $4.5 billion to keep that intellectual property out of Google's hands.

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IT'S A HARD-KNOCK LIFE*

*For Patent No. 6,456,841

JUNE 1999

Eureka!

Takeshi Tomimori of Mitsubishi files for a patent on a way to notify cellphone users that they have messages.

SEPTEMBER 2002

Congratulations, It's a Patent!

U.S. Patent No. 6,456,841 is granted to Tomimori and Mitsubishi.

MARCH 2011

Apple of My Eye

Mitsubishi transfers the patent, and 11 others, to Apple, as global smartphone IP battles rage.

AUGUST 2011

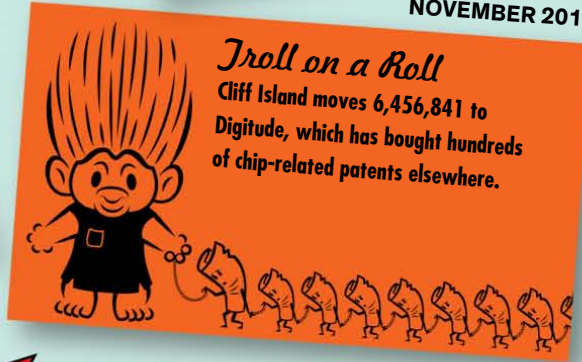
Bad Apple?

Apple turns over all 12 patents to Cliff Island, a shell company set up by patent troll Digitude Innovations.

NOVEMBER 2011

Troll on a Roll

Cliff Island moves 6,456,841 to Digitude, which has bought hundreds of chip-related patents elsewhere.



DECEMBER 2011

Troll Attack!

Digitude sues nine mobile phone and tablet companies (but not Apple) for infringement, citing 6,456,841 and three other patents. It asks the U.S. International Trade Commission to bar importation of infringing devices into the United States.

MAY AND JUNE 2012

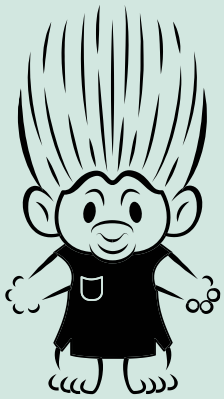
Payday

Digitude drops its lawsuits and ITC complaints and sells 6,456,841 and 500 other patents for $45.8 million to RPX Corp., a company that tries to derail aggressive litigation.

Against that litigious backdrop, on 4 March 2011, Apple quietly acquired Icon and 11 other Mitsubishi patents. (Presumably, Apple either paid the Japanese company for the portfolio or did an in-kind exchange of IP, but neither firm would comment.)

Just five months later, Apple transferred those dozen patents to an entity called Cliff Island, a shell company created by Digitude Innovations. Headquartered in Alexandria, Va., Digitude describes itself as a patent acquisition and licensing company. Some IP experts, however, call it a patent troll, which to judge by its activities in this case, seems apt. Digitude was founded in early 2010 largely through a $50 million investment from Altitude Capital Partners, a private equity IP firm based in New York City. In November 2011, Icon and one other Mitsubishi patent (6,208,879—we'll refer to it as Friend of Icon) were officially conveyed from Cliff Island to Digitude.

Throughout 2011, Digitude was busy acquiring hundreds of other patents through another shell company called Hupper Island. (Cliff and Hupper are the names of islands off the coast of Maine.) Most of those came from Adaptec, based in Milpitas, Calif., which was selling off its chip-related IP.



Finally, in December 2011, the goal of Digitude's acquisitions became clear: It sued nine companies in the Federal District Court of Delaware for infringement of four mobile phone patents—Icon and Friend of Icon from the Mitsubishi deal and two from Adaptec (5,929,655 and 5,926,636). The two Adaptec patents aren't obviously phone related. One is for a dual-purpose I/O circuit that can be implemented without taking up much real estate on a die. The other describes a way to make "remote procedural calls" over heterogeneous computer networks.

The products that Digitude claimed were infringing on its intellectual property included Amazon's Kindle Fire; HTC Corp.'s EVO Design 4G; LG Electronics' Revolution VS910 and Optimus V; Motorola Mobility's Droid Razr and Droid 3; Nokia's Lumia 710; Pantech Wireless's Breakout; Research in Motion's BlackBerry Bold 9930 and Curve 8530; Samsung's Galaxy SII Epic 4G Touch and Focus; and Sony Ericsson's Xperia Play, Xperia Play 3G, and X8 Black 3G. Quite a list—but note the absence of Apple.

Digitude simultaneously filed a complaint alleging infringement of the same four patents with the U.S. International Trade Commission, a Commerce Department agency. Patent experts say the ITC is increasingly being used in this fashion: Parties filing infringement lawsuits attempt to bolster their cases by also registering official complaints. This double-barreled approach pressures defendants to settle rather than fight on two fronts—in the courts and at the ITC.

The companies named in Digitude's complaint were almost identical to those in the lawsuits: Amazon, HTC, LG, Motorola Mobility, Nokia, Research in Motion, Samsung, and Sony Ericsson. The list did not include Pantech—or Apple. In the ITC complaint, Digitude sought an exclusion order to stop the importation of the infringing devices into the United States. The ITC tends to move faster than the district courts, says Rubin of Moritt Hock & Hamroff. It's much more difficult to get a district court to issue such an injunction.

While some IP cases drag on for years, this one wrapped up quickly. Digitude dropped the lawsuits in May 2012 and the ITC complaints the following month. Behind the scenes, it had agreed to sell the four patents, along with more than 500 others, to RPX Corp. for $45.8 million. RPX is what's known as a defensive patent aggregator, meaning it buys up patents in an effort to keep them out of the hands of patent trolls and to protect its clients, which include HTC, LG, Pantech, Samsung, and Sony. Other defendants in the case, not to mention other big consumer electronics companies like Apple, may also be among its clients; the company does not disclose the names of all its customers.

According to RPX's August 2012 10-Q filing with the U.S. Securities and Exchange Commission, the company and 11 of its customers reached agreements in March of that year with Digitude; a Digitude subsidiary called Preservation Technologies; Robert Kramer (chairman of Digitude and managing partner of Altitude Capital); and his wife, Susan Kramer. The agreements granted RPX the 500-plus patents and "all of the issued and outstanding membership interests" in Altitude Capital.

In a written statement to *IEEE Spectrum*, RPX said the following: "The outcome of the deal is that we created immediate savings and value for our client network by removing a key patent portfolio and mitigating future activity of a highly successful non-practicing entity"—or NPE, a term some in the industry apply to patent trolls. RPX now employs Kramer as a consultant, the statement continues. "Kramer has been a leader in the space and we believe his market insights and NPE analysis expertise add value to our offering."

In other words, RPX disarmed its opponent and is now free to use its ammunition. "That's a nice, worthwhile purchase," concludes Bruce Berman, CEO of Brody Berman Associates, an IP consulting firm. RPX's general approach is efficient, he adds. "Many of the RPX members spend $1 billion or much more annually on R&D and $100 million or more on legal costs and filing and maintenance fees. For the $5 million fee to join RPX, they are in a better position to mitigate some NPE risks and, best of all, share in the cost of doing so. I would say that's money well spent."

And so for now, Icon—good old patent 6,456,841—resides with RPX. But at some point it could be on the move again, says Rob Aronoff, founder of Pluritas, an IP advisory firm. Most likely, he says, the deal requires RPX to hold the patents for a certain period of time, after which the 11 companies named in the deal may have the right to buy whatever patents they want. "It's likely that these patents will end up in the hands of an individual RPX member," he says.

If there's an upside to this story, it's that very few patents ever take such a perilous journey. An invention is born, an application is filed, a patent is awarded, nobody except the inventor ever notices, and then the patent dies a quiet death 20 years later.

"Probably 97 percent of the patents out there are of no value," says Berman. "The life of most patents is not very interesting." ■

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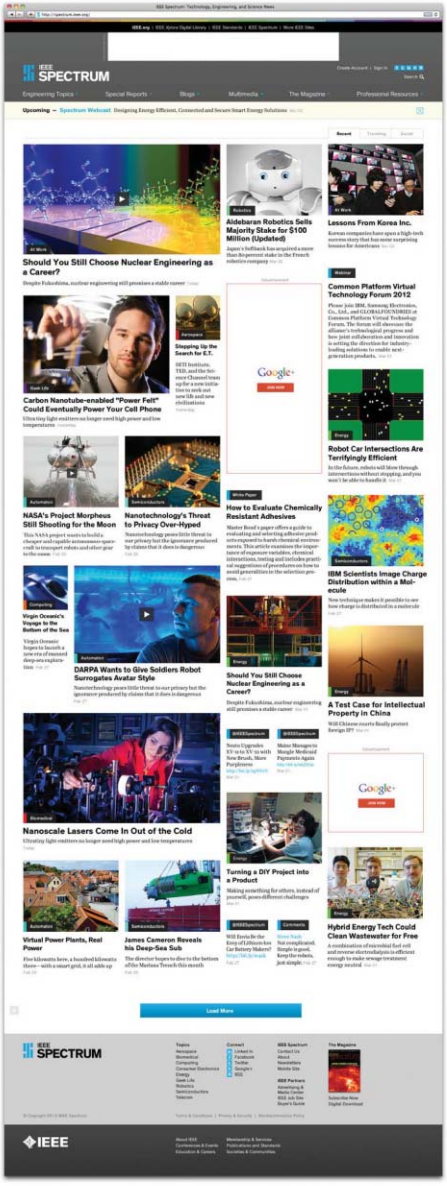

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CAPTAIN CELLULAR

QUALCOMM COFOUNDER IRWIN M. JACOBS'S UPSTART TECHNOLOGY EVENTUALLY WON THE DAY

BY TEKLA S. PERRY

IT WAS SEPTEMBER 1989, and the cellphone industry was booming. Companies were building new towers as fast as they could, using the prevailing analog technology, but they were encountering problems with capacity and quality of service. Earlier that year, the industry had decided to move to digital transmission using time-division multiple access. TDMA shared the airwaves by slicing up each available frequency channel into time slots. A caller's phone transmitted digitized signals in short bursts during the slot assigned to the handset. It wasn't a particularly efficient use of the broadcast spectrum, but it worked.

Irwin M. Jacobs, chief executive officer of what was a little San Diego company called Qualcomm, believed he had a better approach. He wanted to take an idea then being used for secure military communications—Code Division Multiple Access, or CDMA—and adapt it to commercial cellphone networks, which would allow multiple conversations to share the same frequencies at the same time. He knew this technology could serve many more customers with fewer towers. But an awful lot of people didn't believe he could pull this off, and time was running out. The more companies and consumers purchased

PHOTOGRAPH BY Gregg Segal

TDMA equipment, the harder it would be for a new technology to gain a foothold.

In June, Jacobs had pitched CDMA at an industry meeting in Chicago. But talk would go only so far. He had to show industry executives that CDMA worked. The trouble was, it didn't. Not yet. Still, Jacobs believed that if 1989 ended before CDMA went live, neither CDMA nor his company would survive. He set a November date for a demonstration and sent invitations to more than 100 executives of companies that built cellphones or operated cellphone systems. Most of the engineers working for him thought he was nuts.

7 November 1989: Demo day arrived. Qualcomm had installed CDMA equipment on two cellphone towers and in a van. The people Jacobs assembled heard a few presentations about how CDMA worked and why it would help the industry. Jacobs then took the podium, prepared to make a few remarks before sending the executives out to drive around in the van and make phone calls, when he spotted one of his engineers in the back of the room frantically gesturing at him to keep talking. Jacobs didn't know exactly what was going on, but he could guess—the gear wasn't working. Forty-five agonizing minutes later, he got a sign that he could release the crowd. The CDMA equipment was fixed.

"If that demo had failed, we probably would have been dead," Jacobs recalls. The problem, it turns out, wasn't with the CDMA technology. The two demonstration base stations set their clocks to synchronize with each other via signals from the then-nascent Global Positioning System. That morning, one of the GPS satellites was itself out of sync. While the engineers working to diagnose and solve the problem were certainly sweating, Jacobs was remarkably calm. He believed in CDMA with all his heart.

Today CDMA technology powers all 3G cellular networks and continues to expand its reach with 4G. It is for making that happen, for "leadership and fundamental contributions to digital communications and wireless technology," that Irwin M. Jacobs is being awarded this year's IEEE Medal of Honor.

JACOBS'S STORY starts back in Massachusetts, where he worked from the time he was in fifth grade or so as a grocery-store clerk, a lifeguard, a photo developer, and even a lumberjack. As he approached his 1950 high school graduation with top grades in math and science, he expected to study engineering in college. His guidance counselor, however, told him there was no future in science or engineering and suggested agricultural school. When Jacobs rejected that idea, the counselor asked about his parents' work. Jacobs's parents then had a small restaurant, so the counselor pointed him to Cornell's School of Hotel Administration.

Jacobs went through a year and a half of training there, and he worked as a cook at a country club the summer between freshman and sophomore years. He might have stayed on that track had it not been for his college roommate, a chemical engineering major who teased Jacobs about his easy courses, insisting that Jacobs wouldn't be racking up such good grades were he studying engineering. "You can only listen to that for so long," Jacobs says. Halfway through sophomore year he changed his major to electrical engineering and never looked back, going on to earn a doctorate at MIT and eventually teaching there. Then in 1966, drawn by the opportunity to help launch a new engineering school and by California's weather, he put his family in a used Ford Falcon van and drove cross-country to accept a post at the University of California, San Diego (UCSD).

Before he left MIT, Jacobs and fellow faculty member John M. Wozencraft had written a textbook on communications theory, *Principles of Communication Engineering*, first published in 1965 and still used. The book helped bring Jacobs consulting work, and in 1968 he joined with professors Leonard Kleinrock and Andrew Viterbi of the University of California, Los Angeles, to start a consulting company, Linkabit Corp. It began developing products of its own, including very-small-aperture terminal satellite systems for business use and VideoCipher, a home descrambler for satellite television. In 1972, Jacobs left UCSD to manage Linkabit full time. In 1980, Linkabit merged with M/A-Com, and on 1 April 1985 Jacobs left, having netted about US $20 million from the deal.

He could have retired more than comfortably. But starting a company, something he'd initially had doubts about, turned out to be "great fun," he says. "I liked doing the systems and the overview and the long-term thinking, but I also liked all the detail work, going through each aspect of the company, learning best how to do each job, and then bringing in very good people to take over that responsibility."

So after he was finished with Linkabit, he decided to do it all over, joining with six others, including, once again, Viterbi. The group started Qualcomm in 1985, each founder putting in $1500 or so. They intended to initially fund themselves with contract work.

One of those first contracts, a technical review of a proposal by Hughes to develop a mobile satellite system, lit the firecracker that turned out to be CDMA.

THE HUGHES PROPOSAL used conventional spectrum-sharing techniques, which split up the available bandwidth by time slots or by frequencies. Providers of commercial communications weren't considering CDMA, then used for jam-proofing military communications, because it was generally thought to be too complicated.

But on the drive back to San Diego from a meeting with Hughes engineers in Los Angeles, while chatting with Viterbi and another cofounder, Klein Gilhousen, Jacobs got to thinking about gaps in conversations, those moments when people pause to gather their thoughts. He wondered whether you could somehow squeeze parts of other conversations into those gaps. "I realized that CDMA might be able to do this," Jacobs says, "and that this was a significant potential advantage for a mobile communication system."

A few days later, Gilhousen observed that CDMA offered another advantage for cellphones: It's designed to work with interference. TDMA couldn't do that, so cellphone operators had to avoid interference by making sure they weren't using the same frequencies at nearby locales, much the way adjacent cities don't use the same television broadcast channels. Being able to use the same frequencies at every cell site would mean that a cellphone network could handle a lot more calls.

Given these two big advantages, Jacobs and his partners thought that perhaps working through the complexities of CDMA would be worthwhile.

One of the biggest complexities involved controlling the power of the signals sent from the phone and received at the cell tower. A cellular communications system in which different conversations are separated by time or by frequency is like a conversation

taking place in a private room; it isn't really critical how loud two people in the room talk. But in a CDMA system, conversations take place in the equivalent of a noisy room, where a few loudmouths can drown out everyone else. Jacobs and the other engineers at Qualcomm had to make sure this didn't happen.

Jacobs and his engineers laid out a plan that managed the power of the communications signals in three ways. First, he envisioned a rapid-response system: CDMA phones would monitor the power of the signal coming in from the tower; if the signal suddenly dropped, say, when a user walked into a building, the phone would crank up its transmitting signal, figuring that if it was having trouble hearing the tower, then the tower would have trouble hearing the phone. Next, equipment at CDMA towers would take a handful of received bits and calculate an average signal strength; if that signal fell above or below a preset threshold, then the tower would prompt the phone to lower or raise its power. And, finally, the thresholds for each conversation would be adjusted depending on the rate at which incoming packets of information had to be dropped because they couldn't be decoded properly. Digital communications depend on decoding sequences of bits. But these sequences don't have to come through perfectly; the decoders expect some errors. And a strong signal will have fewer errors than a weak one. So the Qualcomm engineers designed the decoders to report when the error rate got higher or lower than normal, so that this information could also be used to adjust signal strength.

"Someone else might have looked at all the complexities and the concerns and concluded that it just wasn't possible," said Richard Atkinson, former president of the University of California. "But Irwin didn't back away."

Making CDMA work was perhaps the easy part. Selling it to an industry already on the TDMA bandwagon was much tougher. The successful San Diego demonstration helped a lot, but it took years for CDMA to be truly accepted. Jacobs repeated the demonstration in January 1991 in New York City, where skeptical executives at wireless carriers thought CDMA would fail when confronted with a sea of tall buildings. He weathered the critics, such as the professor at Stanford who told people that CDMA violated the laws of physics, and *The Wall Street Journal*, which ran a September 1996 article claiming that Jacobs's hype was causing carriers and cellphone manufacturers to throw away billions of dollars. "He was a lot cooler than I was," recalls Viterbi, who went on to receive the 2010 IEEE Medal of Honor. "I got upset with the detractors. He just carried on."

So Qualcomm went ahead to develop the chips needed for handsets and base stations. Jacobs, meanwhile, offered to create an experimental network to test any problematic scenario the skeptics could come up with. "We had a whole group of manufacturers working with us to try to break the system," Jacobs recalls. "The data produced turned out to be very handy when we went through the standards process."

The Telecommunications Industry Association approved CDMA as a standard in July 1993, and the first commercial system began operation in Hong Kong in late 1995. Today, CDMA is the dominant cellphone technology, and Qualcomm, with Jacobs's son Paul at the helm, is a $115 billion company. His dad's being smart "was just table stakes," says Paul. "What made Qualcomm successful was passion and persistence—even though everyone said it couldn't be done, even though he was getting personally attacked, he had a fundamental belief that he was right and that would lead to victory."

JACOBS HIMSELF, according to *Forbes* last year, is worth about $1.5 billion. Thanks to the way he's spending that wealth, Jacobs won't be remembered only for CDMA. In fact, many don't connect him at all with technology. Instead, he's the guy who pledged about $120 million to put the San Diego Symphony on solid financial ground. He put another $120 million or so into engineering education at UCSD, where the school of engineering is now named after him. He also made significant donations to MIT, Cornell, and Technion–Israel Institute of Technology. He and his wife, Joan, also support the La Jolla Playhouse, the Museum of Contemporary Art San Diego, the San Diego Natural History Museum, and local public radio and television. They recently funded a new central library for the city. The *San Diego Union Tribune* has called him the city's philanthropist in chief.

His current passion is High Tech High, a charter school focused on STEM education. Since 2000, it has grown from one high school to five high schools and four middle schools and will soon include three elementary schools. And he's been involved in supporting local and national Democratic candidates for decades. He has joined a philanthropic campaign cofounded by Warren Buffet called The Giving Pledge, promising to donate at least 50 percent of his wealth before he dies.

Jacobs himself isn't a flashy billionaire: Movies aren't made about him, he doesn't wear an iconic turtleneck or hoodie, and he lives fairly modestly, at least from the outside, in an older neighborhood of average-size ranch homes. His son Gary says his father taught them that "just because you have it doesn't mean you get to spend it all on yourself."

Jacobs's house, built on land purchased in 1968 for $37 000, has a spectacular view. The interior boasts art collected from around the world and a large room designed for chamber music concerts. But, Jacobs points out, he has only one house. He received his first Ferrari as a 70th birthday present from his four sons. Paul Jacobs says his father had wanted a Ferrari for 45 years and had been able to afford it for decades, but he would never have bought it for himself.

When people do recognize Jacobs and his wife, they're likely to stop and say, "Thank you." What for? Well, Jacobs says, it depends on the person. The music lover will thank them for supporting the symphony; the educator for support of the university; the art lover for support of the Museum of Contemporary Art; the book lover for support of the Central Library; the theatergoer for their efforts with the La Jolla Playhouse. And then there are the folks who worked for or invested in Qualcomm over the years, who thank him for making it possible for them to buy their houses. The funny thing is, most of the people who stop him are carrying mobile devices that work as well as they do only because of his patents and persistence. But that's something they rarely mention. ■

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PHOTOGRAPH BY Gregg Segal

SPECTRUM AUCTIONS

CONTINUED FROM PAGE 31 | particles in the atmosphere. This phenomenon affects frequencies above about 10 GHz and becomes progressively worse the higher you go.

Radio waves around 60 GHz suffer an even greater problem: They are absorbed by oxygen molecules, and to a 60-GHz signal, clear air will look like dense fog. But systems in this band are still used, for instance, to connect nearby buildings on a single campus. Here, the atmospheric attenuation can be considered a feature rather than a bug, because it allows the same frequency to be employed a short distance away without risking interference.

Fixed-microwave links are among the most reliable forms of radio communications ever built. A system serving critical needs can routinely be kept running 99.9999 percent of the time, or "six nines" in industry jargon. This allows for a total cumulative downtime of only 30 seconds per year—not bad for equipment mounted high in the air and exposed to the elements.

One key to reliability is ensuring that neighboring systems do not interfere with one another. Most countries achieve this through some form of frequency coordination. In the United States, the engineer configuring a new link, often with the help of a frequency-coordination firm, consults a comprehensive database of licensees and prior applicants. The goal is to adjust the design so that it meets certain specified criteria for keeping the system free of interference and for preventing it from interfering with other systems. The designer then sends out details of the proposed system to all other users whose operations might plausibly cause or receive interference. The acquiescence of potential victims of interference is required before the license application goes to the Federal Communications Commission. If another user objects, the engineers on both sides negotiate to resolve the problem. The role of the FCC here is merely to maintain the database, along with setting minimum performance requirements—activities it funds with fees collected from license applicants (currently US $470 per transmitter location for each 10-year license).

HISTORICALLY, EVEN COMPANIES IN DIRECT COMPETITION HAVE BEEN HELPFUL TO EACH OTHER THROUGH THE LICENSING PROCESS

Historically, even companies in direct competition have been helpful to each other through this process (although this spirit of cooperation is starting to break down on certain high-demand routes).

The criteria used to identify interfering signals are conservative, so a system that has passed frequency coordination is very likely to coexist successfully with its neighbors.

Some services get by with no frequency coordination at all. Many Internet providers offer connectivity via directional links in the unlicensed bands near 2.4 and 5.8 GHz. These can operate over tens of kilometers. Because unlicensed users receive no interference protection, they are free to put up antennas almost anywhere they want. Even so, the directional nature and limited power of their transmissions makes interference unlikely. You wouldn't want to control a nuclear power station over these connections, but they can provide satisfactory consumer service. In practice, unlicensed links are also used temporarily for more critical applications that can't wait for frequency coordination.

Once a link is up and running, threats to reliability occur even in clear air due to atmospheric turbulence or strong gradients in air density, which are invisible to the eye. These clear-air fades can reduce the signal-to-noise ratio enough to cause errors in the bits received. In severe cases, they may interrupt communications entirely.

Designers of systems for critical applications must keep their systems working even through the most severe fades. They have three main tools. One is space diversity—transmitting the same information simultaneously over multiple paths, thus improving the odds that at least one keeps working. A second is automatic power control, which has the receiver continuously report back to the transmitter on the strength of the incoming signal. If it drops below some threshold, the transmitter temporarily cranks up the power to compensate. The main disadvantage here is the increased risk of interfering with nearby systems.

The third approach is adaptive modulation. When the receiver reports a drop in signal strength, instead of powering up, the transmitter sends out fewer bits per second. Basic information theory dictates that shifting to a sufficiently low bit rate can maintain some desired (very low) error rate, despite a decrease in the signal-to-noise ratio. It's a little like shouting to someone in a noisy environment: You instinctively speak more slowly than usual.

The use of adaptive modulation has long been accepted in Europe and Canada but not the United States, where the technique ran up against a rule that requires fixed-microwave systems to operate at a minimum bit rate, typically between 2.5 and 4.5 bits per second per hertz. The FCC has approved adaptive modulation, but to prevent the deployment of spectrally inefficient systems, it requires transmitters to maintain the specified minimum at least 99.95 percent of the time. This limits the slower modulations to a little over 4 hours per year. That's enough, though, to keep most links in continuous operation.

The need for fixed-microwave communications is skyrocketing. That's in no small part because of the increasing numbers of

people spending time online and the spread of bandwidth-hungry applications, particularly video. The popularity of smartphones and tablets, whose owners expect broadband speeds no matter where they are, adds to the demand. Their mobile traffic not only requires spectrum for connecting their devices with cell towers but also expands the need for backhaul—the process of moving all the users' data between towers and the carrier's network. The microwave dishes that adorn many cell towers provide those links. Expect to see more of them in coming years.

Like most other radio services, fixed microwave has trouble finding enough suitable spectrum. The relatively low frequencies needed for longer links have been in especially short supply since the mid-1990s, when many countries reallocated radio spectrum around 2 GHz, shifting it from fixed microwave to second-generation cellphones.

In many places, fixed-microwave users must share some of their frequency bands with satellite uplinks and downlinks. Frequency coordination in those bands must take account of the satellite facilities. Sharing is usually manageable in bands allocated for satellite uplinks, which threaten microwave receivers with interference only in the vicinity of the satellite earth stations. The downlinks can be more troublesome. In the United States, the proliferation of backyard "receive-only" earth stations in a shared 4-GHz band is especially problematic. In this band, which is often used for TV distribution, each satellite receiver is entitled to interference protection, making it nearly impossible to coordinate new fixed-microwave links. And the practice of mounting satellite earth stations on moving ships has made band sharing all the more difficult, because these ship-borne systems can interfere with microwave towers when they operate near the coasts or on inland waterways.

When fixed-microwave interests go looking for higher frequencies to occupy, they must squeeze in around satellite applications, space research, navigation systems, radar, aeronautical applications, radio astronomy, and more. And some regulatory bodies have unintentionally exacerbated the spectrum shortage.

In the United States, the problem is this: In 1998, rather than expand the traditional system of having engineers coordinate things before a new license is even applied for, the FCC began auctioning off fixed-microwave licenses, at 28 and 31 GHz, and later at 39 and 24 GHz. Some winners of the early auctions paid tens of millions of dollars for a license. You might think they'd make good use of them, but it hasn't turned out that way. Many auction winners haven't constructed enough links to meet even their minimum requirements for license renewal. As a result, the FCC has since taken back many hundreds of these licenses, leaving the valuable radio spectrum they cover unavailable to anyone in those areas. Not surprisingly, the later auc-

tions of fixed-microwave spectrum brought in far less cash from bidders.

Regulators in the U.K. have tried fixed-microwave auctions as well, with no better results. The first auctions earned limited cash and saw little construction of facilities. Later auctions attracted even less interest from bidders and resulted in even less construction.

Why these auctions haven't produced better results is complicated. Part of the answer may be that the geographic areas being licensed, typically drawn around population centers, do not conform to any one company's actual needs.

A fixed-microwave link is typically just one small part of a complex network. Often that network is used to support other kinds of infrastructure—railroads, electrical grids, oil pipelines—for which the microwave links parallel the underlying assets. Networks that support other kinds of commercial operations tend to connect population centers with one another and sometimes with outlying branches of a business. When used for cellular backhaul, the microwave network will reflect the sometimes idiosyncratic layout of the carrier's facilities. And public-safety backhaul networks, used to relay emergency calls to local police and firefighters, conform to the boundaries of the local jurisdictions they serve.

These users all need highly customized configurations, not the arbitrary areas governments have used in auctioning licenses. But if regulators were to change the areas so that they did align with specific needs, they would each attract a single bidder, undercutting the rationale for auctions in the first place. It's a no-win situation.

So, you might be wondering, why can't one company secure the license for a region and then simply resell or lease out the appropriate microwave configurations to the organizations within the region that need them? Indeed, this model has been attempted, most notably by a San Francisco-based firm, FiberTower Corp. It won fixed-microwave licenses at 24 and 39 GHz and then sold backhaul services to Sprint and to a local county for 911 emergency calls, among others. But last year the FCC took back several hundred of FiberTower's licenses, soon after which the company filed for bankruptcy. Its clients, already skittish about not controlling their own facilities, scrambled to maintain their service. Carriers will probably now think twice before trusting their backhaul to a third-party provider.

In short, auctioning point-to-point microwave licenses just doesn't make much sense—except perhaps for a few very competitive corridors. Otherwise, it's better to let engineers coordinate these point-to-point operations, a system that has used the radio spectrum very efficiently ever since the radar engineers of World War II began turning their dishes into extremely reliable cables of air. ■

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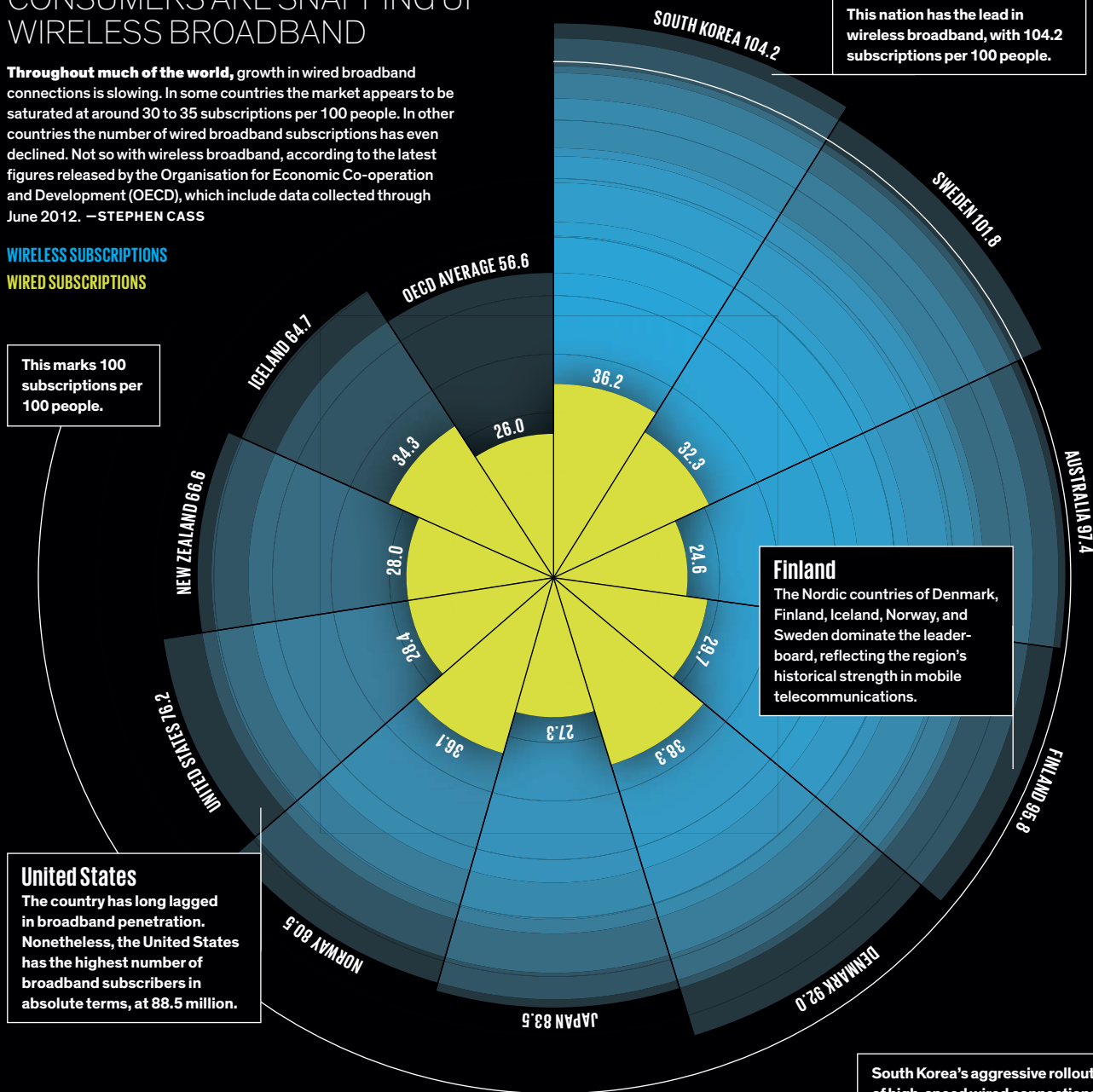
IT'S A MOBILE, MOBILE WORLD

CONSUMERS ARE SNAPPING UP WIRELESS BROADBAND

Throughout much of the world, growth in wired broadband connections is slowing. In some countries the market appears to be saturated at around 30 to 35 subscriptions per 100 people. In other countries the number of wired broadband subscriptions has even declined. Not so with wireless broadband, according to the latest figures released by the Organisation for Economic Co-operation and Development (OECD), which include data collected through June 2012. —STEPHEN CASS

WIRELESS SUBSCRIPTIONS
WIRED SUBSCRIPTIONS



SOUTH KOREA
This nation has the lead in wireless broadband, with 104.2 subscriptions per 100 people.

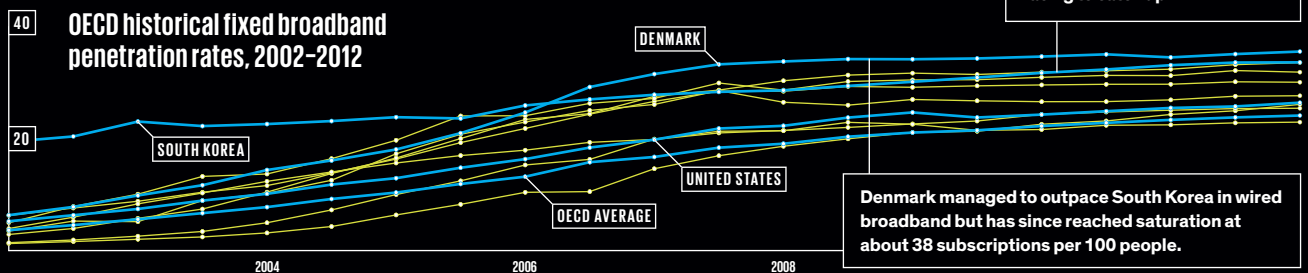
This marks 100 subscriptions per 100 people.

Finland
The Nordic countries of Denmark, Finland, Iceland, Norway, and Sweden dominate the leaderboard, reflecting the region's historical strength in mobile telecommunications.

United States
The country has long lagged in broadband penetration. Nonetheless, the United States has the highest number of broadband subscribers in absolute terms, at 88.5 million.

South Korea's aggressive rollout of high-speed wired connections worldwide left other countries racing to catch up.

OECD historical fixed broadband penetration rates, 2002–2012



Denmark managed to outpace South Korea in wired broadband but has since reached saturation at about 38 subscriptions per 100 people.

SOURCE: ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

INFOGRAPHIC BY Carl DeTorres