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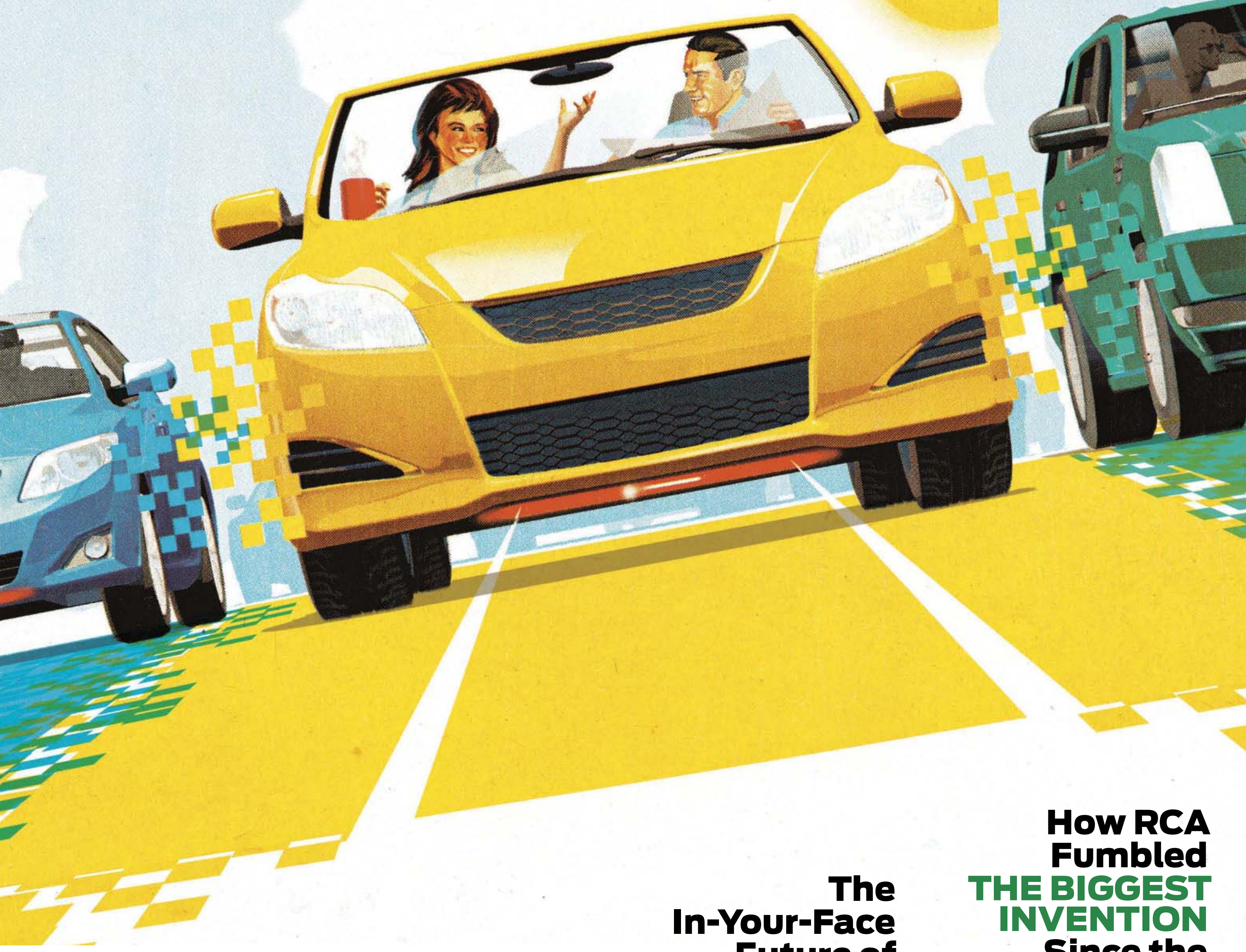
DRIVE MY CAR

CARS COULD CRUISE DRIVER-FREE RIGHT NOW—
AND YOU WOULDN'T NEED A SUPERCOMPUTER IN YOUR TRUNK



The In-Your-Face Future of **TELEVISED SPORTS**

How RCA Fumbled **THE BIGGEST INVENTION** Since the Cathode-Ray Tube

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Winner of the 2012 National Magazine Award for General Excellence

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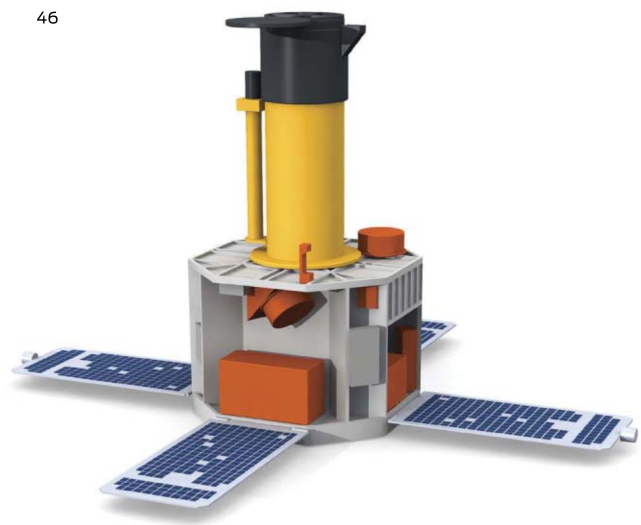

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COVER: TAVIS COBURN
THIS PAGE, CLOCKWISE FROM LEFT: VOLVO; MIKE EGERTON/AP PHOTO; JOHN MACNEILL

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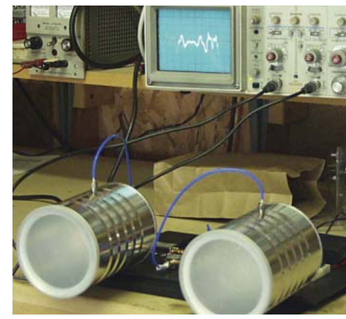
UPDATE

OPINION

DEPARTMENTS

SPECTRUM.IEEE.ORG AVAILABLE 1 NOVEMBER

Video: Make Your Own Radar



Would you believe that with two coffee cans and about $200 in electronic parts you can build a radar set that can measure speed and distance and produce crude synthetic-aperture images? You can indeed. The design originated at MIT's Lincoln Laboratory and is now being used to teach students about radar fundamentals. You wouldn't rely on this one to track enemy aircraft, but it's perfect if you just want to learn a thing or two about how radar works. Watch the video at *http://spectrum.ieee.org/diyradar1112*.

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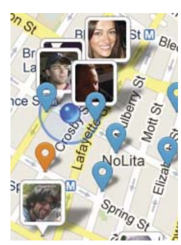
DO LOCATION-BASED SERVICES AFFECT TRUST?



Technology has given us a variety of ways to track the whereabouts of our friends and loved ones, whether it be through Facebook, Foursquare, or other location-based social networking apps. But what are the implications of such surveillance? IEEE researchers studied how these services affect trust in relationships.

STUDENT PROJECT SPOTLIGHT: NEUROGRID

IEEE Graduate Student Member Sam Fok and Stanford classmate Alex Neckar received the 2012 Qualcomm Innovation Fellowship for their work on a device called Neurogrid, which employs silicon "neurons" that mimic the way biological neurons function to perform calculations.

THE FUTURE OF CONSUMER ELECTRONICS

The IEEE International Conference on Consumer Electronics, to be held in Las Vegas in January, will look toward the future of artificial intelligence, home health, transportation, and more.

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back story

HYUNGSUB CHOI

Scanning the Past

IMAGINE YOU'RE A HISTORIAN and you discover, practically in your own backyard, a huge, untouched collection of original source material on a fascinating topic. Now imagine that, shortly after you discover it, the treasure trove vanishes.

Both things happened to Benjamin Gross when he was a second-year graduate student in the history of science program at Princeton University. On a chance visit to the David Sarnoff Library, a few kilometers from where Gross lived, he met the archivist, Alexander Magoun (now with the IEEE History Center). Magoun suggested that Gross look at the early history of the liquid crystal display.

In the 1960s, RCA had pioneered the LCD, transforming a laboratory curiosity into a commercial product. Incredibly, though, no historian had ever explored the library's vast holdings on the topic, which included the notebooks of nearly every RCA researcher who worked at the company's central labs. Gross could hardly believe his good fortune. The subject became the focus of his dissertation (and his article in this issue).

Then the other shoe dropped. In January 2009, not long after he "discovered" the archives, the library announced it would be closing—for good. Gross did the logical thing: He spent the next seven months photocopying and scanning every document he could. Eventually it became a full-time preoccupation. "Toward the end, I was there five days a week, from nine in the morning until five or six at night," he says.

The copied material now resides on his laptop and two backup drives, kept in widely separated locations—"because I'm paranoid," says Gross. He completed his Ph.D. last year and is a research fellow at the Chemical Heritage Foundation, in Philadelphia. The archives moved to the Hagley Museum and Library in Wilmington, Del., but aren't yet open to the public.

Meanwhile, the College of New Jersey, in Ewing, acquired the Sarnoff library's hundreds of artifacts, including some of the earliest picture tubes for black-and-white and color TV sets, one of the first blue light-emitting diodes, and the first commercial electron microscope. Gross is consulting on an exhibition that's in the works.

"New Jersey played a huge role in the history of the American electronics industry," he says. "People forget that. I'm glad the artifacts stayed nearby." ❑

CITING ARTICLES IN IEEE SPECTRUM

IEEE Spectrum publishes two editions. In the international edition, the abbreviation INT appears at the foot of each page. The North American edition is identified with the letters NA. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, The Data is in *IEEE Spectrum,* Vol. 49, no. 11 (INT), November 2012, p. 68, or in *IEEE Spectrum*, Vol. 49, no. 11 (NA), November 2012, p. 92.

contributors

NAZARETH BEDROSSIAN, MARK KARPENKO, and **SAGAR BHATT** detail their attempts to boost satellite performance in "Overclock My Satellite" [p. 46]. Bedrossian, a group leader for vehicle dynamics and control at Charles Stark Draper Laboratory in Houston, takes particular pleasure in projects that "people tell you can't be done." Bhatt was a Draper graduate fellow before joining its staff full-time in 2007. Karpenko is an assistant research professor of mechanical and aerospace engineering at the Naval Postgraduate School, in Monterey, Calif.

TAVIS COBURN credits *IEEE Spectrum* with turning him into "a bit of a car nerd" by hiring him to create illustrations for "The Greening of the Supercar," in 2010. He now reads car blogs every day and designs graphics for Formula One racers. He returns for this month's cover, drawing from classic 1950s auto ads. Coburn relies on an old film-positive printer to give his otherwise digitally produced work an "anticomputer" look.

ERIK COELINGH and **STEFAN SOLYOM** work at Volvo Cars, in Sweden, where they developed technologies for the platooning of cars, as they describe in "All Aboard the Robotic Road Train" [p. 26]. Coelingh conducts research in safety and driver support technologies and serves as adjunct professor of mechatronics at Chalmers University; Solyom specializes in autonomous driving technology. Coelingh says their collaboration aims at uniting the goals of safety and freedom by freeing the driver from driving itself.

DANIEL DERN is a freelance writer (and occasional science fiction author). He is a frequent contributor to *Spectrum*: In July he wrote about technology museums. For this issue, as someone who often needs extra power for his mobile gadgets, he tested out a number of rechargeable battery packs ["Portable Chargers for Your Mobile Gadgets," p. 22]. "It's not just if it works; it's about the usability," says Dern.

HOWARD POSTLEY is the chief technology officer of 3ality Technica, a company that designs products for 3-D sports broadcasting, which he writes about in "Sports: 3-D TV's Toughest Challenge" [p. 32]. This 35-year veteran of the computer, communication, and media industries is an avid beach volleyball player and sailboat racer, but he doesn't play American football—and he doubts any football fans would want to watch him in 3-D if he tried it.

WILLIAM SWEET, an *IEEE Spectrum* contributing editor, looks at the International Energy Agency's proposed "golden rules" for the controversial process of extracting gas from shale deposits [The Data, p. 68]. Sweet, the editor of our Energywise blog, frequently writes about energy, climate, and geopolitics. His recent work includes the e-book *Situating Putin: Why He's Not Going Away and How That Matters.*

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spectral lines

Unleash Your Inner Asimov

An engineer spending time at work reading fiction stories about the future—or worse, watching sci-fi movies—could upset, even anger, his or her manager. But what if there's a possibility that by engaging speculations about the future, engineers can enrich their capacities for creating designs and artifacts, in the here and now, of enduring value?

A small but growing cadre of savvy technologists argue that, at least in measured doses, encounters with imaginary worlds and futuristic devices could have a decisive influence on innovation. David Brian Johnson, Intel's staff futurist, even insists in a recent book, *Science Fiction Prototyping*, that by writing stories about future products, engineers can do a better job of actually making them.

Hold on. Isn't fiction escapist, a waste of an engineer's time?

It depends. Wernher von Braun, the pioneer of rocketry, was inspired by Jules Verne's stories of travel to the moon. Leo Szilard, who worked on the first atomic weapons, was inspired by H.G. Wells's *The World Set Free* (1914).

To be sure, the design for Apple's iPhone11 isn't likely to come from the pen of a storyteller. Yet recall that, in 1988, Apple made a promotional video that introduced an imagined tablet computer called the Knowledge Navigator, which even possessed a talking virtual assistant uncannily similar to the iPhone's Siri. Twenty-two years later—when the key components became small, cheap, fast, and smart enough—the fictional Knowledge Navigator morphed into the iPad.

The value of imagining future systems is partly promotional. Steve Jobs constantly spoke of building products people want but don't know they want. Sony's legendary founder Akio Morita often described the task of engineering in the same way.

Scholars of innovation, such as Clark Miller, an electrical engineer who coteaches a class with me on writing about the future, are keen to encourage engineers to embrace speculative fiction for noncommercial reasons. They say human values are sometimes not reflected in new gadgets and systems and that engineers can better account for the "human dimension" in their work if they imagine what the world would be like—and what adaptations people would have to make—if their inventions came into widespread use.

So how might engineers begin to bridge, through fictions about the future, the divide between human aspiration and the machines and systems they conceive, design, and create?

The short answer is for engineers to write stories or create videos of their own. Here are three easy steps to getting started:

Shrewdly read short fiction (much quicker than novels): Stick to the "hard" stories about the future that engage the everyday issues of engineering. Avoid the popular fantasy species of science fiction, which is dominated by improbabilities and ruled by magical thinking. For guidance, look to David Hartwell and Kathryn Cramer's annual anthology of stories that feature vexing questions about plausible future devices and alternative technological systems. A weightier volume is *The Wesleyan Anthology of Science Fiction*, which contains 52 short stories published from 1844 to 2008.

Imagine a revolutionary gadget that could plausibly be designed and built and inject it into the world as we know it today. Focus on a single character's struggles to cope with the invention, maybe the inventor himself. For an example, watch the film *Limitless* (2011). The lead character discovers a new drug that enhances cognition so dramatically he risks all to keep it to himself.

Choose your medium. Given the advances in multimedia, producing short documentaries and animations is faster, easier, and cheaper than ever. After writing a rough draft, turn it into a visual experience. For inspiration, read the delicious tale "Rogue Farm" (2003), about agro-technology gone amok, and then view the 25-minute animated version created by Scottish TV in 2005.

In the end, when engineers confront and create fiction about the future, they face their own hopes and fears, appetites and longings. More than any work of art, the value lies in this encounter with the unknown.

—G. Pascal Zachary

G. Pascal Zachary is professor of practice at the Consortium for Science, Policy & Outcomes at Arizona State University and a frequent contributor to IEEE Spectrum.

BRIDGET COLLINS

update

more online at spectrum.ieee.org

The Lessons of Thailand's Flood

The hard drive industry shows that responding to disasters can be more important than preventing them

Tawan Suppapunt stands outside the wall of the main building at Western Digital's Bang Pa-In factory, where he is managing director of hard disk drive operations, pointing to a blue line above his shoulder. The line marks the high-water point—1.8 meters from the ground—of the October 2011 flood that devastated this part of southern Thailand. Floodwaters inundated this plant, the surrounding roads, and many other factories in the region for more than a month. Outside the country, the severe shortage of hard drives caused prices to spike and put a big dent in the profit of global PC, chip, and memory companies.

In the past year, the industry has regrouped and rebuilt—faster and more successfully than analysts expected—and is now enjoying higher profit margins than before the flood. *IEEE Spectrum* visited Thailand in August to see how companies like Western Digital managed to rebound.

Thailand is a tropical country with annual monsoons, but nearly 2 meters of water was well beyond most factories' flood prevention plans. When the rain started, Western Digital organized teams of factory workers to fill and stack sandbags around the perimeter of the plant. But it soon became clear that these would be no match for what has been described as a once-in-a-century event. "We were pumping water, and when the amount coming in was more than we could pump out, that's when we knew we were doomed," says Joe Bunya, a Western Digital senior vice president.

Thailand assembles about 40 percent of the world's hard

WASHED AWAY: Workers at Western Digital scrub away the residue of a 2011 flood that inundated this hard drive factory and hobbled the global PC industry.
PHOTO: WESTERN DIGITAL

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update

drives, and if you account for drive component manufacturing, it's the global leader, according to Fang Zhang, a storage analyst at market research firm IHS iSuppli. Seagate was the first company to bring some of its hard drive manufacturing to the country, in 1983, and as it built up a local network of specialized part suppliers and workers, others soon followed. It's now such an important industry to the country that multiple Thai universities offer curricula designed by hard drive manufacturers to replenish their engineering workforces.

This clustering of a highly specialized industry has become common in the global trend toward lean supply chains and just-in-time manufacturing. Companies can save costs by minimizing the components they store in inventory and minimizing their distance to suppliers. "We encouraged suppliers to be nearby so that cycle time was shorter and there was less inventory," says Bunya. For example, Donaldson, a filter company, employs hundreds of workers at a nearby plant that produces only the tiny air filters that collect loose material inside drive enclosures. That facility, along with many others, also went underwater.

DRIVE DIVE: Thai Navy divers were called in to salvage disk drive manufacturing tools. Their efforts contributed to a quick recovery.
PHOTO: WESTERN DIGITAL

Losing so much of the hard drive supply chain meant the flooding had an international impact. "It was very painful during the flood because we actually hurt a lot of our customers," says Bunya. PC makers didn't have enough stockpiled drives to wait out the flood, so by early 2012, they had to start limiting shipments. Dynamic RAM manufacturers, which were already outpacing demand, were further hurt by the dip in PC sales.

Still, the industry managed to recover much faster than analysts predicted. Western Digital's first hard drive rolled off the line just 46 days after the flood; it took another couple of months before the plant was back to normal capacity. The quick recovery didn't come cheap: Western Digital puts the total cost "in the hundreds of millions of dollars." But it seems to have paid off. By the time Suppapunt gave *Spectrum* a tour, thousands of young women were again loading and unloading hard drives into assemblers like clockwork every 11 seconds.

In interviews with more than a dozen manufacturers, it became clear that successful recovery required quick improvisation beyond the insufficient contingency plans most companies had on file. At contract manufacturer Benchmark Electronics, employees fabricated rafts from sheet metal they had on hand to float inventory out of the facility. Instead of waiting for water levels to recede, Western Digital brought in divers to retrieve submerged equipment. Each recovered machine was disassembled, decontaminated, and reassembled. Eventually, 80 percent of the damaged machinery was restored, estimates Sampan Silapanad, vice president of the plant's magnetic-head operations.

Western Digital has taken basic steps to prevent future flood damage by building a 3-meter-high wall around the campus and moving all essential manufacturing equipment off the ground floor. But the company hasn't made major changes to its larger manufacturing strategy. Despite diversifying some production—it recently started manufacturing at a facility in Penang, Malaysia—the company isn't eager to give up the benefits of the Thailand cluster. "There's no perfect location, no matter how you measure," says Michael D. Bennett, a consultant at Jones Lang LaSalle, in Chicago, who helps companies select sites for new facilities. If lots of other factors are favorable—labor supply, tax policies, infrastructure, and so on—then "it's a no-brainer" to spend money to protect the existing investment, Bennett says.

Western Digital and its largest rival, Seagate, were both fortunate that reduced production from the flooding had a silver lining. The recovery expenses have been partially offset by inflated hard drive prices, which "have not dropped to preflood levels since," says Thomas M. Coughlin, a data storage consultant. According to IHS iSuppli, both companies have seen gross profit margins go from around 20 percent before the flood to around 30 percent.

—Joshua J. Romero

Editor's disclosure: Travel and accommodations were provided by the Thailand Board of Investment.

7.7% Proportion of rear-end car collisions that would be prevented by a combination of three radar-enabled technologies, according to engineers at Virginia Tech

Can Japan Phase Out Nuclear Power?

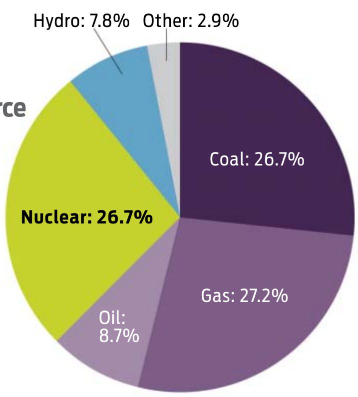
The country wants to go nuclear-free, but many obstacles remain

Before the Fukushima Dai-ichi nuclear accident of 2011, Japan was the third largest producer of nuclear power in the world. Its 54 reactors had a capacity of about 50 gigawatts. Now the Japanese government is contemplating whether it can scale down from 50 GW to zero by 2040 without crippling its economy in the process.

A government policy paper released in September called for the elimination of all nuclear power by 2040, and public opinion polls have shown that the majority of citizens favor a phaseout. But the matter is far from settled: The policy paper elicited strong protests from business groups, and consequently the Cabinet, the executive branch of Japan's government, declined to endorse the zero-nuclear goal.

Here are the sticking points in the ongoing debate over whether Japan can eliminate nuclear power.

Japan's electricity generation by fuel source—2009



Source: International Energy Agency, "Energy Balances of OECD Countries," 2010 edition

How to Phase Out Nuclear

After the Fukushima disaster, all the country's reactors were shut down for safety checks, and only two have been allowed to resume operations. The government has assumed that many more will be declared safe and restarted despite local opposition.

The government's September policy paper proposes two rules regarding nuclear power: It suggests a maximum 40-year life span for all reactors and states that no new nuclear construction should be permitted. Sticking to those two principles, the phase-out can be done largely by attrition, says Yugo Nakamura, a Tokyo-based analyst for Bloomberg New Energy Finance. "Assuming that all the reactors retire after 40 years of operation, then as of 2040 there will probably be only five reactors still up and running," he says. And with only 40 years to recoup a huge investment, even if there was no ban on construction, there'd be no money to be made in building new reactors, he adds.

False Hopes for Energy Conservation?

The government is expected to call for an overall reduction in electricity use: One policy document, issued in July, assumed usage of 10 percent below 2010 levels. Yet thus far the government has released no detailed proposals.

The nation did respond well to the government's call for voluntary cuts in electricity use throughout the past two summers, when energy use peaks. But David Rea, a consultant with the firm Capital Economics, argues that conservation may not be a viable solution. The main reason Japan made it through without shortages last summer was "weakness in the economy," he wrote in a recent report. Therefore "a false picture was created of whether a prospering, growing Japanese economy can exist without nuclear power."

Imported Fossil Fuels

When Japan's fleet of nuclear reactors shut down, the nation's utility companies fell back on power plants fired by coal, oil, and natural gas to provide base-load electricity. These power stations have kept the lights on, but at a cost; some utilities have already raised electricity prices to pay for fuels, which are mostly imported. If Japan shifts away from nuclear, fossil fuels are expected to fill the gap. The government has suggested that utilities decrease the share of coal and increase the share of natural gas to keep carbon dioxide emissions down.

Can Renewables Ramp Up?

Japan's biggest energy challenge is scaling up its renewable power sector in a hurry. In 2009, renewable energy supplied 11 percent

TOP: ISTOCKPHOTO; CENTER: RIE ISHII/AFP/GETTY IMAGES

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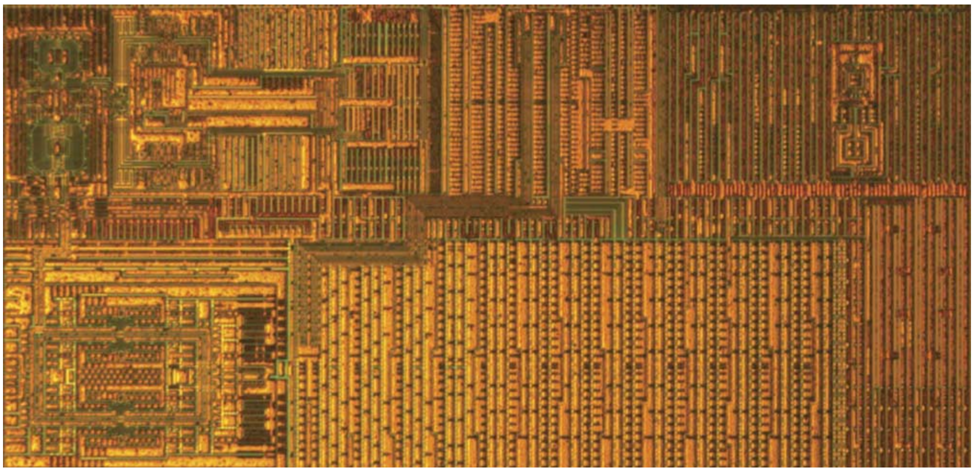
of the country's electricity, with most of that coming from hydroelectric stations. The government made a start on boosting this fraction last year when it passed a feed-in tariff law to guarantee profitable electricity prices for renewable energy projects; early indications are that this law is stimulating new investments. Andrew DeWit, a professor of economic policy at Rikkyo University, in Tokyo, says that in just two months, applications were filed for 72 680 renewable projects totaling 1.3 gigawatts. Most of these projects are small rooftop solar installations, but a few are utility-scale solar or wind farms.

Japan has been slow to develop its solar, wind, and geothermal resources in large part because the energy sector is dominated by the "Big 10" regulated utilities, which had invested heavily in nuclear. But DeWit says that every time a local government or bank funds a renewable energy project and benefits from the new tariff law, pressure grows to deregulate the industry. "It's giving them incentives to push for restructuring of the power sector, because they're invested in so much [renewable] capacity," he says. The government is now discussing how to "unbundle" the generation and transmission sectors to make conditions more favorable for renewable energy. —Eliza Strickland

Wi-Fi Radio Takes a Digital Turn

Intel's new transceiver pushes RF circuitry further into the digital realm, but will it make it out of the lab?



RADIO REDUX: Intel has redesigned a Wi-Fi transceiver to use mostly digital components. *IMAGE: INTEL*

Are analog circuits on their way out? Granted, nature is analog and so, too, are the circuits that drive wireless communication. But analog devices are generally harder to miniaturize and have slowly been ceding ground to digital components. An experimental new radio chip developed by Intel could signal that the trend is accelerating.

The new radio, a Wi-Fi transceiver that Intel says is constructed mostly of digital components, debuted in September at the company's annual developer forum in San Francisco. Intel calls the technology a "Moore's Law radio," for its potential to take advantage of digital circuitry's famed miniaturization trend. Ultimately, the technology could lead to smaller, slimmer portable devices, by integrating a smartphone's radios and processors on a single sliver of silicon. But when that will happen and what sort of impact it will have on products is still unclear.

There's good reason why this chipmaker's fantasy of an essentially single-chip smartphone has yet to be realized. Radio-frequency circuits are especially sensitive to design changes, and the properties of analog components like inductors don't improve as the devices get smaller. As a result, analog chips tend to lag behind their all-digital counterparts by a couple of manufacturing-process generations, which means that their features are much less fine.

Transforming analog radios—or at least some of their components—into digital radios could potentially bridge that gap. And over the years, digital circuits have taken over a bit more of the analog realm. The poster child for this trend is the phase-locked loop, a core signal-processing circuit that is now constructed from digital components.

To make its Wi-Fi transceiver, Intel says it had to go back to the basic mathematics of radio communications. "It's not just a replacement of analog components," says Yorgos Palaskas, who leads Intel's radio integration lab. "It has to be done differently." In the transmitter, for example, information that might

update

otherwise be processed as RF signals is kept in the digital domain until the signal is amplified and goes out on the airwaves. Information on the intended amplitude of the signal is encoded in the timing of when the digital signal switches between 0 and 1.

Intel's new Wi-Fi radio isn't entirely digital yet, Palaskas notes. Some components are still analog. The design also isn't optimized for area and consumes a little more power than a comparable analog transceiver might.

"But the important point about the digital architecture is that it will scale moving forward," Palaskas says. The radios "will get better and better with every single generation." At Intel's developer forum, he noted that a jump from a 90- to a 32-nanometer manufacturing process reduced one transceiver component—a frequency synthesizer—to a quarter of its size while cutting the power consumption from 50 milliwatts to 21 mW.

Intel made an impression when it presented details on core components of the radio at the IEEE International Solid-State Circuits Conference earlier this year. "There's no question from a technical standpoint that they're very novel," says IEEE Fellow Robert Staszewski, an associate professor at the Delft University of Technology, in the Netherlands. Staszewski was previously chief technology officer of Texas Instruments' Digital RF Processor Group, which developed digital radio components that could be integrated with basic cellphone processors.

Intel's radio could potentially play well alongside the more advanced digital processors for today's smartphones. The company previously demonstrated a chip code-named Rosepoint, with two Atom cores and a Wi-Fi radio with more analog components than the one presented in September. But such integration might not be in the digital radio's immediate future. Intel CTO Justin Rattner says the new radio technology may first emerge piecemeal in future radio chips.

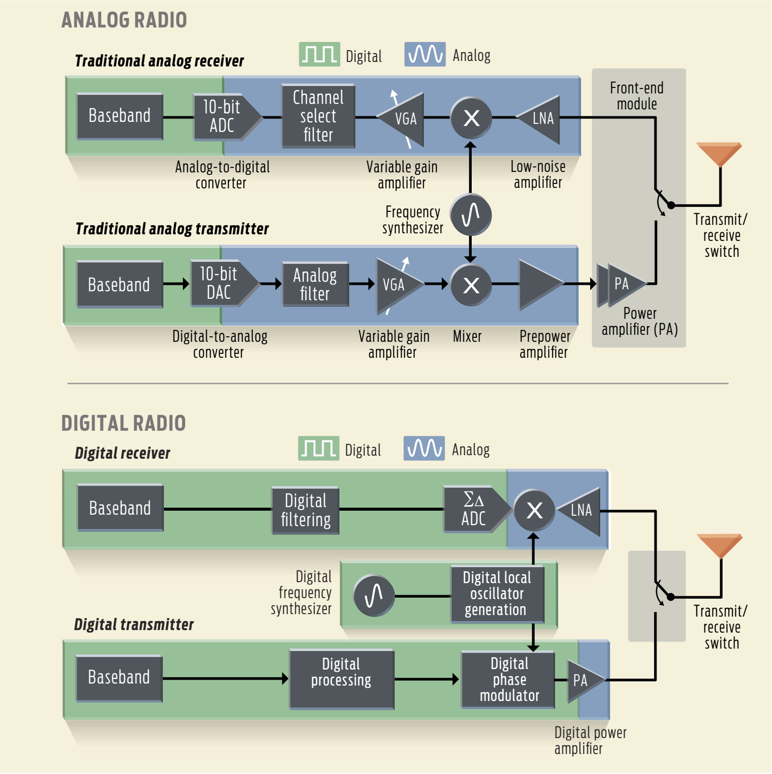
Bringing processors with full digital radios to the market may have more to do with economics than technology. Initial development costs could be higher, and RF standards are less forgiving when it comes to inevitable variations in manufacturing, says Waleed Khalil, an assistant professor of electrical and computer engineering at Ohio State University. Digital processors that underperform can be set aside and sold for less. But with RF, if you have "a very small degradation in performance, nobody will buy your products," Khalil says. Consumers may have to pay a considerable premium for more tightly integrated chips.

At the same time, analog radios are still very much in the running, says Mark Hung, a research director at Gartner. Although analog design takes longer, he says, so far chipmakers have "always been able to come up with new tricks to get it to scale."

Still, Staszewski says Intel's entrance into digital radio could very well inspire a change in the industry. Both analog and digital designers tend to stay firmly committed to their respective camps, he says, and so the industry has just been inching its way toward digitization. "I think Intel is the proverbial 800-pound gorilla," he says. Sometimes when a giant starts doing something, he says, "then everybody will follow suit."

—Rachel Courtland

MOVING BOUNDARY: To create its new digital Wi-Fi transceiver, Intel had to redesign core radio components that are traditionally made from analog circuits. Intel's new transceiver is an approximate match of the digital radio schematic [bottom]; it still includes some analog-based filtering in the radio's receiver.
DIAGRAM: GEORGE RETSECK



1873 TERAWATTS Maximum amount of high-altitude wind energy that can be extracted, according to scientists in California. Get your kites out!

Navigating the Great Indoors

The smartphone industry is gearing up to get you around when you're out of sight of GPS satellites

GOOGLE, DUMPED by Apple as the iPhone's default navigation app, is doing more than chortling at Apple's well-documented mapping troubles. It's fighting back with more navigation features, many likely intended for use indoors. And a number of major mobile device makers and cellphone service providers have teamed up to develop a standard for indoor navigation, an effort that neither Google nor Apple is part of.

Indoor navigation technology is going to be quite a bit different from its outdoor counterpart. Outdoors, navigation relies for the most part on GPS, whose accuracy ranges from 1 to 10 meters. Indoors, because of attenuation and scattering, GPS falls apart. And even outdoors, GPS is vertically challenged; it's about one-third as accurate at pinpointing your elevation as it is at telling where you are on the ground. In other words, even if you do get a signal inside, it's unlikely that GPS will have any idea whether you're trying to navigate the first, second, or third floor of your local shopping mall.

So indoor navigation, while relying on GPS to identify your general location (at the mall, at the airport), needs some other technology to get you around. Google's My Location technology uses nearby cellphone towers for identification when GPS is not available. Although cellphone signal triangulation offers some help indoors, it's not very precise. So increasingly, indoor navigation systems like My Location are supplementing cellular signals with information from Wi-Fi hot spots. It will, however, take time to map venues with information about the comparative strength of Wi-Fi signals at different points. Some proposals would add locator beams that use Bluetooth, WiMax, or other radio standards around indoor venues to help update or correct the system's understanding of your location.

INSIDE OUT: STMicroelectronics and others want smartphones to get you around in malls and other indoor spaces.
IMAGE: STMICROELECTRONICS

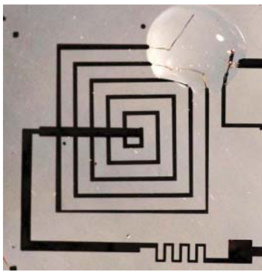
Still, even with all those radio signals, knowing exactly where a mobile phone user is standing in a crowded mall is tricky. So developers are starting to incorporate information from sensors within the phone, like gyroscopes that determine direction, accelerometers that count steps, and even atmospheric pressure sensors to provide an estimate of altitude.

Benedetto Vigna, executive vice president and general manager of the analog MEMS and sensors group at STMicroelectronics, says that the sensor plus radio approach, in which you "basically trust the sensors in the system and once in a while check in with a wireless signal" is the way to go, because it reduces power consumption compared with an approach that relies on constant radio signal access. Mike Stanley, a systems engineer at Freescale Semiconductor, agrees. It may not seem like much, he says, but "powering up a radio once a second instead of constantly stretches battery life." Of course, both companies make the MEMS sensors needed for such navigation, so they have a stake in such a scheme's success. But considering the minuscule electrical requirements for, say, a 3-axis gyroscope—about 6 milliamps—it's a good argument.

While this sounds like a lot of technology to throw at something that's needed only occasionally, the good news is that most of today's smartphones already come fully loaded with much of the necessary hardware. The Samsung Galaxy S III, Vigna says, has all the sensors, and most other phones are just missing the pressure sensors. So, for the most part, it's just a question of getting the software to the phones and collecting additional data, like the location of Wi-Fi hot spots, from indoor venues.

Of course, it would help if these systems were standardized, so that folks with iPhones could go to the same malls as folks with Androids. But while real standardization is not likely anytime soon, indoor navigation is indeed arriving. "I had expected a boom in 2013 or 2014," says Stanley, "but it is happening already." —TEKLA S. PERRY

Portions of this article appeared in IEEE Spectrum*'s Tech Talk blog in September. Yu-Tzu Chiu recently tested STMicroelectronics' technology inside a Taipei museum. She reports the results on* Spectrum*'s website.*



news brief

Dissolving Electronic Implants

Researchers at the University of Illinois at Urbana-Champaign and Tufts University, in Boston, say they have invented functional electronic implants that can dissolve after specified time periods. Researchers encased electronics made of nanometer-thick ribbons of silicon in silk that was modified so it would break down predictably. A conventional silicon chip would take centuries to dissolve in body fluids, but the silicon nanoribbons are gone in weeks.

TOP: ISTOCKPHOTO; RIGHT: BECKMAN INSTITUTE/UNIVERSITY OF ILLINOIS


MARATHON

the big picture

Swimming in Circuitry

It used to be that you went to the beach to get away from it all. But these technophiles, hanging out at Virgin Media's high-tech beach hut at Beach Green in Shoreham-by-Sea, England, have so much electronic gear at their fingertips that the sun and the surf might be an afterthought. In addition to the iPad he's using to surf the Web and the audio player she's enjoying, the 3- by 2.4-meter hut comes equipped with a suite of gadgets including a Samsung Smart TV with 3-D, a wireless sound system, a Microsoft Xbox and Kinect, a home weather station, and a wind-powered lighting system.

PHOTO: REX FEATURES/ AP PHOTO

hands on

FIELD TESTS: Ranging is done in place, but for imaging the gear must be moved laterally [inset]. *PHOTOS: GRACE SCHNEIDER*

COFFEE-CAN RADAR

How to build a synthetic-aperture imaging system with tin cans and AA batteries

As I stand on the side of the road, a couple of joggers stop to ask about the two coffee cans sprouting coaxial cables. "I'm testing a home-brew radar," I explain, adding as they jog off, "you're showing up just fine." It reminded me of an old "Star Trek" episode in which Mr. Spock is transported back in time and must construct a futuristic electronic gadget using only 1930s-era vacuum-tube technology. "What on earth is that?" asks his landlady. "I am endeavoring, ma'am, to construct a mnemonic memory circuit using stone knives and bearskins," he answers.

Leonard Nimoy's wry delivery reflects how I felt trying to turn two coffee cans, eight AA batteries, and a few hundred U.S. dollars' worth of mail-order parts into a synthetic-aperture radar (SAR). Such sophisticated radar systems provide information about the shape of objects they scan, and high-resolution SAR can produce images with photographic levels of detail.

I succeeded, but credit goes to Greg Charvat, who designed this startlingly simple hardware while working at MIT's Lincoln Laboratory in order to give students some hands-on experience during a three-week radar course. A detailed description of the radar and how to build it is available at MIT's open courseware website.

Having little experience with radio frequency circuitry, I worried that this project might be too challenging. Ironically, the RF section was the easiest part to construct. It merely required screwing together a few microwave components. And as long as you follow the prescription in the lecture notes exactly, you won't need a network analyzer to match the antennas to the radar circuitry.

Most people's mental picture of how radar operates is that the apparatus gives off a radio pulse and then waits to receive an echo, timing how long it takes to return. Dividing by the speed of light gives the round-trip distance to a target. Some radar sets do just that, but this one uses a different strategy: One antenna emits a continuous stream of waves while the other receives a continuous stream of echoes. The circuitry for this isn't complicated, but interpreting the received signals requires some computational horsepower.

The key to this design is that the frequency of the outgoing radio waves increases linearly over time (for a short period, after which the cycle repeats), so the frequency of the reflected waves also increases linearly. But the reflected waves return to the receiving antenna after a short delay, by which time the waves being emitted are at a slightly higher frequency. The farther away the target, the greater the difference between these two frequencies.

To measure this difference, you use what radio engineers call a mixer, which here generates an output signal containing two new frequencies that are the sum and difference of the transmitted and received frequencies. Only the difference matters for this application, so the radar circuitry filters out the high frequencies, including the sum, and amplifies what's left. This final signal is in the audio frequency range and can easily be recorded using a computer's sound card—much more practical than trying to build a system that works directly with microwave frequency signals throughout.

I first set up the radar next to my garage and recorded about a half minute of data as I ran up and down the driveway. I captured that data with Audacity, a free audio editor, running on an old desktop PC that had a sound card with a line-in port. I analyzed the recording using a Matlab script provided by the instructors at MIT. Running the script proved a challenge, though, because Matlab was too pricey for my shoestring budget. But I found a free open-source alternative that served as a reasonable stand-in: Octave.

It took about 4 minutes to process the data, but it was worth the wait: The script transformed subtle changes in the audio signal into a zigzag plot that matched my back-and-forth movements. Wow!

I was eager to put the radar to more of a test. But a desktop computer is awkwardly immobile. And, like many laptops, none of mine are capable of recording in stereo (two channels are needed to capture both the radar signal and the sync pulses). Happily, I discovered that my digital sound recorder, a Zoom H4n, could operate as a USB audio interface, allowing any laptop to record in stereo.

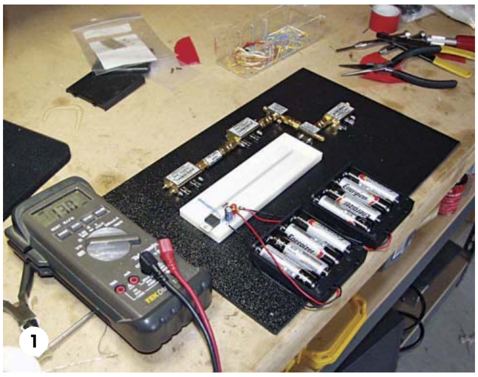
I took the radar out to a nearby ball field, where I discovered that it was surprisingly sensitive: Without difficulty, it could track me running to at least 50 meters away, and it can follow vehicles out more than 100 meters. It can even measure ranges in real time, if you use Python code written by Gustavo Goretkin, an MIT student who took the build-your-own radar course when it was first offered in 2011.

After having established that my coffee-can radar could measure the range to various targets, I set about to create a SAR image, which requires moving the radar laterally 5 centimeters at a time and recording multiple "snapshots." This took some doing. It was a big challenge just to reproduce the example image provided with the courseware. That's because the Matlab script for processing SAR data caused a pesky out-of-memory error in Octave. The problematic operation turned out to be a matrix rotation, so I had to do some hacking to get around that.

My initial attempts to create a SAR image produced underwhelming results. But when I looked harder at the images the folks at MIT produced, I realized that I would have to find a really big target for this to work. So I selected a building-size water tank that I could scan from a balcony located about 40 meters away. That exercise produced a plot with a clear radar hot spot located at the right distance and location. Calling that an "image" might be a little generous, but, well, what do you want from not much more than stone knives and bearskins?

—David Schneider

Watch the video at http://spectrum.ieee.org/diyradar1112



MAKING MICROWAVES: The prepackaged radio-frequency components simply screw together [1]. Constructing the coffee-can antennas is similarly straightforward [2]. Adding some simple analog circuitry to a protoboard completes the assembly [3]. An oscilloscope shows the system sensing reflections [4], but extracting useful information from the signal requires computer processing.

PHOTOS: DAVID SCHNEIDER

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film

SINGULAR SUBJECT: Ray Kurzweil believes in an unimaginable future.
PHOTO: MARK WOLOSCHUK

THE SINGULARITY

Will humans and machines merge?

WILL TECHNOLOGY so radically alter human existence that it is literally impossible to imagine what life will be like in the 22nd century? Ray Kurzweil and a contingent of like-minded thinkers believe so, and that beyond the so-called singularity lie advances in nanotechnology and biotechnology that will reengineer our environment and ourselves at a fundamental level, and perhaps even eliminate death.

Then there are those who believe that this vision is little more than wish fulfillment. Doug Wolens's latest documentary, released 1 November, captures the argument between the two sides. *The Singularity* takes the form of a series of intercut interviews, with animations illustrating various points (intentionally or not, they're a little reminiscent of how entries in the fictional *Hitchhiker's Guide to the Galaxy* were depicted in the classic BBC television adaptation).

Wolens's subjects include, unsurprisingly, people like Kurzweil himself, roboticist Cynthia Breazeal, and gerontologist Aubrey de Grey. But Wolens also interviews people not normally associated with the speculative edge of artificial intelligence and biomolecular engineering, such as Richard A. Clarke, the former chief counterterrorism advisor to the U.S. National Security Council, and the current U.S. secretary of defense, Leon Panetta.

Kurzweil's core argument is that the exponential development of information technologies will reach a critical inflection point within the next few decades, blurring the distinction between machine and human intelligences. His opponents accuse him of glossing over significant issues—such as the complexity of the brain—that limit both the value of an exponential model of progress and the desirability of the technologies Kurzweil espouses.

These skeptics include *IEEE Spectrum*'s own executive editor, Glenn Zorpette, who makes a couple of brief appearances in the film, but it is environmentalist Bill McKibbon who emerges as the most forceful critic. His frustration with Kurzweil's counterargument—that some people just don't get exponential growth—is palpable.

While *The Singularity* doesn't cover a great deal of ground that's new to anyone already familiar with the concept, it does provide crisp snapshots of the current state of the debate and many of the main players. What also becomes obvious is that the players shown, on both sides of the divide, appear to be exclusively white. I don't believe this is racial bias on Wolens's part—when compiling our own June 2008 special issue on the singularity, *Spectrum*'s editors noticed a similar demographic dominance. It does, however, raise a question: Why is an issue so potentially critical for the entire human race of interest only to such a narrow group of people, globally speaking? Is the pursuit of such speculative lines of query an issue of privilege? Or is the singularity a concept that non-Western cultures don't find engaging?

While this question will have to be answered another day, *The Singularity* remains a lively introduction to an extreme vision of our technological destiny.

—STEPHEN CASS

The Singularity. *76 minutes. Directed by Doug Wolens. DVD and Blu-ray available from http://www.thesingularityfilm.com. Downloadable edition available from iTunes on 15 November.*

profile

SEA POWER: Allan Robinson develops highly reliable submarine turbine systems that generate electricity from the tides.
PHOTO: SEAN AND YVETTE PHOTOGRAPHY

ALLAN ROBINSON

An engineer taps the tides with cutting-edge energy systems

THE TIDES may be predictable, but for an engineer testing and developing some of the world's first commercial-scale tidal turbines, conditions can be more than a little unpredictable. Just ask Allan Robinson, a senior electrical engineer at OpenHydro Group, a leading tidal power company based in Dublin.

Robinson recalls one afternoon last March, when he was putting a turbine through its paces at an offshore test site near Scotland's Orkney Islands. He and his colleagues were working on an elevated platform, installing power-metering equipment for the massive turbine that was whirling grandly beneath the waves, when they received word of an incoming gale. They had 20 minutes to evacuate before high seas would have forced them to spend the night on the cold metal platform.

Corrosive seawater and marine organisms are tough on electronics, and Robinson says that's what makes this line of work so interesting. Because going out to visit a turbine at sea is expensive, the company designs systems that require as little servicing as possible, says Robinson. "We need to have high reliability and high redundancy for all the critical components."

While a few experimental tidal power stations have been built in past decades, a number of companies are now racing to develop durable turbines that can be deployed in "tidal farms." OpenHydro, founded in 2005, is at the forefront. For engineers like Robinson, it's a chance to invent a new industry. "We're doing things that no one has ever done before," he says.

Robinson, a Canadian, came into this field after collecting one bachelor's degree in mechanical engineering and another in electrical engineering, with a focus on power and control systems. After completing his studies, he worked for a marine power company in British Columbia, Canada, for more than five years. In 2010, OpenHydro recruited him and moved him to Ireland to help with the company's R&D on turbine control systems and grid connections.

OpenHydro's system is invisible from the surface. Its massive turbines—at 16 meters in diameter, they have open centers to let fish swim through—rest on the seafloor. Power is sent back to shore with submarine cables.

Robinson tests these cutting-edge turbines and their control equipment in saltwater pools at the company's engineering center in Greenore, Ireland.

The company has begun its first commercial deployment off the coast of Brittany, France, where the first of four 2.2-megawatt turbines was being installed at press time. Other tidal farms are in the works around Britain's Channel Islands. "We're still at the early stages of the tidal power industry," says Robinson, but for an engineer who doesn't mind a little excitement, unpredictable conditions are just fine.

—ELIZA STRICKLAND

tools & toys

PORTABLE CHARGERS FOR YOUR MOBILE GADGETS

Power sources that balance complexity, convenience, and capability

THE BATTERIES in your smartphone, Bluetooth headset, tablet, and pocket digital camera are usually good for a full day—unless you're using them a lot. Then, finding an AC outlet can be critical. There are a plethora of outlet-free solutions, and because the mobile electronics industry is finally making USB the standard for charging, third-party companies have been encouraged to innovate. Even Apple, which has eschewed USB sockets on its mobile products in favor of its own designs, uses a standard USB connector at the cable end that plugs into a computer or charger.

If you need to charge a tablet—the iPad can require up to 2100 milliamperes of current, roughly double what a smartphone requires—the field is narrowed significantly. Happily, there are tablet-class rechargeable power packs aplenty, with a variety of sizes, weights, capacities, and features. Here's a look at a few that run the gamut.

First up is Innergie's 3000-milliampere-hour **PocketCell** (US $80, pictured in [1], opposite page), a slim battery about the size of a pack of gum that's still capable of delivering 2100 mA. It comes with the company's distinctive **Magic Cable Trio**, a three-in-one USB cable (also shown in [1]; $20 if bought separately), which combines a mini USB, a micro USB, and a 30-pin Apple connector, cleverly hinged to avoid those all-too-easy-to-lose tips or having to carry three separate cables.

(As a reference point for this and the other packs below, with a 3000-mAh-capacity battery I was able to fully charge my iPhone about one and a half times.)

The Trio cable is only about 20 centimeters tip to tip, so it can include the micro USB connector and still carry iPad-level power at the correct voltage. If you're trying to pack as lightly as possible, the PocketCell is a good choice.

If you think you're going to need a little bit more juice (heavy tablet users, this means you), there's Targus Group's **4800-mAh backup battery for iPad** ($60, [2]). At 17 by 67 by 112 millimeters—slightly bigger than a deck of cards—the Targus packs a good amount of power into a nice, flat shape.

The **myCharge Peak 6000** ($100, [3]) incorporates USB, micro USB, and 30-pin Apple plugs on short, permanently attached cables that fold neatly into slots on the front and sides. Storing up to 6000 mAh, it can be charged from an outlet via a set of fold-out prongs or via a USB port or AC adapter. A distinctive feature is its voice alerts, issued when you plug in to charge or connect a gadget.

At 25 by 75 by 133 mm and 240 grams, the Peak might not be something you'd throw into your pocket (unless you're wearing a fishing vest). But it would go easily into whatever you're carrying your tablet in—and you've now got enough power for a tablet (the latest iPad has batteries that store up to 11 700 mAh, so if you have one of those, you'll only get about a half-charge), a smartphone, a Bluetooth headset, and maybe something else.

Satechi's **10 000-mAh portable energy station extended battery charger pack** ($60, [4]) packs an even bigger charge into a compact package and has two USB charging ports—a 2000-mA port suitable for iPads and other products and a 1000-mA for everything else. The Satechi unit is smaller and lighter than the myCharge Peak—19 by 50 by 140 mm and 210 grams (but that doesn't include cables or an AC charger)—but it's still a little bulky for a pocket.

Unfortunately, the Satechi unit comes with a series of six easy-to-forget-or lose adapter tips. Unless you need a proprietary connector that matches one of the more exotic tips, I recommend getting an Innergie Magic Cable Trio along with the Satechi and skipping the tips.

OFF THE GRID

Of course, all these battery-containing power packs ultimately have the same problem that mobile devices do: They, too, eventually need to be recharged from an AC outlet (or a laptop connected to an outlet). They are, in effect, AC time shifters.

One AC-free option is a charger that uses AA batteries—easy to carry, easy to buy—like the **Quickertek Little Black Box** ($29, [5]). But again, that can be a problem if there aren't any stores nearby.

Solar and wind chargers have been around for a while now, but they require enough sun and wind to produce enough energy for a charge. A number of long-anticipated alternatives, however, have gone from "coming soon" to "available." (And even more options are on the way, such as the butane-based cartridge system that Lilliputian Systems expects to release next year—see "A Butane Recharger for Your Cellphone" on the *IEEE Spectrum* website.)

None will put out enough current to charge an iPad, but they can recharge the battery packs mentioned above. Note: Although I tested the rechargeable battery packs, I haven't yet checked out the power makers below personally, so caveat emptor.

The **nPower PEG** ($170, [6]) harvests kinetic energy from vertical motion, storing it in a 2000-mAh battery. Normally, you would put it in a bag or attach it to a backpack to let it harvest energy as you walk around, but if you need power in hurry, the manufacturer says that shaking it for a few minutes will get you enough juice for a quick phone call.

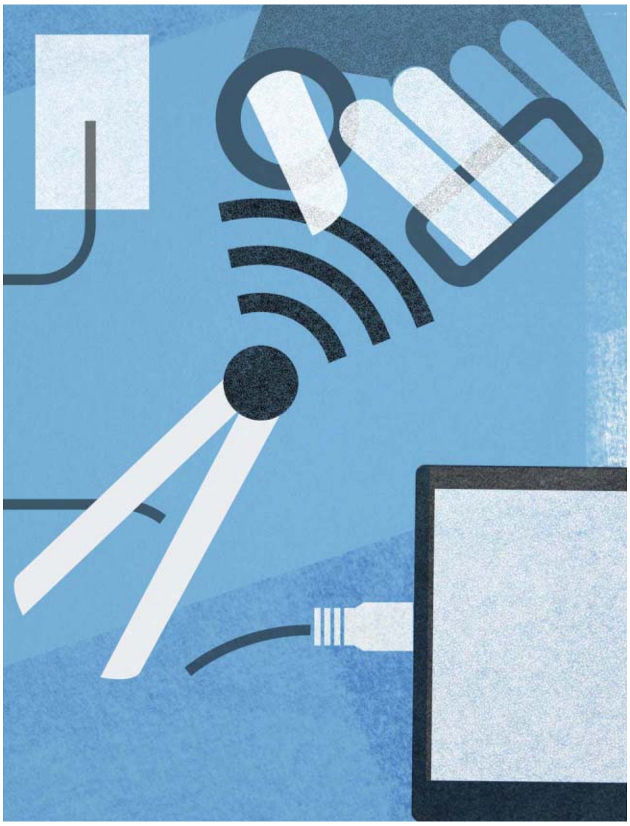
The **Horizon Minipak** ($114, [7]) uses air-breathing fuel cell cartridges. Each cartridge uses a solid hydride to store 15 watt-hours of energy (equivalent to about 10 AA batteries), so a cartridge or two should see you through most situations. You can buy or recharge cartridges through local dealers in some places, or you can recharge them yourself using Horizon's desktop Hydrofill system, which consumes water and power from either an AC adapter or a solar panel to generate hydrogen for the cartridges.

And if you don't mind being old-school, there are hand-cranked power generators, like the **Freeplay Freecharge 12V** ($40, [8]). Just make sure you have a Bluetooth headset—you'll need both hands to use this one!

—Daniel Dern

reflections

BY ROBERT W. LUCKY



MATTHEW HOLLISTER

Wires and Wireless

IN THE BEGINNING, all real-time communication across distances was wireless—bonfires, smoke signals, semaphores. Centuries of wireless passed before Samuel Morse pioneered telegraphy in 1837 with electrical transmission over wires. By the time Alexander Graham Bell invented the telephone in 1876, wires had already crossed the American continent and the Atlantic Ocean.

Guglielmo Marconi demonstrated modern wireless telecommunications in Italy in 1895. Then in 1899 he sent the first radio signals in America from a ship covering the America's Cup race to a receiver at a lighthouse overlooking New Jersey's Sandy Hook Bay. Standing at that very lighthouse, looking down on the bay below, I have wondered: Why demonstrate wireless in this way?

I tried to put myself in Marconi's shoes. He aspires to be a great entrepreneur. He has this magic new box that sends telegraphy without the need for wires, but what is it good for? Is there a market? After all, there are already wires everywhere of importance, and have been for decades. The answer seemed to lie below me, there in the bay. No wires can stretch out to ships at sea.

Many of Marconi's early deployments featured ship-to-shore and ship-to-ship transmission, culminating on the infamous day of 15 April 1912, when the *Titanic* sank and Marconi's wireless telegraphy played a critical role in the rescue of the survivors. However, wireless became mainly a conduit for commercial broadcast. For most of the 20th century, personal, point-to-point communication was done through wires, and with the rise of the cable industry, even television transmissions moved from air to earth.

Eventually, plans for cellular telephony began to emerge. AT&T was pondering the same questions as Marconi—what was wireless good for, and was there a market for it? The answers came back from a consultant: Wireless phones were good only for emergency communications, and the market would be small. But we have since learned the opposite—that wireless is equally good at the trivial ("I'm here already, where are you?") and the market is huge.

I can hardly fault the consultants. On the day that Apple introduced the iPhone in 2007, I got a call from a journalist representing a large newspaper. What did I think of Apple's new phone? I told him that this phone would revolutionize the wireless business and create a whole new vision of phones as smart appliances.

Well, no, I didn't tell him that; I only wish that I had. I actually said something not worth printing either in the newspaper or here. Apparently I was not alone. A designer from another cellphone maker has told me regretfully that its own focus groups had not liked the idea of a touch screen—the screen was small, and people don't have pointy little fingers.

After a century of wires, now everything is wireless. I see the forlorn public phones at airports. I'm not even sure if they work anymore, and if you tried to use one, passersby would look on you with pity. I think that the whole idea of being tetherless is a compelling state of mind. (My sleepy dog just looked up at me in seeming agreement.) Take the wireless mouse. It's confined to its pad. It doesn't go out and roam the world. Why does it need to be wireless? Yet I like it that way. Give the little creature some freedom. When I am in a hotel room there is usually a choice of wireless or wired, right at the desk, where I set my laptop down. I invariably choose wireless, even though the connection is almost surely worse.

The pendulum has swung, and anything that can be wireless must be wireless. With 4G, more and more people are even getting their broadband access through the air. Nevertheless, all that wireless access is but a surface coating over a gigantic, unseen, wired infrastructure beneath. One of my research friends used to say, "Wireless isn't." So the curious thing is that in the last century, broadcast was all wireless and personal communication all wired; now it is exactly the reverse—but stay tuned. ❑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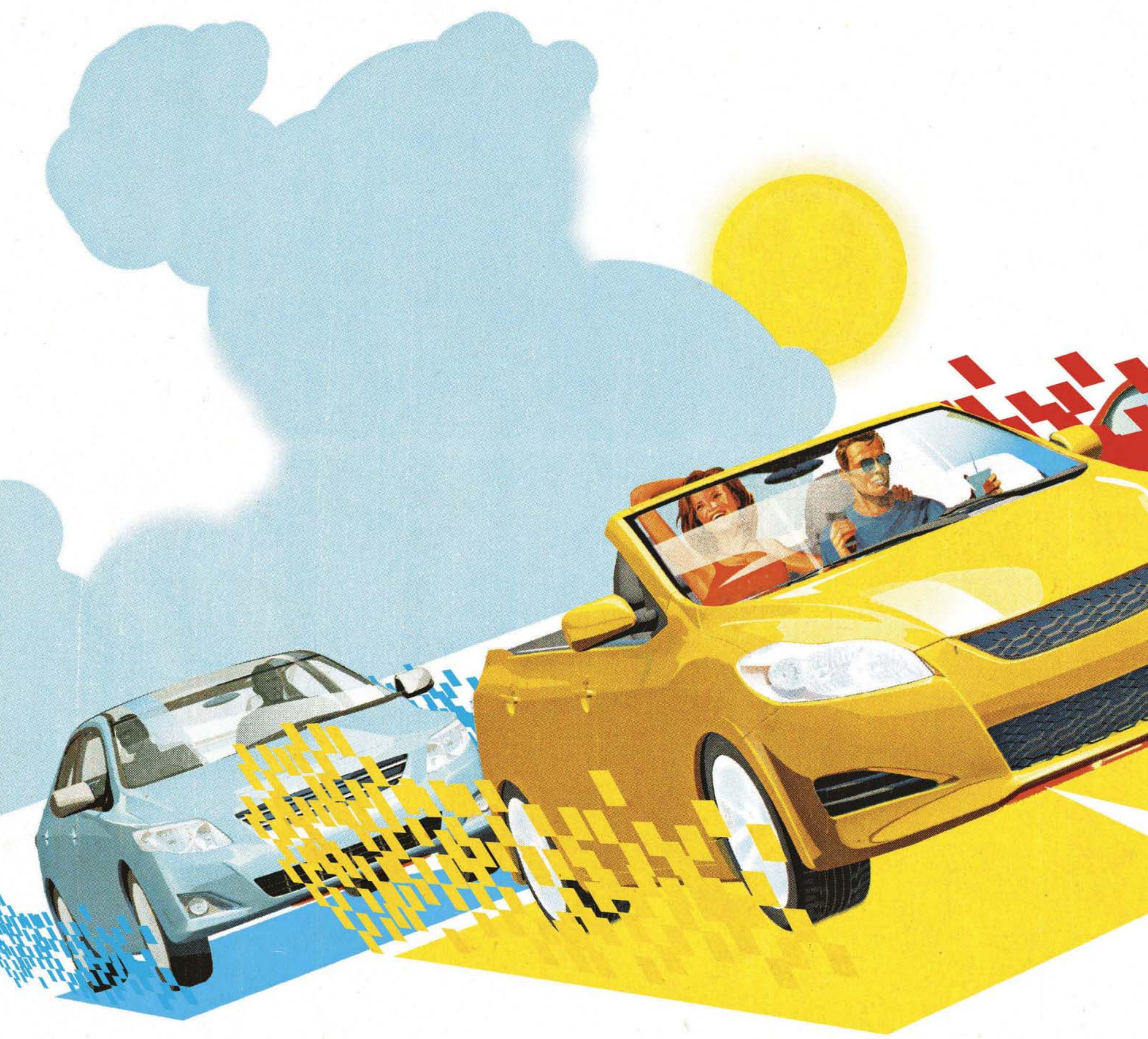


All Aboard the

SIT BACK, RELAX, AND LET THE CAR IN FRONT OF YOU DO THE DRIVING

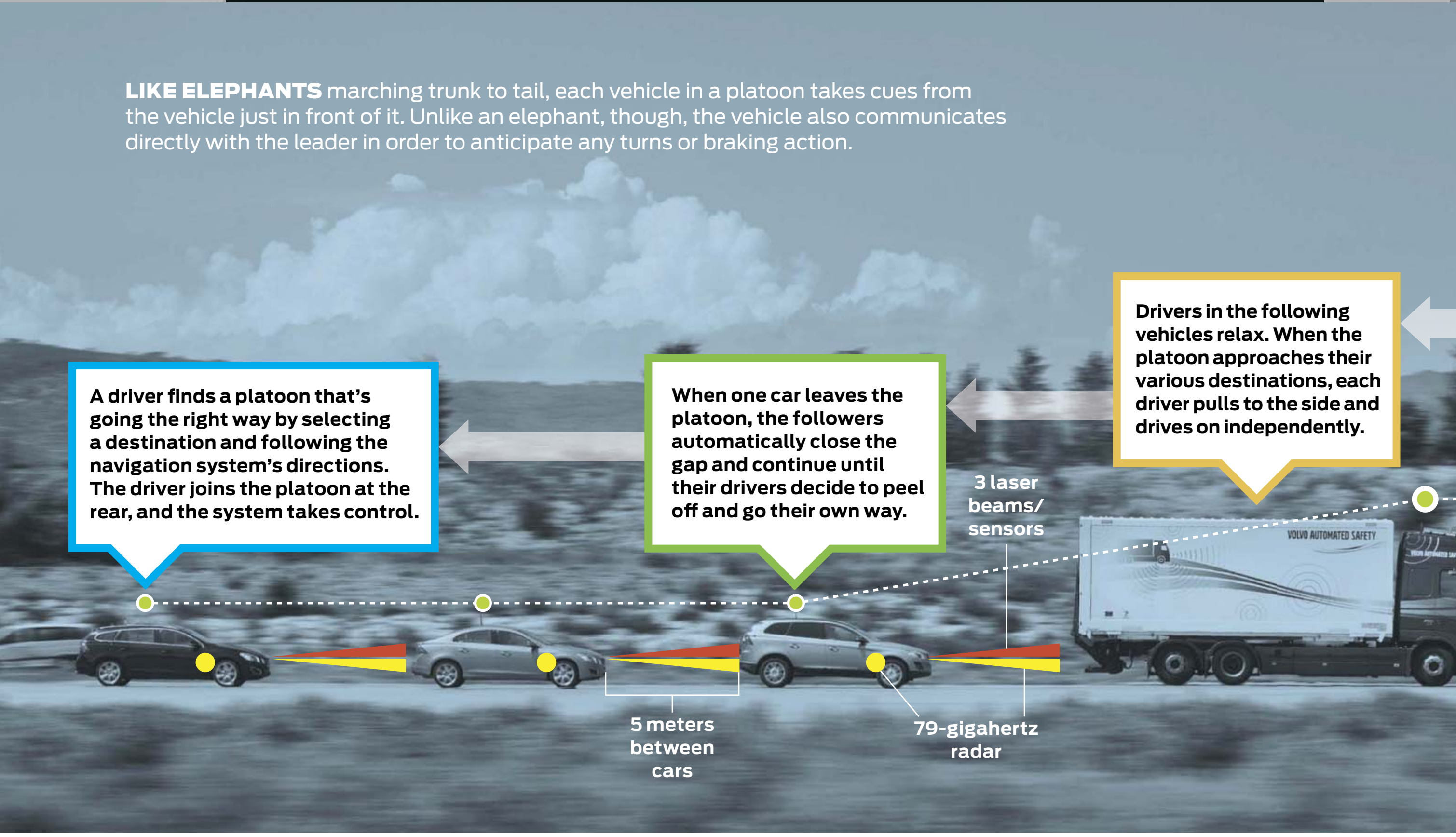
IN CAR COMMERCIALS, EVERY ROAD is clear and curvy, every vista is framed by mountains and the sea, and every driver is relaxed and in the moment. In real life, though, driving is often as much a pain as it is a pleasure—a car, once a symbol of independence, is now perhaps the last place where you can't use your smartphone. Even when the roads aren't clogged, you must be constantly alert because, let's face it—too many other drivers are inattentive or downright maniacal (characteristics that never apply to you, of course!). Public transportation has its own drawbacks: Buses and trains don't start at your home and don't end at your destination, nor do they leave just when you'd like or even guarantee you a seat.

To get the best of both worlds, we could teach our cars to work together, as closely grouped cyclists do in a peloton. The lead car could be entrusted to a professional driver to whom the other drivers would of course each pay a small fee; all the other cars would follow it automatically. The cars would all use networked communications coupled with the optical or electromagnetic sensors already installed in some luxury cars to avoid head-on collision, stay in the proper lane, and brake in case of emergency. These systems have been developed at great expense to provide active safety, as distinguished from the passive kind afforded by seat belts. But this investment, having been made, can now be exploited for other things—like allowing you to relax and read the paper. If only we'd let them.

Active systems are improving at a splendid rate. Adaptive cruise control, for example, maintains a car's speed while using radar or lidar to keep a safe distance from the car in front of it, thus automating much of the braking and accelerating. The latest generation of this system can follow a lead car from highway speed to a stop and then resume automatically when that car drives away. Soon the system will get additional data from vision sensors and digitized maps and additional support for the steering, allowing it to slow down on curves.

Robotic Road Train

BY ERIK COELINGH & STEFAN SOLYOM / ILLUSTRATION BY TAVIS COBURN



LIKE ELEPHANTS marching trunk to tail, each vehicle in a platoon takes cues from the vehicle just in front of it. Unlike an elephant, though, the vehicle also communicates directly with the leader in order to anticipate any turns or braking action.

RUBBERNECKING'S OKAY: Drivers in this five-member platoon, led by a truck, can sit back and enjoy the scenery. Guidelines allow for up to 10 members; any more makes it difficult for outsiders to use exit ramps from the highway.

VOLVO (5)

Clearly, passenger vehicles are on the verge of being capable of some kind of autonomy. The question is, what kind is best? The answer may surprise you.

WHAT ABOUT GOOGLE'S SELF-DRIVING CARS, some of you are probably wondering. More specifically, why would we want partially automated cars when not only Google but also the Technical University of Braunschweig have recently demonstrated fully automated ones? The Google project and its German analogue, Braunschweig's Stadtpilot project, both stem from technology developed for the 2007 DARPA Urban Challenge, in which driverless cars navigated a 96-kilometer course in a city setting. The fully autonomous vehicles in this U.S. Defense Advanced Research Projects Agency competition must deal with all possible scenarios in typical city traffic by using advanced sensing, such as laser scanners, several radars, cameras, and more. Great progress has been made, but the sensing technology is not yet cheap enough for use in mass-market cars. More important, verifying this technology in all potential traffic situations is an enormous and imperfectly understood task.

A few years ago, my colleagues and I at Volvo asked ourselves how we could build on our adaptive cruise control system to give a car full autonomy. We realized that the chief problem lay in making sure that such a system would be utterly safe. Just to verify Volvo's pedestrian detection with fully automatic braking had required driving more than 500 000 km and collecting more than 3 terabytes of data (mostly to confirm that the risk of inadvertent braking would be acceptably low). To ensure that an autonomous car would almost never make severe mistakes, no matter what the weather and traffic situations might be, would be vastly harder. We concluded that such a fully autonomous car would, for now, be a step too far.

To advance the state of the art, we decided to come up with an intermediate goal. We quickly focused on the concept of platooning, which gives the lead driver responsibility only in the middle part of the trip. In this scheme, the person behind the wheel of each of the following cars does all the work at

DASH-MOUNTED CONSOLE: This is one of the few pieces of equipment the Sartre project added to the functions that were already built in to the car. The driver adjusts the gap separating the cars [top]; the console confirms that the car is under automatic control [middle], and then shows the status of the car in the platoon and the distance to the driver's destination [bottom].

the beginning, before joining the platoon, and at the end, after peeling off for a specific destination.

Platooning is not a new concept. During the 1990s, the California Partners for Advanced Transit and Highways (PATH) program at the University of California, Berkeley, installed magnets in a dedicated lane on a highway in California. The magnets acted as detectable guides that a vehicle could use as reference points to control its position within the lane. The project found that on average a car in the platoon saved about 10 percent in fuel when subjected to less wind resistance, a savings that depends on how closely the car follows its leader. Another advantage is safety: All members of a platoon ought to be as safe as the professional driver leading them, who is aided by the most advanced collision-avoidance technologies available.

The main problem with the PATH system was that it couldn't be easily extended to other roads. It's a long, expensive job to change the roads, and it's not likely to happen when there are no vehicles to use them. Nor will carmakers want to build vehicles that use magnetic guidance if there aren't many roads to drive them on. We need a way for autonomous cars to run on existing roads.

To work out such a system, the European Community funded the Safe Road Trains for the Environment (Sartre) project, which started in 2009 and ended in September 2012. The participants included Britain's Ricardo, which coordinated the project; Spain's IDIADA Automotive Technology and Tecnalia Research & Innovation; Germany's Institut für Kraftfahrzeuge Aachen; and the SP Technical Research Institute of Sweden, Volvo Car Corp., and Volvo Technology. Our strategy with Sartre was to rely, to the extent possible, on technologies already available in production cars, rather than on exotic and largely unproven new technologies. And to tame the problem of verification, we not only entrusted the lead vehicle to a professional driver who could deal with exceptional situations but also limited the automated driving to roads that had at least two lanes going in the same direction. On such roads the traffic situations usually are not complex, and it's easy for faster-moving cars to pass a road train.

We put the heaviest vehicles up front to reduce the risk of collisions during emergency braking, because a heavy vehicle decelerates more slowly than a lighter one. We programmed each vehicle to align laterally with the leader and to maintain a proper distance from the car directly in front of it; that way, if the leader changes lanes or engages in evasive maneuvers, all the other cars will follow the path it blazes while remaining in their queue. We also calculated that, at a maximum speed of 90 kilometers per hour (56 miles per hour), the platoon could have no more than about 10 vehicles or its close-packed formation would block access to exit ramps. Drivers would join a platoon either on the spot, by means of an electronic request, or by booking a place in advance. Highway driving was our sole interest because it is the least complicated kind, lacking intersections, traffic lights, bicyclists, and so on.

NONE OF OUR REQUIREMENTS are outlandish, yet they do define the problem narrowly enough to make it solvable with existing technology. We implemented a limited number of critical platoon scenarios representing how the cars interact—for instance, Join Platoon, Maintain Platoon, Leave Platoon, and Dissolve Platoon. Anyone joining the platoon would normally do so at the rear, but we could allow for someone to join in the middle by enabling the controlling system to tell one member of the pack and those following it to slow down, thus opening up a space.

These transitions to and from automatic driving are crucial because a driver should never be unsure whether he or the lead car is in control. To avoid any such uncertainty, we have chosen to coordinate these transitions with a user interface that, although new, will still be familiar to drivers because it is based on the existing ones in active cruise control systems.

DRIVER DISTRACTION: This side effect of our sometimes excessively linked-in world is here not a bug, but a feature. Within a few minutes of joining a platoon, drivers tend to kick back and take their attention from the road. *PHOTO: VOLVO*

To join from the rear, a driver would send a request to the lead vehicle, get confirmation, approach the platoon from behind, and then put the car into semiautomatic mode, in which braking and accelerating is automatic and the steering is still manual. This ensures that the driver will pay full attention to traffic in case anything unusual happens. Only when the car is locked into the determined following distance does lateral control pass to the automatic system. An indication of the change appears on the car's display, accompanied by a voice message, letting the driver know that he can release the steering wheel, lean back, and just enjoy the ride.

Sartre designed a prototype system consisting of a lead vehicle, a following truck, and three cars—a Volvo S60, a V60, and an XC60, modified to allow for fully automatic driving. We started development in 2009 and began testing vehicles in the summer of 2010, mostly at Volvo's Hällered proving ground in Sweden. We performed tests of fuel consumption at IDIADA in Spain and a test drive on 200 km of public roads, also in Spain.

Within a car, the system communicates with the power train, brakes, and steering through Volvo's standard adaptive cruise control and lane-keeping guidance. Measuring the distance between cars involves two other standard systems: a short-range system of three laser beams, which measures distances of up to 8 meters ahead, and the 76-gigahertz

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radar in the active cruise control, which measures the ranges of objects up to 200 meters ahead.

The side-to-side movement of the car up ahead is monitored by a forward-looking camera that's used in our current production vehicles to detect pedestrians and recognize traffic signs.

To keep the platoon and its lead driver apprised of traffic in neighboring lanes, the cars also come with two rear- and side-looking radars, also at 76 GHz. Not only do the radars watch out for swerving cars in the next lane, they also help the system track and then accommodate the entry of any car that may join the platoon.

We noticed a potential glitch during trials on our test track in Sweden, where the sun shines from a low angle. Every time we rounded a particular curve, the sun would blind our camera, making the car lose sight of the vehicle in front of it and suddenly veer out of its lane—a very unpleasant feeling! We tried several backup plans and finally hit on the solution. We took the lead vehicle's estimation of the curvature of the path it is taking and the radar's measurement of the azimuth angle—the horizontal angle between our own car's radar sensor and the car directly in front of us. This technique is normally rather imprecise, as the radar reflections don't necessarily come from the center of the preceding vehicle; sometimes they come from the corners or even the side. To assure ourselves that it worked well, we put tape on the windshields to simulate camera blockage and drove many laps. We remember sitting in the vehicle for about two hours, quite comfortably listening to a football match on the radio. The road train was finally working as intended.

The new, custom-made equipment we added to make the system fully automatic includes an interface that allows the cars (though not their occupants) to communicate. The system could also feed real-time video from a camera in the lead vehicle to people in the platoon to make them more comfortable with their short following distances. A touch screen displays the status of each car (joining, maintaining, or leaving the platoon), and vibrators in the car seat provide warning whenever the driver has to take immediate action—for instance, when part of the platoon has to be dissolved because another vehicle has wormed its way into it.

We also incorporated a prototype wireless system, based on the 5.9-GHz IEEE 802.11p Wi-Fi standard, to allow direct data links among all the vehicles in the platoon. The 802.11p standard was originally devised to allow vehicles to communicate automatically with roadside beacons—to collect tolls, for instance—and with other vehicles to avoid accidents.

Overall control is distributed throughout the platoon. The lead vehicle contains the "organizational assistant," which keeps track of the platoon as a whole—the number of vehicles, their order, speed, gap size, and so on. It gets this information through direct communication links to all the other vehicles. The organizational assistant sends out a series of set points describing longitudinal acceleration and the curvature of the path that is driven—not that of the road. It's as if the lead car were dropping bread crumbs for the others to follow. Each follower contains control units that strive to follow these set points while keeping a minimum gap and a maximum lateral offset with respect to the vehicle directly in front. The lead vehicle tracks these separation distances, and it can command a follower to open up a larger gap should another vehicle try to merge.

Note that the lead vehicle of the platoon is the one they're following in a real sense—they merely sense and avoid the other cars. If, for example, the lead driver suddenly slams on the brakes, the communication system commands all the other vehicles to brake, decelerating all of them at once so that none collides with the car in front of it. Without that communication link, there would be a small delay, and the delays would add up as they progressed through the chain; the last vehicle would thus have to brake much faster and harder than the first one. Similar effects—they're called string instabilities—would occur if the leader's decisions on steering were not also immediately communicated to all the followers.

We are still validating the prototype, driving at different speeds and with different amounts of space between the vehicles. We find that though shorter separations decrease aerodynamic drag, they also require stiffer control, which often means a heavier robotic "foot" on the accelerator or the brake, which can undo some of the fuel savings. On the other hand, our tests indicate that drivers prefer the stiffer control; it seems that they feel more secure, as if their car were driving on rails. At first, they tend to be alert and ready to take over at any time, but within a few minutes they relax and take their attention from the road.

A FEW PROBLEMS REMAIN. For instance, during our winter tests in Sweden, we found that trailing only 5 meters behind a heavy vehicle meant getting a windshield full of salty spray and gravel. We had to clean the windshield constantly to keep the forward-looking camera unblocked; sometimes it felt as if we were consuming more washer fluid than gasoline. Also, the gravel dinged our car quite a bit. Conclusion: Although 5 meters may be aerodynamically attractive, we may have to increase it sometimes.

In the end, though, the biggest challenges will probably be legal ones. Right now driving on autopilot isn't allowed in most areas in Europe and North America, and there is no consensus on who would be responsible for any accident.

What we have learned is that there is a practical way station on the road to fully self-driving cars, and that today's vehicles already have most of the technology they need to get there. Airplanes have been moving among similar way stations for decades now, using flight control systems, coupled with ever-closer coordination with ground control stations, to supplement rather than replace the pilots on board.

If on land, as in the air, semiautomated systems can save fuel and perhaps lives, and if they give drivers freedom to spend their time as they wish, then it will be a clear gain. And experience with such systems will undoubtedly teach us much of what we need to know to devise fully autonomous drivers that do not know fatigue, impatience, or the temptation of skirting the dictates of law and decorum on the road. ❏

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SPORTS

3-D TV'S TOUGHEST CHALLENGE

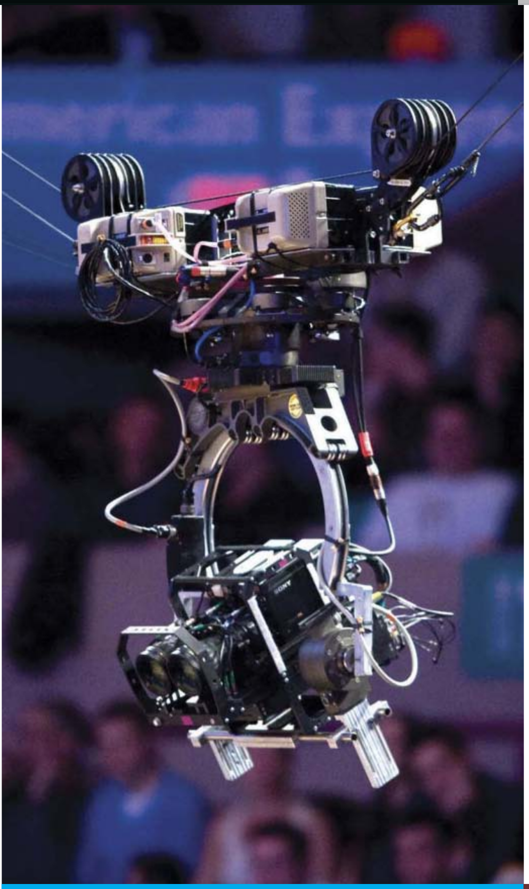
MIRROR, MIRROR: In 3Ality Technica's Beamsplitter rigs, a horizontally mounted camera looks through a mirror, and a vertically mounted camera sees the mirror's reflection. This allows the cameras to be placed much closer together than in a more conventional setup and is useful for close-up shots. *PHOTO: PRESS ASSOCIATION/AP PHOTO*

THE MOST POPULAR 3-D SHOWS ARE THE HARDEST TO PRODUCE

BY HOWARD POSTLEY

If you're one of the 24 million or so people around the world who purchased a 3-D television in 2011—or the 42 million doing so this year—you might know what it takes to watch 3-D on your home television: a pair of 3-D glasses. But you likely haven't thought much about what it takes to produce the 3-D spectacle that comes to life in your living room. More cameras, or at least more lenses, you might think, and that's probably about it.

In fact, that's not it—particularly when it comes to producing the kind of 3-D show that people watch more than anything else: a live sports broadcast. Making a 3-D program work well—especially when it's happening live—is one of the greatest and most interesting technological challenges facing TV production at the moment.



LIGHTS, CAMERA, ACTION: ESPN's 3-D cameras record the 2012 X Games in Los Angeles [top left] and a 2010 National Basketball Association game in New York City [top right]. The 3ality Technica TS4 camera rig [left] can separate camera lenses by up to 500 millimeters, enabling the rig to capture a high-quality 3-D image from far away. An ESPN staff member [below] previews a 2010 FIFA World Cup Game between South Africa and Mexico.

PHOTOS, CLOCKWISE FROM TOP LEFT: RICH ARDEN/ESPN; BEN SOLOMAN/ESPN; JOHN ATASHIAN/ESPN; MIKE EGERTON/AP PHOTO

BACKSTAGE PASS: Producing shows in 3-D is complex. Here, a director faces a bank of screens showing ESPN's coverage of a 2010 football game between Boise State and Virginia Tech [above]; BSkyB's team monitors its 3-D rig systems [top right]; and a BSkyB engineer oversees the control of a camera rig [right].

PHOTOS, CLOCKWISE FROM LEFT: RANDY SAGAR/ESPN; BSKYB/TELEGENIC (2)

The biggest difference introduced by 3-D involves the viewer's relationship to a shot. With 2-D, the viewer sees what's happening but feels separated from it. A 3-D image can blur the line between the "audience space" (where you are) and "scene space" (what the cameras see). Instead of looking through a window, you feel as though you're standing on a sideline. That means that when a 100-kilogram athlete speeds toward you, you are likely to duck.

And producers want you to duck: The point of 3-D TV is to make you forget you're in your living room. When it works well, it's amazing, but any little mistake that breaks the illusion ends up being not just a minor annoyance but an extreme disruption that can literally give you a headache.

These days, most of us who produce 3-D sports usually do it well, but not always, and we've had to learn a lot in the past few years. I'm going to take you behind the scenes and show you what we've learned and what we have yet to figure out. So the next time you watch 3-D sports on TV, you'll see what the producers of that broadcast do right, understand some of the choices they make during the broadcast, and maybe even spot a few errors.

I'm going to use the United States' National Football League (NFL) as the archetypal sport for TV coverage. Other broadcast sports, like soccer and hockey, share many of the same challenges of an American football broadcast, such as the shooting angle, the lighting issues, and the camera placement. Other challenges are unique to certain sports: For example, the all-white surface of an ice rink has no texture or color variation, both of which contribute to conveying a sense of depth.

First, let's look at how a sports network covers a football game in 2-D.

IN 2011, THE NFL NETWORK used either 26 or 27 cameras for its game coverage; most other networks covering football fielded about the same number. The operators of those cameras work independently for the most part, looking for interesting shots on their own. The instructions they do get from the director tend to come in the form of a general request: "Find me some facial expressions" or "Follow number 45."

The directors take the feeds from these cameras and choose what shots to include in the broadcast, typically picking a new shot every 2 to 5 seconds. Directors usually start with wide shots to establish a context for the viewer and then make their way to tighter shots.

The production team mixes those camera feeds with replays, prerecorded footage, and computer-generated graphic elements, including the game clock, period, score, and game context (in the case of American football, the down, yards to go, and current ball position). Most broadcasts also include a branding "bug" of some type—for example, the ESPN logo. They also tap augmented reality tools, like a telestrator (which lets a commentator sketch over a moving image), a virtual first-down line, and virtual signage. And, of course, various canned transitions like wipes and fades separate different shots, graphics, and other elements that don't easily flow together.

Such is the world of 2-D NFL broadcasting as we know it today. And audiences want it all. Skip the virtual first-down line or the virtual scoreboard and many viewers will simply write off the show as impossible to watch. Audiences are surprisingly inflexible and unforgiving.

ENTER 3-D. At first glance, it seems as though you could simply take a 2-D sports broadcast and add depth. But it's not that simple.

Take the most common 2-D editing technique, the fast cut. In 2-D, a fast cut simply changes what picture is in front of you, the viewer. You see a close-up, perhaps, then a wide-angle shot. But you don't feel as if you've actually moved;

you're just looking at a different picture. In 3-D, a fast cut seems to relocate you to a completely different place. In one shot, you may feel as if you are looking across a wide expanse; in another, you may feel as if you're close enough to touch the player. Everything about your perspective—whether the image appears to jut out from the screen, recede into it, or sit near the surface of the TV—changes with each cut, and that can take some time to adjust to. If you don't have enough time, you feel disoriented. So directors of a 3-D broadcast tend to cut between shots less than a fifth as often as they do for 2-D. The good news for directors is that they need about half as many camera positions. In 2-D, all those different camera angles make up for the inherent loss of excitement that comes from the loss of immersion. In 3-D, you have no need to compensate. It turns out, though, that producers still need the same number of cameras, because you need two cameras for each 3-D shot.

Some of the graphic enhancements sports viewers have grown accustomed to are hard to pull off in 3-D. Consider the virtual line of scrimmage in American football—the computer-created line marking the distance reached by the football in the previous play. Today's broadcasts superimpose the line on the picture, making it look as though it's been chalked right onto the grass of the playing field. It takes about 5 gigaflops to determine how to display it in a 2-D scene, but it takes a thousand times as many computations—about 5 teraflops—to display it in 3-D. That's because painting a virtual line in 2-D requires simply finding the two end points of the line in the video image and then drawing the line between them in perspective. The system determines what is grass and what is player and then creates a line that covers the grass but falls behind the players. It doesn't need to follow the curves of the grass precisely, because from the viewer's perspective, the entire image is flattened, and as long as the line blocks the grass and not the players, it will appear painted on the grass. In 3-D, however, the image is not flattened, so you can't just obscure the grass. The system must track the grass geometrically, following its every curve, or the line might seem to be floating above the ground where people could trip over it. That precise tracking takes hundreds of x-y coordinates, not just two.

In the same way we need fewer camera positions, we don't need all the fast cuts and as many graphics, for in the 2-D world they exist to compensate for the inherent loss of visual richness and energy compared with watching an event live. The 3-D coverage itself provides much of that extra visual richness and energy. Admittedly, sometimes we cut back on complexity simply because we have yet to create good 3-D equivalents of 2-D. However, in most cases it's because we simply don't need them.

Giving up on fast cuts and trimming down the graphics aren't the only changes producers are making in switching to 3-D. In general, camera operators shoot 2-D sports from high up in the stadium, but 3-D is more compelling when shot from the ground, simulating an on-site spectator's point of view. At that level, it's hard to find places to put cameras, and stationary objects as well as moving people tend to block the view. But whereas a 2-D camera views a scene shot from above as a simple rectangle, with a height and width that don't change when the camera pans, in 3-D the addition of depth means that the camera captures a prism. Even though the TV screen displays this prism as a rectangle, from the viewer's perspective all three dimensions of the prism change relative lengths as the camera moves. Trying to mentally adjust to such changes disturbs and disorients viewers, and shooting from a lower angle minimizes these changes.

These adjustments—slower cuts, fewer graphics, and a lower viewing angle—are straightforward and relatively simple to do. But that's not all it takes to make a 3-D broadcast work.

The images in a 3-D broadcast must be of higher technical quality than those in 2-D productions, where a bit of sloppiness won't be noticed. For instance, if the color of the grass as it appears on the screen doesn't quite match reality, viewers will overlook the defect because they have no handy reference for comparison. But in 3-D, every shot has a reference: the other eye. Color has to match. Focus has to match. Zoom, camera angle, signal quality, and graphics—every single thing that's done has to be exactly right, which it often isn't in 2-D. Take the 2012 Super Bowl (the NFL championship game). One camera had a smudge on the lens. Viewers noticed it, but it wasn't a showstopper; in 3-D, that camera would have been unusable.

And it's not just a matter of annoying the viewer. A bad 3-D shot can actually be painful. There are two types of technical mistakes that can make you physically ill. First, cameras can be misaligned—for example, the image sent to the left eye is 10 pixels higher than the image going to the right eye. When you're watching a broadcast and this happens, one eye has to point upward more than the other, and in many cases, the strain that causes will give you a headache. Then there are mismatched depth cues. Depth perception comes from a number of different aspects of an image. Parallax cues, for example, let the brain extract depth information from the different viewing angle perceived by each eye. Occlusion cues let the brain calculate depth based on which objects overlap other objects. If these two kinds of cues don't match—for example, if parallax cues place the ball in front of the screen while occlusion cues place it behind—you'll tend to feel nauseated. In both cases, the egregiousness of the error determines the severity of the headache or nausea.

Getting a perfect shot every time at a live sporting event is tough. What makes it even tougher are zoom lenses, used extensively in sports coverage today. A zoom lens is made up of a large number of moving glass elements. No two zoom lenses will match at every point in the zoom range, but 3-D requires that they come much closer to perfect than before. That's why production teams carefully test lenses to find the best match.

Then there's the question of where to put graphics in 3-D space. In the 2-D world, most graphics live in an artificial space. You would say they're "in front" of the other objects on the screen, but they aren't really. They're at the same depth, that is, flat; they simply block other objects in the way a sticker on a book cover blocks part of the photo.

Take something as simple as a scoreboard. In a 2-D broadcast, producers generally place the graphic score block in a consistent position on the screen—for example, the upper third, regardless of the underlying content. It just stays there, blocking part of every scene. The same technique does not work in 3-D; everything must be placed at some depth. As a result, producers have to consider something we call the depth budget.

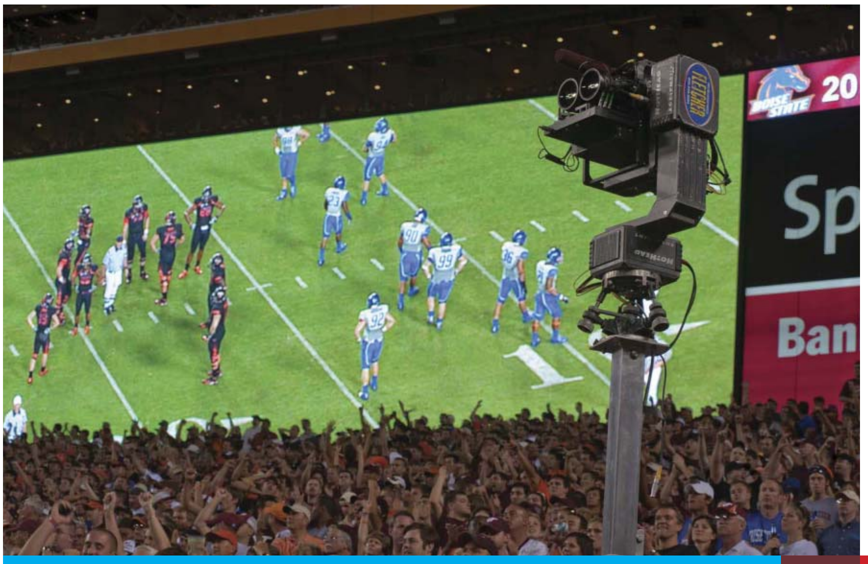
To view things moving around in the third dimension, your eyes have to look straight ahead for some objects and cross for others; this causes fatigue. Situations that force the eyes to diverge are even more uncomfortable, so producers try to avoid those altogether. Producers use depth budgets to limit the eye motion to a comfortable range. What is comfortable is subjective and can evolve; that's why most 3-D shows use less depth in the beginning and add more later after the audiences' eyes have "warmed up." Viewers can't tolerate shots with lots of depth disparity for long stretches of time. Good 3-D shows therefore include "rest stops," shots with little depth to give the viewer's eyes a rest.

To keep viewers from straining their eyes, producers of 3-D content must consider the limit to the depth that a viewer can comfortably perceive in a 3-D television scene. This limit is set by several factors, but the most important are the size of the TV screen and the viewing distance. For objects in the foreground, the closer an object appears to a viewer, the greater the difference in the view presented to the left and right eye. This difference is measured as a linear distance—the physical difference between the left- and right-eye views—and that distance is in turn expressed as a percentage of the width of the television screen. Television producers consider a reasonable limit for the living room, where the typical viewing distance is about 1.8 meters, to be about 4 percent of the screen width for objects perceived as being very close to the viewer and about 2 percent of the screen width for objects receding into the background. For foreground objects on a 55-inch diagonal screen, which is about 1.2 meters wide, that translates to about 5 centimeters between the pixels seen by each eye.

Even within the depth limits, it's tough for viewers to focus on near and far objects simultaneously. Here the depth budget comes into play: When you have something deep in the background, as you would in the kickoff of a football game, you are limited in how far foreground objects extend toward the viewer. So in scenes like these, directors or camera operators must frame shots without objects in the extreme foreground.

Now let's get back to the issue of graphics. Unlike a 2-D image, where the directors can place graphics on the top or bottom of the screen and rarely block important action, a 3-D image has no position where the graphic is guaranteed not to collide with the scene. While the safest depth is in front of the screen, the farther in front of the screen an object appears, the more of the depth budget it uses.

Another technique 2-D producers use for graphic overlays is partial transparency: Making graphics see-through helps integrate them into the live scene. In 3-D, this just doesn't work. Focus, intensity, brightness, and color all provide depth information to the viewer. Partial transparency modifies each of these elements, which can break the 3-D illusion.



CROWD PLEASER: A 3-D camera records a 2010 football game between Virginia Tech and Boise State at FedEx Field in Landover, Md. *PHOTO: RANDY SAGAR/ESPN*

MAINTAINING THE ILLUSION of 3-D isn't tricky just when producers are mixing graphics into a scene. They have to manage the live footage carefully as well.

If a football player is, say, in front of the convergence point of the two eye views being recorded by the cameras on the field, he should appear to be in front of the screen. And if he's in the middle of the shot, indeed he will. But if he's at the edge of the scene for you at home, he will appear to touch the edge of the TV itself. If that happens, your mind will no longer allow you to see him in front of the screen. If he's touching the side of the TV, then you will see him aligned in depth with the TV frame, breaking the illusion of 3-D and startling you.

Alignment, managing the depth budget, watching out for edge problems, and placing graphics carefully are basic 3-D production issues. They are essentially mathematical problems that can be handled by software, like that developed by my company, 3ality Technica. People carefully monitoring and adjusting the graphics and camera feeds can make these adjustments manually. That's tough to do in live television, however, so when not using automated tools, directors typically cut away from problematic shots as quickly as they possibly can.

But not all the problems of 3-D are mathematical. It gets much more complicated when producers combine images from many sources. Remember, each shot has a different trapezoidal 3-D geometry, and each one uses its depth budget differently. A commonly used composition in football coverage is a head-to-chest shot of two announcers, followed by a cut to a high wide shot of the entire field. Each of these individual shots can easily be done well in 3-D. However, the former generally does not have much spatial volume, while the latter feels very large. In the real world, such a transition doesn't happen instantly. You may be talking to someone next to you, but you don't close your eyes, spin, and open them to see the Grand Canyon. If you did, you might experience just what you would if you saw such a fast transition on a 3-D screen—instant vertigo.

So the more different the geometries of two shots are, the longer the transition between them must be. For example, a producer might insert a midrange shot between that shot of two announcers and the view of the computer. Or a computer system can mathematically analyze the two geometries, find (in essence) a common denominator, and then re-create each shot in the new geometry. As you might imagine, performing these operations live is computationally expensive. However, not doing so results in hard-to-watch 3-D.

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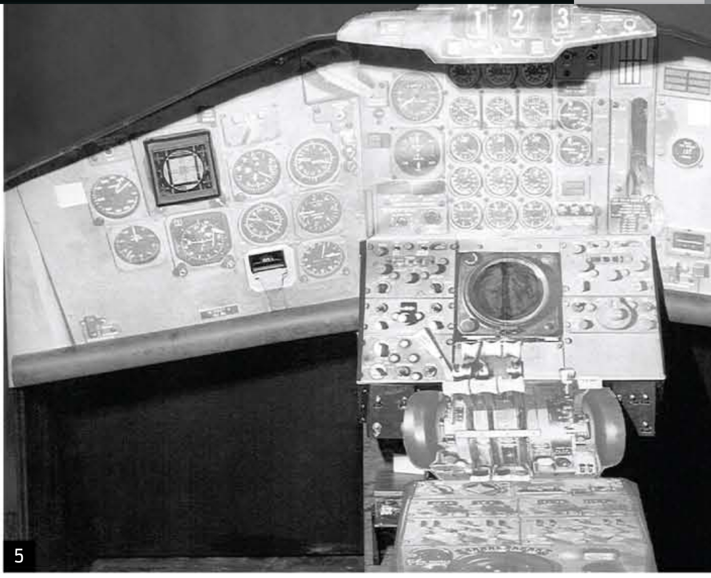
How RCA *Lost the* LCD

IT OWNED THE EARLY PATENTS BUT FAILED TO COMMERCIALIZE THE LIQUID CRYSTAL DISPLAY

By BENJAMIN GROSS

IN SEPTEMBER 1967, Richard Klein and his boss, Lawrence Murray, traveled to RCA's central research facility in Princeton, N.J. It was a familiar trip for Klein, an associate engineer at the company's semiconductor division in nearby Somerville, whose work with light-emitting diodes kept him in close touch with solid-state researchers in Princeton. On this occasion, though, Murray assured him he was going to see something new.

Sure enough, upon arriving in Princeton, Klein and Murray were escorted to a room where electrical engineer George Heilmeier presented them with a seemingly ordinary piece of glass attached to a power supply. Then Heilmeier flipped a switch, and a familiar black-and-white image suddenly appeared on the previously transparent square. "It was a TV test pattern," Klein recalled. "The thing pops up, and I almost fell over!"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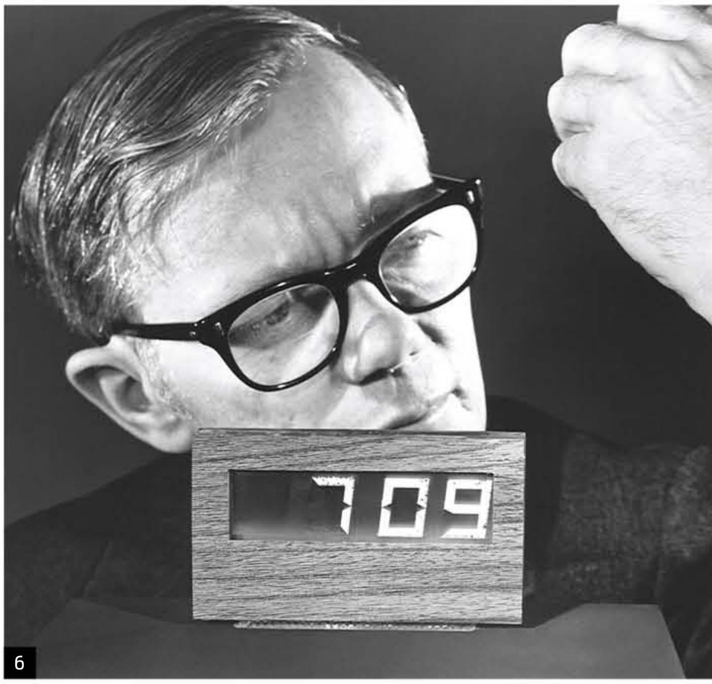

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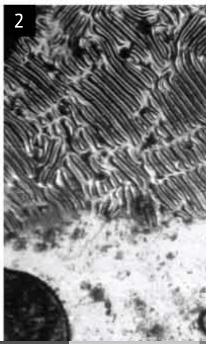
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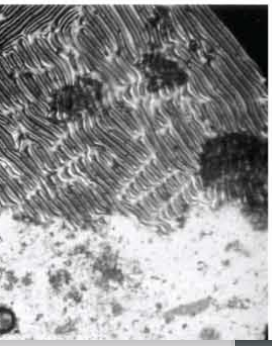

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BRIGHT BEGINNINGS: In the 1960s, RCA, the company that commercialized black-and-white and color TV, seemed poised to do the same for the liquid crystal display. Richard Williams [1] in 1962 noticed a crinkling effect when voltage was applied to a liquid crystal sample [2]. George Heilmeier [3] picked up on Williams's work and in 1965 observed "dynamic scattering" [see the illustration "LCD Approaches"]. Heilmeier persuaded RCA management to form an LCD research team. Over the next several years, the group built several products based on this new effect, including animated advertising displays [4] as well as prototypes and mock-ups, such as cockpit instruments [5], an electronic clock [6], and digital wristwatches [7]. Heilmeier and his technician Louis Zanoni [left, 8] also took their LCD prototypes on the road, showing them off at trade shows around the United States.

PHOTOS: HAGLEY MUSEUM AND LIBRARY (8)

SINGLE DIGIT: Among the few LCD products developed and sold by RCA were numeric readouts.

PHOTO: HAGLEY MUSEUM AND LIBRARY

Once Klein had recovered, Heilmeier explained that this prototype was a new form of display that relied on an obscure class of compounds called liquid crystals. Since the 19th century, chemists had known about these strange materials, which flowed like a liquid but retained the optical properties of a crystalline solid. But nobody was quite sure what to do with them.

Then, in 1962, RCA researcher Richard Williams hit upon the idea of using the crystals in some type of display, and he succeeded in getting the material to electronically modulate the passage of light. Fifty years ago this month, Williams filed for what would become RCA's first patent on the new technology. Heilmeier and his colleagues then spent several years expanding on Williams's findings. Now they wanted to work with their Somerville colleagues to transform these liquid crystal displays (LCDs) into commercial products.

Murray's group in Somerville had done research on electro-optic phenomena, and so it was well suited to introduce liquid crystals to a division more comfortable with silicon. Klein was given the job of examining the technology from a manufacturing perspective, a task he embraced enthusiastically.

Just eight months after the Princeton demonstration, RCA vice president James Hillier trumpeted the LCD's fine qualities at a high-profile press conference at the company's New York City headquarters. Hillier predicted that the electrically triggered opalescence observed in Heilmeier's prototypes would find its way into a wide range of products—perhaps even portable flat-screen televisions. "You could take such a set to the beach," he joked, "and, in between bikini watching, see the Mets on TV figure out a new way to lose a ball game."

The press latched on to Hillier's far-out predictions, and for the remainder of the 1960s and into the early 1970s, it seemed like RCA, the company responsible for the commercialization of both black-and-white and color television, was again poised to revolutionize the field of electronic displays. Yet in 1976, less than a decade after the LCD's unveiling, RCA sold off its liquid crystal operation, and key personnel associated with the project left the company. What began as an American innovation would mature under the auspices of firms in Europe and Asia.

Today, liquid crystals are one of the most widespread technologies of the information age and the foundation of a multibillion-dollar industry. Nevertheless, RCA's abrupt exit from the field has largely obscured the pioneering contributions of its chemists, physicists, and electrical engineers. The events and decisions that drove the company to abandon its efforts are worth revisiting for what they reveal about the unpredictable nature of innovation—and about the tendency of large corporations to fail to capitalize on it.

THE TRAIL OF RESEARCH that led Klein and Murray to Princeton had its start across the Atlantic nearly 80 years earlier. In 1888, a plant physiologist named Friedrich Reinitzer at the Charles University in Prague was investigating chemical derivatives of carrots when he noticed that one compound—cholesteryl benzoate—behaved strangely when heated. At 145.5 °C, the substance changed from a solid into a cloudy liquid, and at 178.5 °C, the cloudy liquid became transparent. That is, the material seemed to possess two melting points. Other pure substances, of course, melt at just one temperature.

At a loss for an explanation, Reinitzer sent his findings along with a sample to Otto Lehmann, a physical chemist working in Aachen, Germany. Lehmann confirmed that in its cloudy state, cholesteryl benzoate kept its fluidity. He also noticed that it refracted polarized light like a solid crystal, indicating a higher degree of molecular organization than an ordinary liquid. Lehmann coined the term *fliessende Krystalle*, or "flowing crystals," to describe such substances.

Within two decades, European scientists reported more than 200 compounds exhibiting similar behavior. The majority of RCA's LCD investigations years later would concentrate on "nematic" liquid crystals, which are composed of elongated, rodlike molecules whose long axes run in parallel. That structure allows the molecules to slide past one another like matches in a matchbox and to easily realign when subjected to an electric field.

Despite much theoretical interest in their behavior, few attempts were made to commercialize liquid crystals. Most scientists considered them little more than laboratory oddities. Even in the early 1960s, it was not obvious that RCA would be the company to finally move liquid crystals out of the laboratory and into the real world.

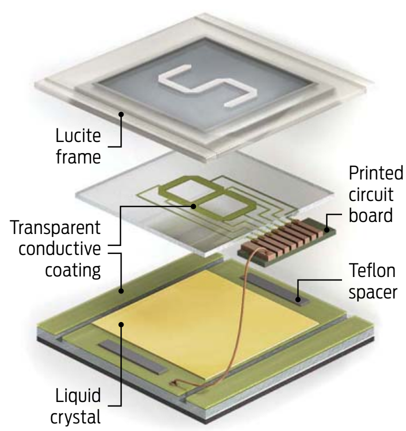
At the time, RCA had only just started to recoup its decadelong investment in color television, and research managers in Princeton had authorized exploratory work to develop a replacement for the cathode ray tube. But the engineers assigned to that project did not consider liquid crystals suitable for such a product. In fact, RCA's initial work on the technology that would become the LCD began as one of those small-scale, open-ended investigations that big corporate labs of that era routinely funded, with no obvious commercial payoff.

Physical chemist Richard Williams wasn't even thinking about displays when he started experimenting with liquid crystals in April 1962. He was more interested in their electro-optic properties. In particular, he wanted to understand how applying electric fields altered the wavelengths of light absorbed by nematic materials. In one experiment, he placed a few grams of a liquid crystal called para-azoxyanisole between two Pyrex slides whose inner faces were lined with a transparent, electrically conductive coating. When he subjected the liquid crystal to a field of 1000 volts per centimeter, he saw a curious "crinkling effect," with a corresponding increase in light absorption. When he removed the voltage, the sample returned to its settled, transparent state.

Before he began these experiments, Williams had envisioned a high-speed light shutter that would, for example, protect a pilot from being blinded by the flash of an atomic bomb. However, after showing the crinkling effect—which he termed domain formation—to his colleagues, he realized that liquid crystals could be used as electro-optic elements in displays, and he composed a patent detailing his ideas.

Despite this early success, he found it difficult to persuade engineers of his new display's practicality. Among other drawbacks, the materials had to be heated to over 117 °C. In the absence of room-temperature liquid crystals, he moved on to other projects.

In all likelihood, Williams's decision would have marked the end of liquid crystal research at RCA had it not been for Heilmeier, who was searching for a way to modulate laser light for use in telecommunications. Existing crystalline modulators were either difficult to synthesize or required too much power. Heilmeier thought Williams's liquid crystals offered an alternative, and in July 1964 he proposed replacing the solid crystals with a pleochroic dye—one whose color depended on its orientation to polarized light—dissolved in a liquid crystal solvent. He would then place this mixture into a "sandwich cell" similar to Williams's, between two pieces of conductive glass. Heilmeier suspected that when a field was applied across this solution, the liquid crystal molecules would realign, causing the dye molecules to rotate and generate a color change when viewed with polarized light.



THE NUMBERS: In RCA's early dynamic scattering numeric readouts, a layer of liquid crystals was placed between a conductive backplate and a front plate with seven segments made of conductive coating. The printed circuit board applied voltage to any given segment, causing dynamic scattering in that part of the cell. To render the numeral 5, it applied voltage to five segments.

ILLUSTRATION: EMILY COOPER

Subsequent experiments confirmed Heilmeier's prediction. Applying just a few volts across the solution could switch its color—for example, from red to transparent. Heilmeier referred to this as the "guest-host" effect, the dye being the "guest" and the liquid crystal the "host." In a series of tests, he applied conductive coatings to the glass in different patterns, along with strategically placed insulating photoresists. In this way, he could produce static images.

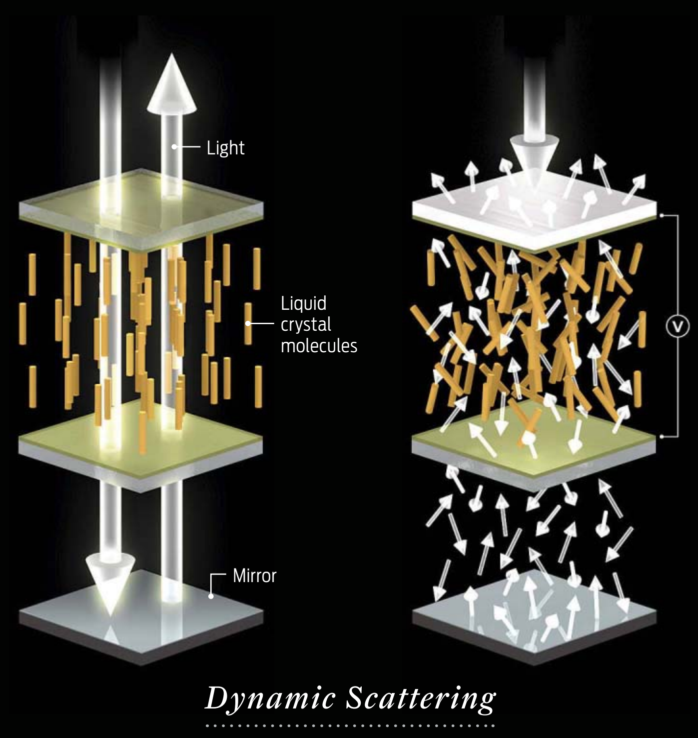
(Today's LCDs are, of course, much more sophisticated, incorporating thousands of picture elements, or pixels, that are individually activated by a corresponding number of thin-film transistors. Each pixel serves as a light shutter, selectively allowing the passage of polarized light. The pixels' high switching speed, measured in microseconds, and tiny size, with widths of tenths or even hundredths of a millimeter, and the inclusion of red, green, and blue filters for an otherwise white backlight enable modern LCD televisions to present full-color moving images—far beyond the simple patterns offered on RCA's early displays.)

Heilmeier, an ambitious 28-year-old, made the rounds at RCA's Princeton lab, demonstrating the guest-host effect. His strategy paid off: By March 1965 his superiors agreed to establish a seven-member LCD research group. This team would more than double in size by the time RCA introduced the LCD to the public three years later.

The researchers soon realized that the guest-host approach had serious shortcomings: The dyes and hosts were unstable, the polarizing filters sharply diminished the display's brightness, and the entire apparatus had to be heated to maintain the liquid crystal phase. Then in May 1965 came a breakthrough: Heilmeier observed what he called the dynamic scattering effect, which required neither dyes nor polarizers. In this incarnation of the "sandwich cell," the sheet of liquid crystal material started off transparent and then turned milky white when a voltage was applied.

Heilmeier and his colleagues hypothesized that this effect was due to ions disrupting the orderly arrangement of liquid crystal molecules under an electric field, like boats pushing their way through a logjam. Later researchers confirmed that the molecules were realigning parallel to the glass plates until a charge buildup caused them to spin, leading to turbulence that randomly scattered light and caused the display to turn opalescent [see illustration, "LCD Approaches"].

Dynamic scattering became the Princeton LCD group's main research priority, and they immediately started working on incorporating the effect into small displays capable of producing static images or simple animations.



LCD APPROACHES

RCA'S DYNAMIC SCATTERING DISPLAYS consisted of two pieces of glass sandwiching a thin layer of liquid crystal material. The inside faces of the glass had a transparent conductive coating [shown here in green]. When a voltage was applied, the molecules realigned and charge began to build up, until eventually they started rotating, causing turbulence that scattered the light and led to a milky white

BY THE TIME Richard Klein saw Heilmeier's prototype in Princeton, the LCD group had taken several important steps toward this goal. Most notably, they had synthesized materials derived from anisylidene p-aminophenyl acetate that exhibited nematic behavior at room temperature, a breakthrough that made commercial applications possible. The group had also built several prototypes, including an electronic clock with a liquid crystal readout and a cockpit display.

To Klein, the most attractive feature of Heilmeier's LCD was its low power consumption. Because it reflected light rather than emitting any of its own, a liquid crystal display could run at voltages and currents compatible with existing integrated circuits. A numeric display, for example, might require only 10 to 15 volts to operate, while the neon-gas-filled Nixie tubes then being used in similar applications required at least 10 times the voltage.

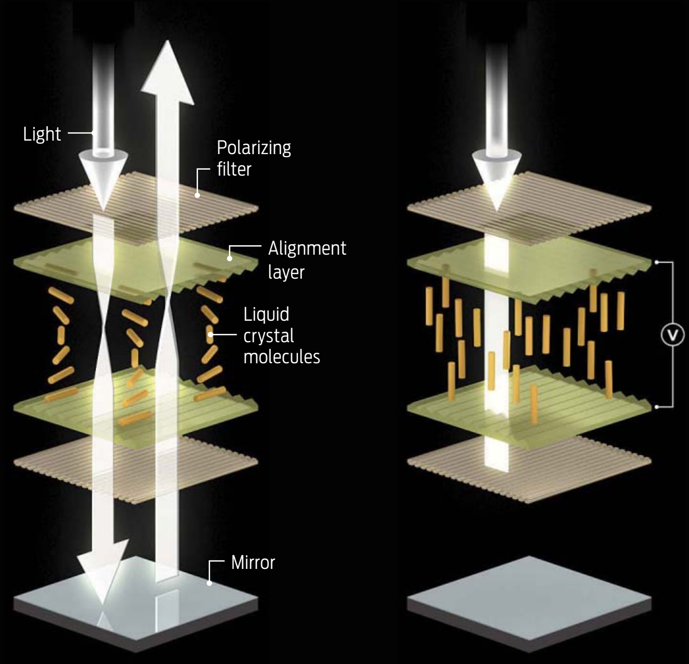
But as much as Klein respected what his Princeton colleagues had done, it was clear that a great deal of work remained before Heilmeier's LCDs would be ready for sale. Klein and his team would eventually transform nearly every aspect of LCD fabrication. These changes included new procedures to generate larger batches of room-temperature liquid crystals and improved techniques to fill and seal the displays.

In 1969, the liquid crystal operation moved to a warehouse in Raritan, N.J., which offered sufficient space for RCA's first LCD assembly line. Auspicious as this move appeared, uncertainty loomed over the project. Despite Klein's best efforts, executives in New York discounted the technology's commercial potential. And so, rather than directly financing the LCD's development, they told the Raritan operation to pursue external funding. Klein's team eventually lined up three contracts. The first was with a public relations firm called Ashley-Butler, which offered RCA US $100 000 to construct an animated display to advertise soft drinks, aspirin, and other products. Veeder Root Co., a producer of gauges and mechanical counters, matched that sum in exchange for a liquid crystal readout for gasoline pumps. And Jervis Corp. supplied $50 000 for an automobile rearview mirror that used dynamic scattering to reduce headlight glare.

The Raritan engineers delivered all three products on time. Still, RCA executives continued to deny the group funding, which worried members of Klein's team, as did the company's unwillingness to endorse what Klein and Heilmeier felt was an obvious LCD product: the electronic wristwatch.

They were not the first to propose such an idea. In the 1965 paper articulating his eponymous law, Gordon Moore had noted that only the lack of a display that could be driven directly by integrated circuits prevented the construction of an electronic watch. LCDs met that criterion, and RCA engineers had already filed a patent application for the concept based upon their dynamic scattering clock. Meanwhile, though, an internal marketing study concluded that the digital LCD watch was at best a

EMILY COOPER



Twisted Nematic Liquid Crystals

appearance. A reflective backplate sent the light back toward the viewer. Patterns could be created by either applying photoresists or by etching away the conductive layer with acid.

Dynamic scattering displays eventually gave way to twisted nematic LCDs. In the latter, light enters through the top polarizer and then twists by 90 degrees along the helix of the liquid crystal molecules before passing through the lower polarizer. When voltage is applied, the molecules straighten out of the helix and no longer redirect the polarized light, so that no light passes through the lower polarizer.

long-term prospect. That conclusion did not prevent Heilmeier from pitching the idea to executives, even as Klein assembled mock-up watch displays.

Despite these efforts, the two men would soon face additional opposition from a particularly imperious manager.

UNTIL THE END OF 1968, the semiconductor division had allowed Klein's group to work with minimal supervision. Shortly before the establishment of the Raritan plant, however, company officials decided that the liquid crystal project needed a more formal management structure. In place of Murray and his laissez-faire style, they named Norman Freedman, who had helped design the assembly lines that produced the first color television tubes.

Freedman was a forceful manager who insisted on maintaining complete control over all aspects of his projects. This approach proved disastrous for the LCD, because it alienated personnel whose support was needed to nurture the emerging technology. Freedman refused to allow collaboration between the LCD facility in Raritan and the semiconductor division in Somerville. "We were told explicitly, 'You may not talk to anybody in integrated circuits,' " Klein recalled. "And we talked to our friends in integrated circuits under the table, and they were told by their managers, 'You are not to cooperate with these guys.' And it was because they all hated Norm." Freedman also promoted outside personnel over veterans like Klein and disregarded input from the liquid crystal researchers in Princeton.

Compounding tensions between Princeton and Raritan was a growing pessimism within Heilmeier's team over RCA's ability to commercialize the LCD. Several researchers, including Heilmeier's long-time technician Louis Zanoni and organic chemist Joel Goldmacher, left the company to join Optel, an LCD start-up firm. Others felt that dynamic scattering had reached its limits and moved on to other projects. Between 1968 and 1970, the number of personnel assigned to LCD research in Princeton dropped by half, to just eight people. In 1970, an exasperated Heilmeier, frustrated with managers who, in his words, viewed liquid crystals "more as a threat than an opportunity," applied for a White House fellowship and departed RCA for a new career in government service.

Heilmeier's decision left the LCD without its strongest advocate at a critical juncture. There were great pressures within RCA stemming from a 1969 order to make computing the company's main strategic priority. That edict came from RCA's CEO (and later chairman) Robert W. Sarnoff, who had succeeded his legendary father, David. RCA had been designing and selling its own computers since the early 1950s, and its Spectra 70 systems were for a time competitive with IBM mainframes. Sarnoff's new strategy spurred a rapid expansion of computer-related projects; in Princeton nearly half the staff was drafted into computer research. Though he harbored no illusions of outselling IBM, Sarnoff vowed his firm would become the nation's No. 2 computer maker.

It didn't. Just two years later, in 1971, RCA sold its computing division to Sperry Rand. The resulting $490 million write-off was the largest such loss to that point suffered by an American business. The news reverberated throughout the corporation, and all projects suddenly fell under scrutiny. The LCD effort was particularly vulnerable. The already dwindling Princeton team shrank to a paltry half dozen, and the majority of the staff at Raritan was laid off. Among the latter group was Richard Klein, who landed a new job with Ashley-Butler, the underwriter of RCA's advertising displays. Freedman, the manager responsible for the liquid crystal operation's isolation from the rest of RCA, retained his position.

THE COMPUTER CRISIS did not kill the liquid crystal operation—not immediately, anyway. What remained of the Raritan group was reabsorbed into the main semiconductor division, and in 1972 RCA announced plans to produce a new line of dynamic scattering numeric readouts. By then, however, it was too late.

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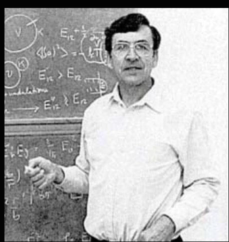
The Road to TWISTED LIQUID CRYSTALS



THE DYNAMIC SCATTERING displays developed at RCA were used in the first liquid crystal wristwatches and calculators. The devices' bright white readouts were well suited for indoor use, but their reflective backplate made them hard to read in sunlight. RCA physicist Wolfgang Helfrich [left] devised a new LCD configuration to solve this problem.

Scientists already knew that you could align the molecules in a nematic liquid crystal by placing them on a glass plate that had been rubbed in one direction with a piece of paper. If you placed the liquid crystal between two such plates and rotated one plate by 90 degrees, the molecules nearest to each plate retained their original orientation, while those in the middle formed a helical structure. This helix, it turned out, could rotate the plane of polarized light.

Helfrich's plan was to sandwich this "twisted" liquid crystal between two pieces of conductive glass and then bookend the glass plates with a pair of crossed polarizers. Normally any light passing through the first polarizer would be blocked by the second, but in this case the helix rotated the light so it could proceed through the cell. If you then applied a voltage, the liquid crystal molecules would align themselves with the field, demolishing the helix and preventing light transmission.

Twisted nematic displays used less power than their dynamic scattering counterparts and had higher contrast in direct sunlight. According to Helfrich, Heilmeier rejected the idea due to its reliance on polarizers. Helfrich left RCA to develop the concept elsewhere. At Hoffmann–La Roche, he and Martin Schadt constructed a functional twisted nematic display in November 1970. A few months later, James Fergason of the International Liquid Xtal Co. filed a patent on a similar device, which he said he had developed in December 1969. Between them, Helfrich, Schadt, and Fergason confirmed the viability of the twisted nematic display and set the stage for the emergence of the modern LCD industry. —B.G.

In affirming its commitment to Heilmeier's technology, RCA was out of step with an increasingly crowded field of LCD manufacturers, including start-ups like Optel and more established electronics companies like Texas Instruments. Most of these firms had phased out work on dynamic scattering displays, whose reliance on reflective backplates led to washed-out images in direct sunlight, in favor of new "twisted nematic" displays, whose contrast actually increased when viewed under similar conditions [see sidebar, "The Road to Twisted Liquid Crystals"]. Ironically, one of the coinventors of this technology, Wolfgang Helfrich, claims to have conceived of the idea while working at RCA. Helfrich recalled presenting it to Heilmeier, only to have it rejected because it used polarizers. A disappointed Helfrich left RCA to join a liquid crystal group at the Swiss pharmaceutical firm Hoffmann–La Roche, where he and physicist Martin Schadt soon constructed a twisted nematic LCD.

Eventually, RCA came around and established a facility dedicated to the production of twisted nematic displays. But much like the Raritan operation that preceded it, the new factory had to fund itself through external contracts; Robert Sarnoff's failed computer venture had left the firm financially wounded and even more wary of side projects. If there was an upside, it was that the LCD had become a more established technology, and firms that hesitated to work with RCA in 1969 were now willing to invest in liquid crystals. Yet RCA's leadership continued to view LCD manufacturing not as the possible future of its display business but as a drain on company profits. In 1976, they sold the entire liquid crystal operation to Timex, which saw the purchase as a means of expediting its entry into the digital watch market.

Few were surprised by RCA's withdrawal from the industry, nor should they have been. For while it was not always obvious, RCA's LCD program had been suffering a slow death since its public unveiling in 1968. Insufficient funds, tensions between scientists and manufacturing personnel, and shortsightedness among both managers and researchers all contributed to its ultimate collapse.

Nevertheless, it would be a mistake to treat RCA's foray into LCD production as an unmitigated failure. Despite ceding its advantage as the industry's first mover, the company had a lasting effect on the course of electronic display development. The sale of its factory to the United States' largest watchmaker, for example, positioned the LCD to become the display of choice in digital timepieces.

RCA also played a crucial role in the emergence of the international liquid crystal industry. Around the time that it introduced LCDs to the public, RCA was also negotiating agreements with a number of European and Japanese TV makers that wanted to license its patents related to the manufacture of color cathode ray tubes. As an inducement, RCA executives would offer licenses on some of its new inventions, including the LCD. Licensees frequently visited RCA's labs, where they would witness demonstrations of the company's liquid crystal technology. Despite frustration among RCA researchers that others were capitalizing on their ideas, company leaders expressed no concern that such arrangements might foster the emergence of new competitors. By the early 1970s, Japanese corporations were already encroaching on the U.S. radio and television markets. Soon firms like Sharp, Seiko, and Sony would do the same with liquid crystals.

Today, companies in Japan, South Korea, and Taiwan dominate the LCD industry. Meanwhile, the corporation that started it all has faded from memory, purchased by General Electric in 1986. Nevertheless, RCA's technological legacy can be seen in every LCD wristwatch, calculator, laptop, and television. All of these screens trace their origins to that firm's laboratories and factories. As much as they are portals to the digital future, liquid crystal displays are also reminders of a past filled with possibilities for the once-dominant American electronics industry. And in their story are lessons for any technology company willing to learn them. ❑

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/lcdhistory1112

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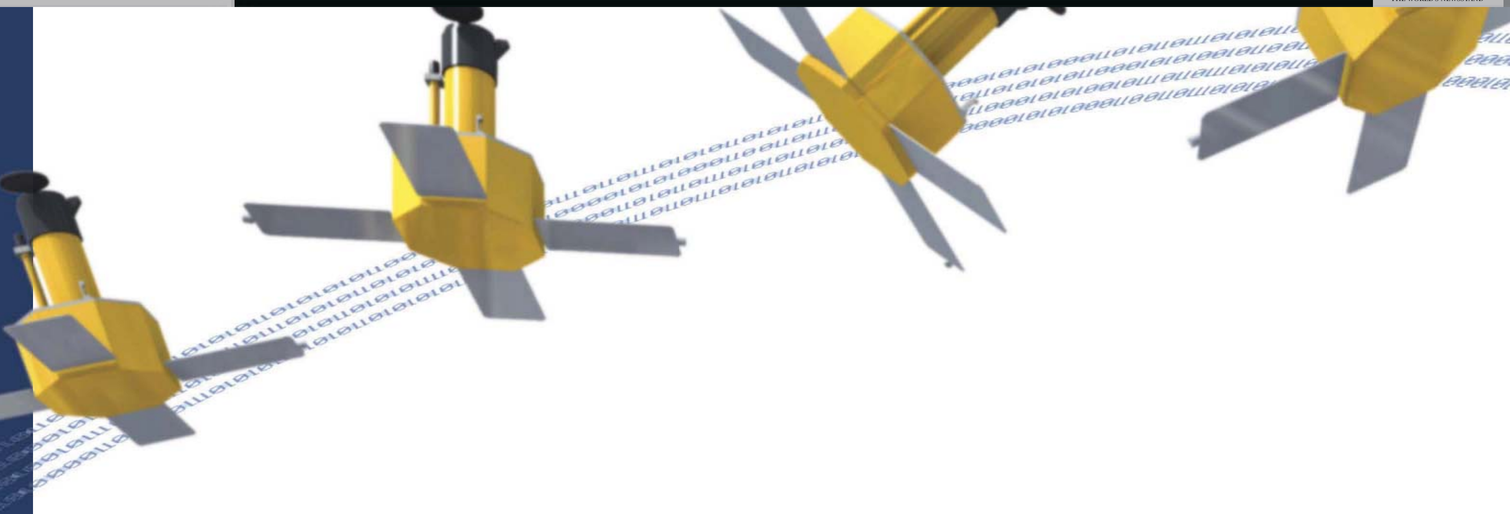


Overclock My Satellite

Sophisticated algorithms boost performance on the cheap

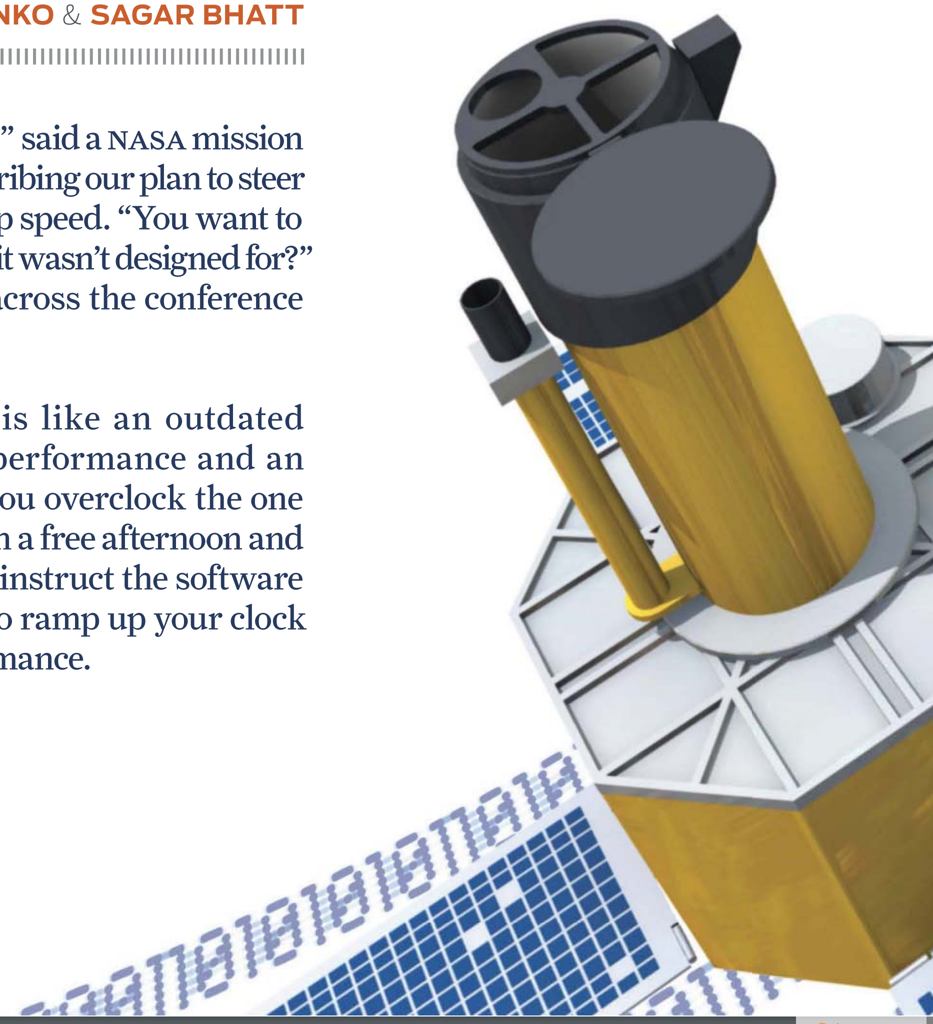
BY **NAZARETH BEDROSSIAN**, **MARK KARPENKO** & **SAGAR BHATT**

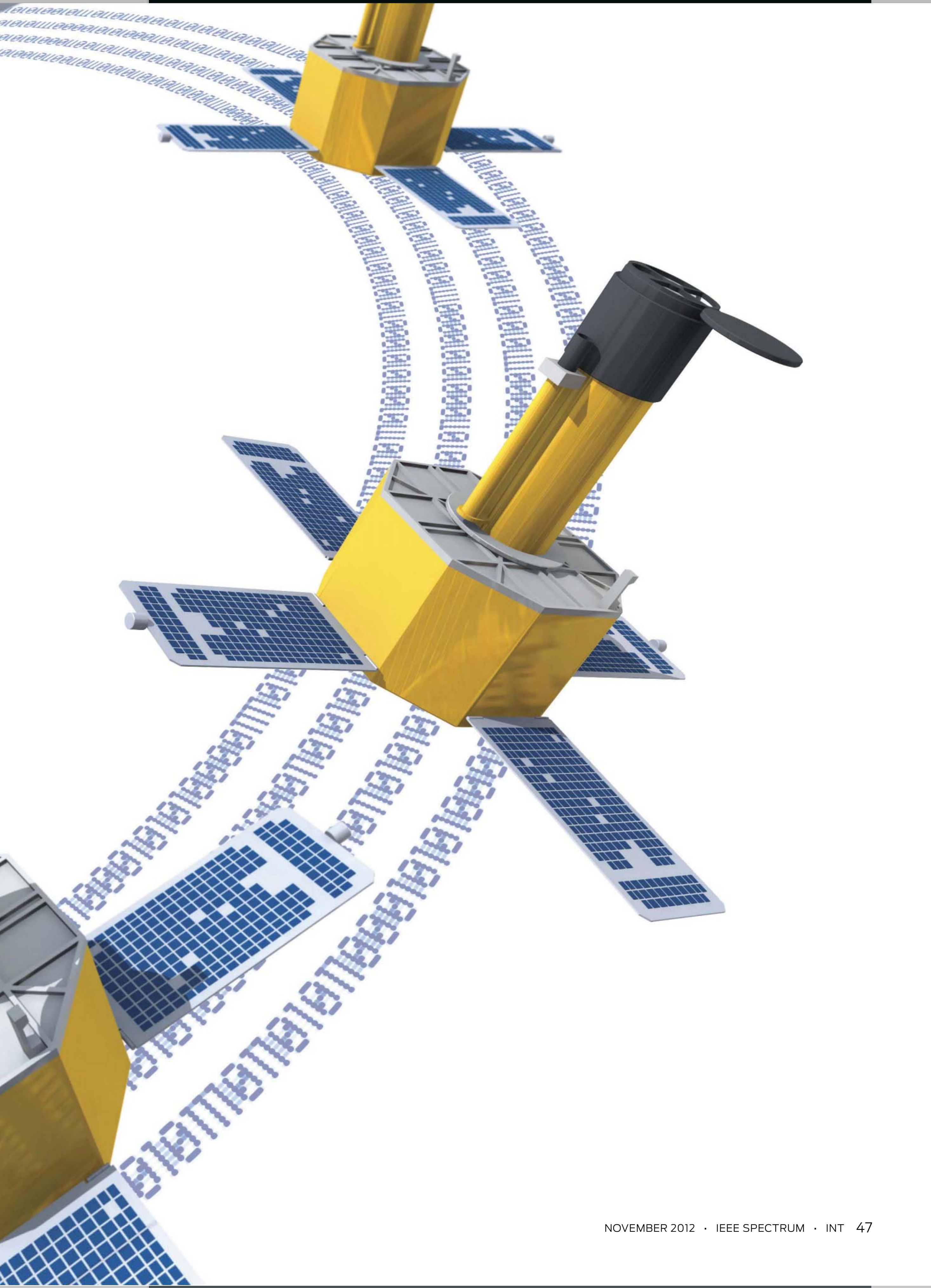
"LET ME GET THIS STRAIGHT," said a NASA mission controller after we finished describing our plan to steer a sun-observation satellite at top speed. "You want to make the satellite do something it wasn't designed for?"

We glanced at one another across the conference room table.

"Well...yeah!"

In some ways, a satellite is like an outdated computer: You want better performance and an upgrade is too expensive, so you overclock the one you've got. With little more than a free afternoon and a bit of hacker know-how, you instruct the software operating your motherboard to ramp up your clock speed, and voilà! Better performance.





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As we told the mission controllers at NASA in 2010, we're taking this concept to a new level by improving the performance of an entire satellite. We're not overclocking its onboard CPUs, but the idea is similar. By carefully choreographing the satellite's movements, we can command it to do something it wasn't originally designed to do—rotate faster. Such speedy maneuvering would allow existing imaging spacecraft, such as military and weather satellites, to more quickly capture time-sensitive events, such as the birth of a hurricane or the movement of enemy troops. And, like a savvy overclocker, we can do this without making any modifications to the hardware.

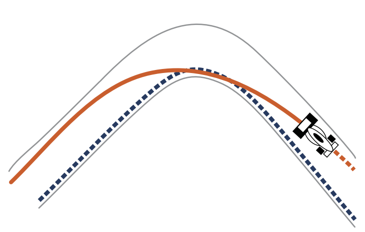
We were confident we could pull off the feat because we had done something similar before. Back in 2007, NASA used a method developed by our team members at the Charles Stark Draper Laboratory in Houston to rotate the International Space Station without using a single drop of fuel. Typically, turning this football-field-size spacecraft—to allow a resupply vehicle to dock at an available port—requires firing its thrusters and can cost NASA upward of US $1 million in propellant.

This time, the Draper group teamed up with engineers at the Naval Postgraduate School, in Monterey, Calif. And in 2010, we carried out our promise to make the NASA observation satellite scan the sky faster than even its mission controllers thought possible. By operating spacecraft beyond their purported limits, we can extend their life and usefulness without installing new hardware and driving up costs.

So how do we achieve this clever hack? Ultimately, we overclock a satellite by uploading a set of precise steering instructions from the ground to its onboard flight computer, essentially overriding its automated route. But that's the easy part. The real challenge is figuring out what those instructions should be, which requires solving mathematical puzzles known as optimal control problems.

That may sound simple enough. After all, we merely want to find the optimal path a satellite must take to reorient itself in the least amount of time or using the least amount of fuel. But we'll give you a hint: The fastest or most fuel-efficient route isn't always the shortest one. When we take into account all the variables that might affect how a satellite moves—its mass, its shape, its altitude, the influence of gravity, and the configuration of its solar arrays, among many other things—the problem quickly grows extraordinarily complex.

Only within the last decade have we achieved the computing power and mathematical algorithms necessary for solving optimal control problems that reflect all the harsh realities of space. Now that we have these tools, their uses are many. Beyond improving satellite performance, we could equip airplanes, ships, and cars with software for solving optimal control problems on the fly, enabling them to compute the best routes based on real-time conditions such as wind patterns, ocean currents, and freeway traffic.



ALL ABOUT THE LINE: Like the "racing line" [orange] followed by a race car, the fastest possible turning path a satellite can take is rarely the shortest one [blue].

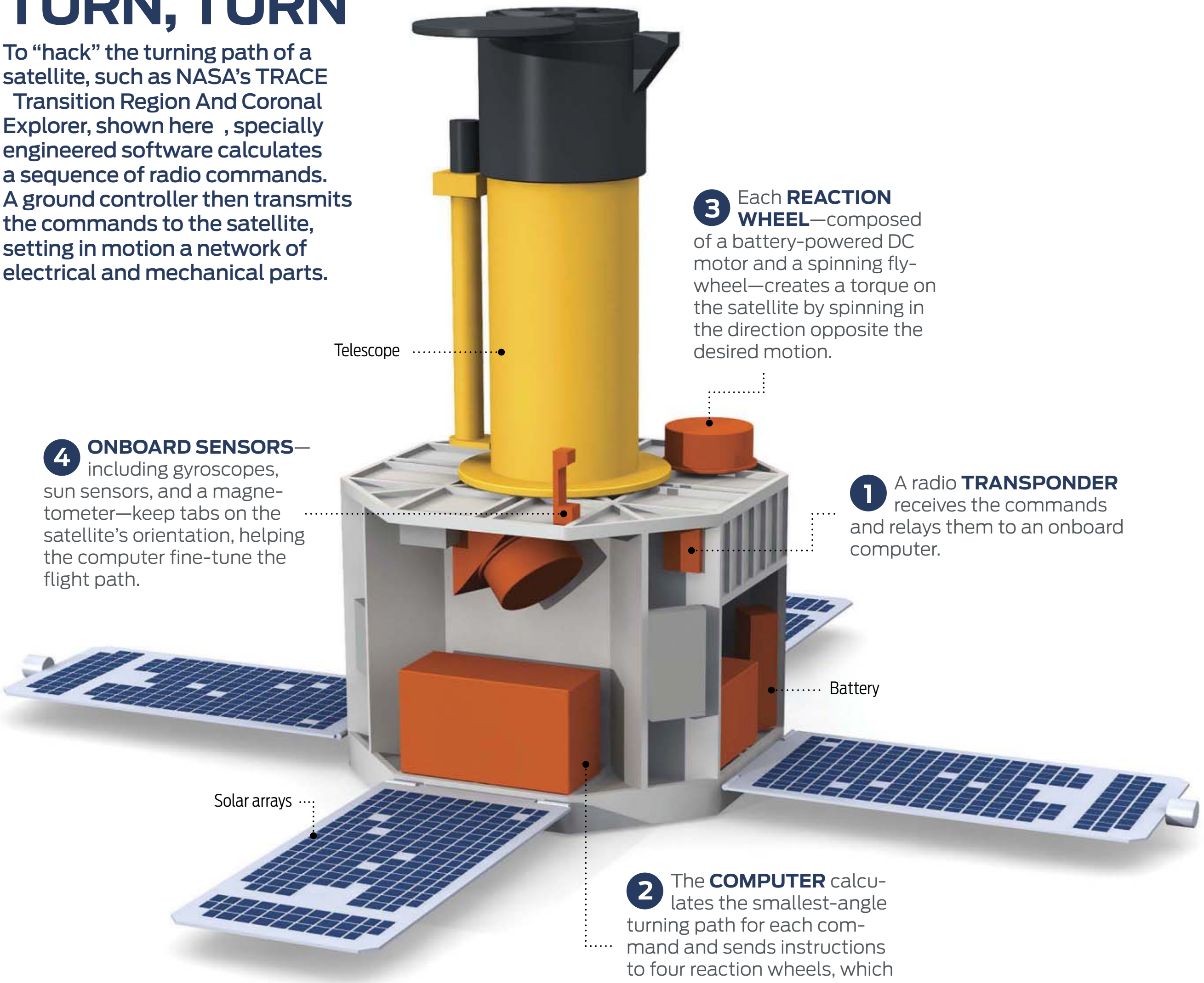
MANEUVERING A SATELLITE takes many steps. In order to rotate an observation satellite toward a new target, for example, an operator must first transmit a command from a ground station on Earth, typically by using frequencies in the S band (2 to 4 gigahertz). A command consists of a target orientation in space and a time code that tells the satellite when to start moving. A radio antenna mounted on the spacecraft receives the signal and relays it to an onboard computer, which stores the command in its memory.

To execute the command, the computer calculates the path the satellite must follow to reach its destination. All satellites today are equipped with basic software programs that simply compute the shortest route from start to finish. This "smallest-angle rotation" describes the arc of a circle, like the path traced by the hand of a clock. The flight computer then guides the satellite along this path by controlling battery-powered electric motors, which speed up or slow down a set of flywheels. These spinning mechanical wheels store angular momentum. When the speed of a flywheel changes, it creates a torque on the satellite that causes the spacecraft to rotate in the direction opposite the change in the whirring wheel. By simultaneously activating several flywheels in different positions, we can direct a satellite to turn in any direction, as a ball bearing would.

Although the smallest-angle path is the most direct and the easiest to compute, it is rarely the quickest or most fuel-efficient way to rotate a satellite. The concept is analogous to cornering in a race car. Drivers know that if they take a corner too sharply at high speed, the sideways force on the wheels will overcome their traction on the road, causing the car to spin out. The driver can maintain a higher speed and complete a course fastest by following the longer arc of the "racing line" rather than hugging the inner, albeit shorter, edge of the track [see illustration, "All About the Line"].

TURN, TURN, TURN

To "hack" the turning path of a satellite, such as NASA's TRACE Transition Region And Coronal Explorer, shown here , specially engineered software calculates a sequence of radio commands. A ground controller then transmits the commands to the satellite, setting in motion a network of electrical and mechanical parts.

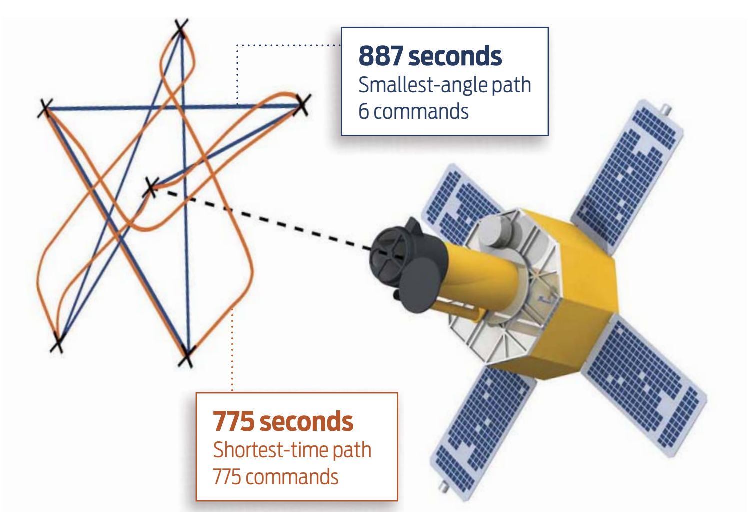


1 A radio **TRANSPONDER** receives the commands and relays them to an onboard computer.

2 The **COMPUTER** calculates the smallest-angle turning path for each command and sends instructions to four reaction wheels, which guide the spacecraft without fuel or rockets.

3 Each **REACTION WHEEL**—composed of a battery-powered DC motor and a spinning flywheel—creates a torque on the satellite by spinning in the direction opposite the desired motion.

4 **ONBOARD SENSORS**—including gyroscopes, sun sensors, and a magnetometer—keep tabs on the satellite's orientation, helping the computer fine-tune the flight path.



DANCING WITH THE STARS

In one experiment with TRACE, mission controllers rotated the satellite to point at six different celestial targets by following two different paths. The typical smallest-angle path [blue] required ust one command per target and took 877 seconds to complete. The shortest-time path [orange], calculated using state-of-the-art optimal control software, required 77 commands total. TRACE executed them all in 77 seconds—a speed upgrade of 12 percent.

PREVIOUS PAGES AND THIS PAGE: JOHN MACNEILL

Steering a satellite is not much different, although here the problem isn't traction but how quickly the flywheels can rotate. Satellites typically have four or more motor-flywheel sets, each oriented along a different rotational axis. Taking the smallest-angle path often limits a satellite to using only a few of its flywheels. So in order to execute a turn more quickly and avoid overburdening its motors, the satellite must take an alternate path. While it may be less direct, the longer path lets the spacecraft make optimal use of all its flywheels at once, generating more torque.

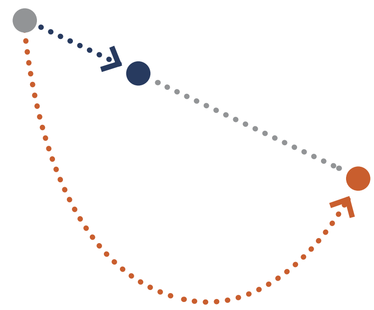
Aerospace engineers have known for decades that when they guide satellites along the shortest path, they can't maneuver them at top speeds. But without sophisticated computational tools, they had no way of knowing until recently what the optimal rotational path should be. The solution, we can assure you, isn't intuitive. In fact, it took many generations of mathematicians and computer scientists to develop the methods we used to solve this optimal control problem.

ANY MATHEMATICIAN asked about the origins of optimization theory will surely recount the story of Queen Dido. According to the Roman poet Virgil, Dido fled her murderous brother's kingdom in what is now Lebanon and led her followers to the coast of North Africa. There, she struck a deal with the locals: She could take a small piece of land, but only as much as she could enclose using the hide of an ox. Dido cleverly carved the ox hide into a long, thin strip, and then laid the strip in a semicircle so that each end dipped into the Mediterranean Sea. Thus she founded the ancient city of Carthage.

Now immortalized among mathematicians as "Dido's problem," the queen's solution describes the largest possible area whose boundary is a line intersected by a curve of a given length. No one knows how she arrived at this result, which mathematicians did not rigorously prove until the 19th century. By then, they had realized that solving even the simplest optimization problems was no easy task. For centuries, some of the greatest mathematical minds struggled to find a systematic way to tackle them.

Another famous optimization problem was posed in 1696 by Johann Bernoulli, an early master of calculus. The brachistochrone problem, whose name is derived from the Greek words *brachistos* (shortest) and *chronos* (time), asked for the quickest path between two points in the presence of gravity. Imagine, for instance, a marble resting on a ledge. Your task is to construct a ramp to roll the marble from the ledge into a bucket across the room. Assuming there is no friction, how would you shape your ramp to plop the marble into the bucket in the least time possible?

At this point, you have probably guessed that the answer is not a straight line. Indeed, many famous mathematicians, including Bernoulli himself, showed that the optimal marble-rolling path is a special kind of curve known as a cycloid, which is generated by tracing the path of a point on the rim of a wheel as it rolls along a straight line. Unfortunately, their methods for deriving this solution worked only for simple problems like the brachistochrone. There were many more optimization problems out there, but still no universal method by which to solve them.



IN GOOD TIME: A famous puzzle asks for the quickest path between two points in the presence of gravity and the absence of friction. By following a cycloid curve [orange], a falling ball arrives at the finish faster than if it had taken any other route, including the shortest one [blue].

In the 18th century, the great Swiss mathematician Leonard Euler finally devised a general approach for attacking these problems. His method involved breaking up a problem into several smaller problems that are easier to solve. Take the rolling marble problem: In reality, the marble is constantly moving, accelerating and decelerating. But if you slice up its motion into a sequence of time-frozen snapshots, like the pages of a flip-book, you create solvable equations with fixed speeds and positions rather than varying ones. Then, by reassembling all your slices, you can find a very close approximation of the solution to your original problem.

Euler's method of discretization eventually evolved into the powerful calculus of variations, which served as the standard for solving optimization problems until about the 1960s. While the technique was great for solving the brachistochrone problem and other relatively simple puzzles, it was of little use for addressing real-world engineering systems. The trouble was that Euler's method considered only how systems change naturally, in the absence of human intervention. The rolling marble, for instance, couldn't be bumped or pushed halfway through its journey.

But most real-world systems, such as airplanes, involve knobs or other controls that can be adjusted to change the behavior of the system. Such variables may include the amount of pressure on a gas pedal or the position of the flaps on an airplane wing. In order to account for them, mathematicians Lev Pontryagin in the Soviet Union and Richard Bellman in the United States expanded on Euler's ideas in the 1960s to develop what is known as optimal control theory.

Yet there was only so much complexity mathematicians could deal with when doing calculations by hand. Computers were ideal for solving optimal control problems, because these problems could be broken down into smaller, parallel parts. And as computers got faster, they were able to solve ever more detailed problems. But there were still some optimal control problems—maneuvering satellites, for example—that continued to fall under what Bellman called "the curse of dimensionality." In order to get an accurate solution, you had to slice the problem into smaller and smaller pieces until eventually, the number of pieces grew so large that the problem became intractable and a computer could no longer solve it within a reasonable amount of time.

In the past two decades, mathematicians have focused on developing more efficient ways of approximating optimal control problems by taking fewer, smarter slices. Rather than divvy up a problem uniformly, these methods tailor the slicing to best reflect how a system is changing. As a very simple example, suppose you're tracking daylight intensity during a 24-hour period and are limited to making just 24 measurements. In order to get the most accurate picture, you would logically want to make more frequent measurements during sunrise and sunset than during nighttime. Researchers are now building these ideas into software packages. For instance, engineer Michael Ross and mathematician Fariba Fahroo at the Naval Postgraduate School, in Monterey, Calif., have developed a computer program that has allowed us to solve even the thorniest problems involving satellite systems.

Appropriately, they have named this clever computer program Dido, in a nod to the queen of Carthage.

It is one thing to develop promising new computational theories but quite another to test them in action. In March 2010, NASA announced it was retiring a veteran sun-observing satellite, the Transition Region And Coronal Explorer, or TRACE. But before mission controllers powered down the spacecraft and shut off communication, its engineers decided to try one last experiment. They knew it was theoretically possible to calculate the commands for rotating a spacecraft at optimal speed, but it had never been tried before on a real satellite. They wondered if TRACE, which had not veered more than 15 degrees during its 12-year life, could execute a "perfect turn."

So they called up Ross at the Naval Postgraduate School and asked if he was interested in putting Dido to work. Ross, in turn, called us. Three years prior, our Draper team members had used Dido to successfully solve a different optimal control problem: the rotation of the International Space Station using no fuel. By making optimal use of gravity and aerodynamic drag, our solution—dubbed the zero-propellant maneuver—guided the station in a long, curved path, such as a boat takes when sailing. The little artificial power needed came from the spacecraft's gyroscopes—spinning momentum storage devices that run on solar-powered batteries and are normally used to make small adjustments in orientation. Although the full 180-degree turn took nearly 3 hours rather than the typical 40 minutes, flight controllers never had to power up the station's fuel-guzzling thrusters.

Our goal for TRACE wasn't to save fuel but to move the satellite faster. The first step was to create a mathematical model of the satellite that was as detailed as possible, incorporating all the physical properties of its various parts and position in space. Next, we had to identify any constraints on its speed. These included the size and configuration of its four sets of motors and flywheels, as well as the quality of its sensors. Because TRACE wasn't designed to move quickly, its three simple mug-size gyroscopes could detect speeds of up to only 1 degree per second—about a sixth that of the second hand of a clock—along each of its three axes of rotation. To keep TRACE from drifting off course, we decided to play it safe and cap its speed at half a degree per second along each axis.

Finally, we plugged all this information into Dido and churned out optimal rotation paths, or shortest-time maneuvers, for TRACE to follow from one destination to another. In all, we choreographed more than 20 different maneuvers—in each case pointing the satellite's telescope at multiple points in the sky. As we expected, the paths were never straight lines. Rather, they looked

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more like the meandering footsteps of a dancer performing a waltz. For this reason, TRACE's flight controllers at NASA took to calling the experiment "dancing with the stars."

Getting TRACE to perform these dance steps required a bit of trickery. The satellite's onboard software, remember, is programmed to guide TRACE along the smallest-angle rotation given a target destination and a starting time. TRACE would therefore execute any commands we gave it using this smallest-angle algorithm. If we wanted the satellite to follow a more complex curve, we had to break up the route into a sequence of very short, small-angle rotations that, when stitched together, closely approximated our original curve. In order to perform a single shortest-time maneuver with TRACE, we had to upload to its onboard flight computer a sequence of several hundred commands.

In total, TRACE can store 900 commands, so we could upload all our commands for a maneuver at once. For instance, we designed one maneuver to point TRACE toward a series of six targets arranged in a star-shaped pattern and uploaded 775 commands to be executed, one every second. To our delight, TRACE dutifully performed them all in exactly 775 seconds. When we directed TRACE in the same maneuver using the typical single command per target, the satellite took 877 seconds to complete these six smallest-angle rotations. The experiment showed that our optimal maneuver could speed up TRACE by more than 12 percent over its normal capability [see illustration, "Dancing With the Stars"].

This may not sound like a dramatic improvement. But given the constraint posed by the satellite's rate sensors, we believe this experiment, though impressive in its own right, underestimates the potential of our technology. In fact, we have tested similar maneuvers on stripped-down replicas of satellites on Earth and were able to increase turning speeds by as much as 50 percent. For a military or weather satellite, such a performance boost could mean the difference between capturing a critical event and missing it. For commercial imaging satellites such as GeoEye and France's SPOT satellites, it could provide a significant bump in business.

It took three centuries to bring Bernoulli's math to market—or 28 centuries, if you concede that his inspiration began with Queen Dido. And the work goes on. Eventually, optimal-control problem-solving software will be built in to satellites themselves. This will allow them to generate optimal maneuvers autonomously and in real time, saving operators even more time or fuel.

One way to do this may be to program a dedicated processing core that could be built in to a satellite's avionics hardware. For example, Elissar Global, founded by Ross and his colleagues in 2007, has developed a processor called the KR8100, which is the world's first embedded general-purpose optimal control computer. (Elissar, by the way, was Queen Dido's Phoenician name.) It's not hard to imagine that someday soon, these smart chips will be installed in airplanes, ships, robots, and perhaps even race cars. ❏

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3-D TV's Toughest Challenge

Continued from page 36

Some 3-D productions start off with a "we can fix it in post" mentality—that is, in postproduction, after the cameras capture the footage and send it to the editors. Fixing problems during production hasn't always been an option in live sports coverage, but today we do have automated systems that can fix some things nearly in real time. For example, most camera systems can't be aligned dynamically in the field, so getting the two stereoscopic images from a camera in perfect alignment doesn't always happen. But an image processor can quickly and automatically correct the most common alignment problems, like vertical shift, focus mismatch, or color mismatch. In the 2-D world, production teams do little postprocessing beyond color correction.

Unfortunately, although automated systems can correct a little vertical alignment mismatch without degrading the image quality much, correcting a focus mismatch is a bigger problem. In general, when matching two images, systems usually defocus the sharper image to match the softer image. You might think that with a stereoscopic camera—in which two almost identical images of the same scene are captured at the same time—information from the sharper image could be used to sharpen the softer image. However, it is precisely the subtle differences between the two images that create the sense of depth. Matching the two images in the wrong way destroys the depth information. With 3-D camera systems, it is far more effective in terms of cost, quality, and time to perfectly match cameras from the beginning and strive for perfect images.

IN THE EARLY DAYS OF 3-D, producers threw people at all these technical problems. People at the cameras and in the control rooms managed the depth budget, alignment issues, graphics placement, and all the other complications of the 3-D broadcast world. These days, however, they're replacing those people with automated systems. Such systems, though, also need more than just the video and audio streams that flow from the cameras to the control room and between the different systems in the control room. They need vast amounts of metadata, including time code, camera name, focus distance, relative vertical position, relative rotation, and color information. That's a lot. The most advanced 3-D production systems available today allow for 256 channels of metadata. And, unlike video streams, metadata isn't flowing in just one direction; the various production systems need to talk to one another.

This requirement for two-way communications is pushing the media production world toward the use of complex networks that route packet-switched data. This change also means production teams need a lot more computing power. Right now, a pair of cameras on the field requires about 2 teraflops of processing power in the control room. That will likely double in the next year or so as computer processing replaces mechanical correction by operators. Then it'll double again in the following two years as automated processing capabilities increase.

Network bandwidth will also need to grow. Right now, each 3-D pair of cameras sends its video and audio streams and metadata at 3 gigabits per second.

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IEEE MEDIA

That will soon double because producers are moving to shooting sports broadcasts in a progressively scanned format that records a full 60 frames per second (50 in countries that follow the European standard). Today, producers use an interlaced format that records only half the frame (every other line) at that rate. Processing needs will double again as more metadata accompanies the video streams. Today's cameras typically have 2K resolution—a bit less than 2048 horizontal pixels—but down the line, cameras with 4K resolution and even 8K resolution will push demands for more bandwidth even further.

Producing live 3-D broadcasts of sporting events has its challenges. But with the right equipment, knowledge, and experience, it should be neither more difficult nor more expensive to produce a 3-D show than a 2-D show. Over time, the equipment will get smaller, cheaper, and easier to use. A few years ago, a general-purpose 3-D camera system with two cameras and two lenses and some onboard signal processing capabilities weighed hundreds of kilograms and cost hundreds of thousands of dollars. Today, such a system weighs 15 kg and costs about US $100 000. In less than five years, an equally capable system will weigh less than 2.5 kg and cost a few thousand dollars.

The final, biggest challenge is not technical but psychological. The 3-D experience often isn't what the audience expects. At 3ality Technica, one of the comments we heard most often from audience members after screenings of the concert movie *U2 3-D* was that they "didn't know what to do." Said one viewer, "I went to see a movie and ended up at a concert, but I couldn't get up and dance or make noise."

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Sports broadcasts in 3-D face a similar problem: They make the remote viewing experience a lot more like the in-person viewing experience, which can seem odd to the viewer. The trick is to make the expectations, the viewing environment, and the content all support one another. When this happens, watching 3-D sports can be uniquely compelling. When it doesn't, the experience can be just plain weird.

Broadcasters have done some experiments. Britain's Sky Sports has had a lot of success showing soccer in pubs, in no small part because of the communal experience. That's surprising, given that all viewers wear 3-D glasses, which would ordinarily make them feel like they're each in a private bubble. To date, the best audience responses I have seen have been where venues created a hybrid environment by mixing in some aspects from the live experience with those of the "standard" remote viewing experience. At some remote football viewing venues, for example, seats are spaced more like those in a stadium, there is much more ambient light than you would expect in a theater, there are live cheerleaders to engage with the live audience—and of course, you can buy beer.

We can't practically put live cheerleaders and bartenders in every living room. But we can figure out how to make the 3-D broadcast version of a live game give you everything you've learned to expect from 2-D broadcasts. The real challenge is, as it has always been, to engage the audience. In that sense, the challenge never changes. ❑

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NSA: MORE FOCUS ON CYBERSECURITY

If information assurance, systems security engineering, information systems management, threat analysis, security production development, computer science, cryptography or vulnerability discovery are on your resume, or even among the skills you would like to develop, the National Security Agency may have a job opening for you.

NSA plans to hire 1,200 people in the upcoming fiscal recruiting year. "At least half and perhaps as many as two-thirds of the new hires might be considered cybersecurity professionals or perhaps science, technology, engineering and math (STEM) professionals," notes Cindy Smith, chief of NSA's Office of Recruitment. "NSA has a long history of successfully attracting people in these fields," says Smith. NSA's approximately 30,000 employees, most of them based at the agency's headquarters in Fort Meade, Maryland, outnumber the workforces of other intelligence agencies, including the CIA.

"We're looking for people across the board, including entry-level individuals," says Smith. "That includes people with military backgrounds who may or may not have directly related college experience, but may have other experience that we're looking for. We hire folks with bachelor's, master's and Ph.D degrees, and we hire people without degrees, but often with some great experience."

When necessary, NSA can fill in the gaps with its very robust training program. "We know that a lot of the work we do is only done here. So, a training and development process is built into our culture," says Smith. The current list of jobs includes multiple openings for software engineers and developers, computer engineers, cryptanalytic computer network operations development specialists, mathematicians and electrical engineers. "These are the types of individuals we have always needed here at the agency. I think that while the competition for these people is tight, it's not something we haven't seen in the past."

"The reason we are successful," Smith says, "is we're always looking. We have developed really good relationships with colleges and universities and the organizations we are affiliated with, and those relationships are long term and deep. Another component of this is the importance that our senior management here at the agency places on hiring. Across our agency, especially these days, we have the highest level of support."

NSA will continue its program of recruiting on college campuses and attending the many professional recruiting events that begin in the fall. And it recruits former military personnel. "There are a lot of folks in the military that may not have completed work towards their degree, but they have that wonderful military training. We look to them anytime we can."

The agency also funds research at universities and sponsors cyber competitions at several schools. "So, we're going right to individuals who are interested in that kind of activity," says Smith.

Signals analysis is a critical technical discipline at NSA and requires specialists in this area to gather and analyze intelligence from foreign signals. Most candidates for positions in signals analysis have backgrounds in computer science, mathematics and engineering. Another area is cryptanalysis, where the focus is on analyzing information systems with the goal of finding hidden aspects of that system and recovering hidden parameters from it. This is one of the areas NSA believes will remain constant in the ever-changing global information security environment.

Of course, anyone who applies for a position at NSA must be a U.S. citizen, and must undergo a rigorous security clearance, even if they have already gone through this process for another agency, and that includes transitioning military personnel.

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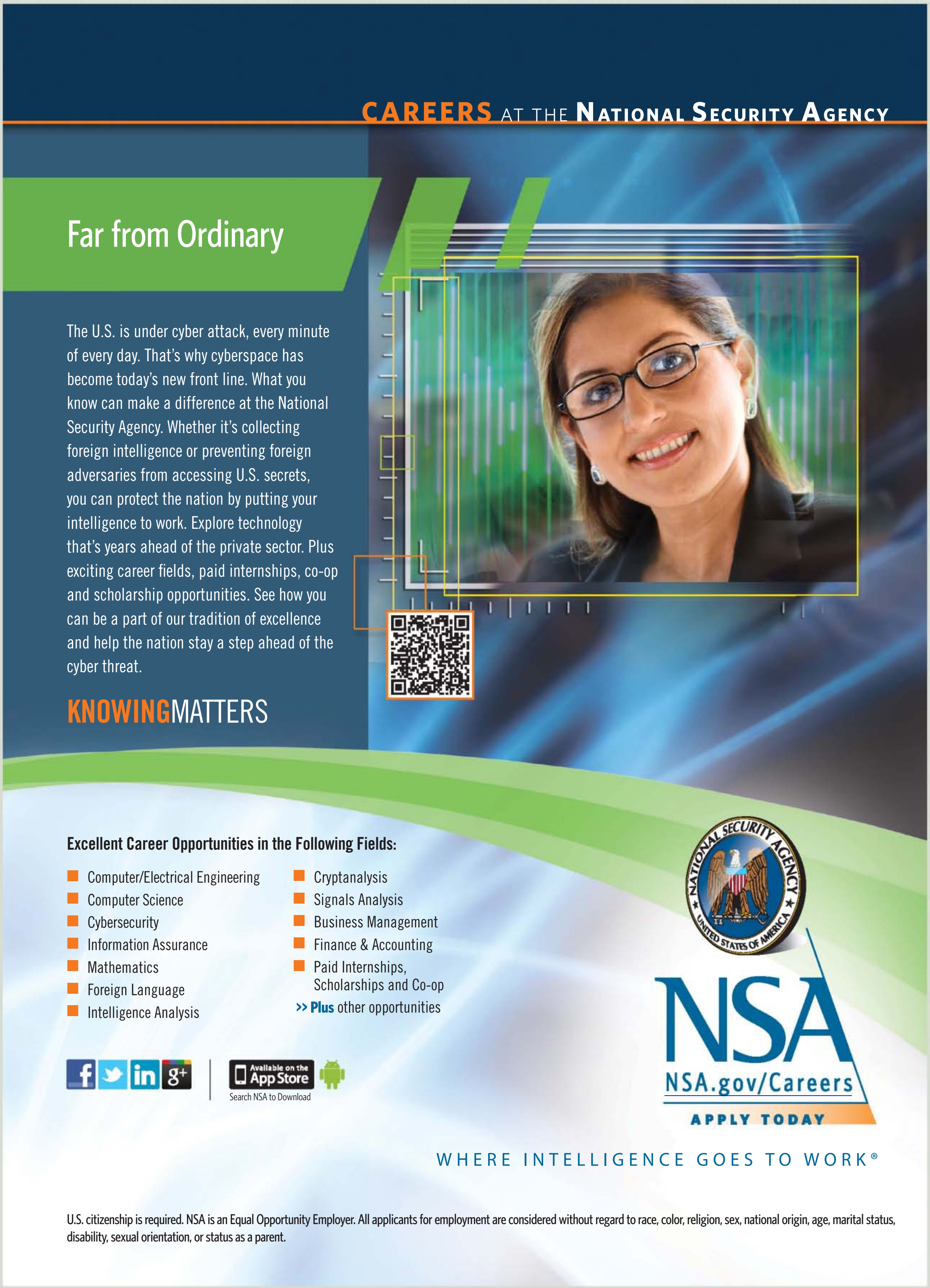
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Erik Jonsson School of Engineering and Computer Science
The University of Texas at Dallas

The Erik Jonsson School of Engineering and Computer Science at the University of Texas at Dallas invites nominations and applications for the position of Executive Director of the Cyber Security and Emergency Preparedness Institute (CSEPI) at UTD. Candidates must have a PhD degree in Computer Science, Software Engineering, Computer Engineering or equivalent, and must have demonstrated leadership ability in developing and expanding funded research programs in the area. A faculty position at the level of Associate or Full Professor is also available in the Department of Computer Science for candidates with a distinguished research and publication record in cyber defense and security.

The Cyber Security and Emergency Preparedness Institute (CSEPI) currently has four centers 1) Emergency Preparedness Center, 2) Global Information Assurance Center, 3) Cyber Security Research and Training Center, and 4) Cyber Defense Center (a 501(c) 3 partnership located at UT Dallas). Industrial experience in dealing with cyber related problems is highly desirable. CSEPI manages major programs that have brought in over $21 million dollars of research over the past 10 years. These programs are both fault tolerant and disaster tolerant and have operated securely over the internet at 99.999% availability. The programs are also certified to BS 27001:2005 in information security and are audited each year. The labs and work areas are both physically and electronically secured 24/7/365.

The CSEPI Executive Director is the driving force behind UT Dallas maintaining its Centers of Academic Excellence in Information Assurance Education and Research awarded by NSA and DHS. The Department of Computer Science offers a minor in Cyber Security. CSEPI awards certificate in information assurance (cyber security) at the bachelor's level and a graduate certificate program at the Master's level upon completion of a set of regular curriculum courses. For additional information regarding CSEPI and the certificate programs please visit **http://csepi.utdallas.edu** .

The University of Texas at Dallas is located in Richardson, Texas, one of the most attractive suburbs of the Dallas metropolitan area. There are over 800 high-tech companies within few miles of the campus, including Texas Instruments, Alcatel, Ericsson, Hewlett-Packard, Nokia, Fujitsu, Raytheon, Rockwell Collins, Cisco, etc. The Computer Science Department has received more than $18 Million in new research funding in the last 18 months. The University and the State of Texas are also making considerable investment in commercialization of technology developed in university labs, with a new start-up business incubation center opened at UTD in September 2011.

The Erik Jonsson School of Engineering and Computer Science has experienced very rapid growth in recent years. The University and the State of Texas are investing significant resources to move towards a Tier 1 status. For more information, contact Gopal Gupta, Search Committee Chair, via email at **gupta@utdallas.edu**.
Apply online at **http://www.utdallasjobs.com**.

The Executive Director is a security sensitive position. The University of Texas at Dallas is an Equal Opportunity / Affirmative Action Employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability, age, citizenship status, Vietnam era or special disabled veteran's status, or sexual orientation.

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Faculty positions in School of Information Science and Technology
ShanghaiTech University

The School of Information Science and Technology (SIST) at the inaugural ShanghaiTech University offers both undergraduate and graduate degree programs in all primary areas of information science and technology. ShanghaiTech is founded as a world-class research university aimed at training future generations of scientists, entrepreneurs, and technological leaders in China. ShanghaiTech is located in the Zhangjiang High-Tech Park in the cosmopolitan city of Shanghai. We are committed to building an open and free academic environment by seeking excellence through diversity and inclusion.

SIST is recruiting highly qualified candidates to fill multiple tenure-track as well as tenured positions at all levels to join us in this exciting inaugural phase. Candidates should have an exceptional track record or demonstrated strong potential in active research areas of information science and technology or closely related fields. Besides maintaining an active research program, successful candidates are also expected to contribute substantially to the educational missions of undergraduate and graduate programs within SIST.

Academic Disciplines: We seek faculty candidates in all cutting edge areas of Information science and technology, with special focus on: advanced futuristic computer architecture and technology, nano-scale electronics, ultra-high speed and low power circuits, intelligent multimedia and integrated signal processing systems, next-generation computer systems, computational foundations, big data, data mining, visualization, computer vision, bio-computing, smart energy devices and systems, highly-scalable and multi-service heterogeneous networking, as well as various inter-disciplinary areas involving the foundation and applications of information science and technology.

Qualifications: Candidates must demonstrate
- a strong interest in undergraduate and graduate education;
- well developed research plans and demonstrated strength;
- Ph.D. (Electrical Engineering, Computer Engineering, Computer Science, or closely related field);
- A minimum relevant research experience of 4 years.

Applications: Qualified applicants are invited to submit a cover letter, a 2-page research plan, a CV including copies of up to 3 most significant publications, and the names of three referees to: sist@shanghaitech.edu.cn.

Mailing Address: School of Information Science and Technology, Shanghai-Tech University Building 2, 319 Yueyang Road, Shanghai 200031, China

ShanghaiTech University Website: http://www.shanghaitech.edu.cn

Deadline: December 31st, 2012 (Late submissions may be considered until all positions are filled.)

Compensation and Benefits: Salary and startup fund are competitive, commensurate with experience and academic accomplishment. ShanghaiTech also offers a comprehensive benefit package to employees and their eligible dependents, including housing benefits.

University of Michigan-Dearborn™

Department of Electrical and Computer Engineering
Assistant/ Associate/Full Professor

The Department of Electrical and Computer Engineering (ECE) at the University of Michigan-Dearborn invites applications for a tenure-track faculty position. Consideration is primarily at the Assistant Professor level but applicants with outstanding experience at the Associate Professor and Professor levels will also be considered. Research thrust areas of interest include power systems, smart grids, and sustainable energy. The successful candidate is expected to develop strongly funded research to enhance the power/energy program in the department.

Qualified candidates must have, or expect to have, a Ph.D. in EE or a closely related discipline at the time of appointment and will be expected to conduct scholarly and sponsored research as well as teaching at both the undergraduate and graduate levels. Candidates at the associate or full professor ranks should exhibit a strong track record in funded research and scholarly work. The ECE Department offers several BS and MS degrees, and participates in three interdisciplinary programs, MS in Energy Systems Engineering, Ph.D. in Automotive Systems Engineering and Ph.D. in Information Systems Engineering. The current funded research areas in the department include intelligent systems, power electronics, hybrid vehicles, computer networks, wireless communications, and embedded systems.

The University of Michigan-Dearborn is located in the southeastern Michigan area and offers excellent opportunities for faculty collaboration with many industries. It is one of three campuses forming the University of Michigan system and is a comprehensive university with over 8500 students. One of university's strategic visions is to advance the future of manufacturing in a global environment.

Applicants should submit a cover letter, curriculum vitae, teaching statement, research statement, and names and contact information of at least three references to *Prof. Chris Mi, ECE Search Committee Chair, 4901 Evergreen Road, Dearborn, Michigan, 48128, or email to ecesearch@umich.edu.* Application review process will begin immediately, but the applications will be accepted until the position is filled.

The University of Michigan-Dearborn is an equal opportunity/affirmative action employer. We are dedicated to the goal of building a culturally diverse and pluralistic faculty committed to teaching and working in a multicultural environment, and strongly encourages applications from minorities and women.

BAYLOR UNIVERSITY

The Electrical and Computer Engineering Department of Baylor University

seeks faculty applicants for two Tenure-Track Assistant/Associate Professor Positions in all areas of electrical and computer engineering, with preference in the areas: embedded systems, computer/network security, software engineering, sensor networks, power, and energy. Applicants seeking a more senior position must demonstrate a record of sustained research funding. All applicants must have an earned doctorate and a record of achievement in research and teaching. The ECE department offers B.S., M.S., M.E. and Ph.D. degrees and is poised for rapid expansion of its faculty and facilities, including access to the Baylor Research and Innovation Collaborative (BRIC), a newly-established research park minutes from the main campus.

Chartered in 1845 by the Republic of Texas, Baylor University is the oldest university in Texas. Baylor has an enrollment of approximately 18,000 students and is a member of the Big XII Conference. Baylor's mission is to educate men and women for worldwide leadership and service by integrating academic excellence and Christian commitment within a caring community. The department seeks to hire faculty with an active Christian faith; applicants are encouraged to read about Baylor's vision for the integration of faith and learning at **www.baylor.edu/profuturis/**.

Application reviews are ongoing and will continue until both positions are filled; however, applications received by January 1, 2013 will be assured of full consideration.

Applications must include:
1) a letter of interest that identifies the applicant's anticipated rank,
2) a complete CV,
3) a statement of teaching and research interests,
4) the names and contact information for at least four professional references.

Additional information is available at **www.ecs.baylor.edu**. Send materials via email to Dr. Robert J. Marks II at *Robert_Marks@baylor.edu*. Please combine all submitted material into a single pdf file.

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

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LAFAYETTE COLLEGE

***Lafayette College** is a selective, private, liberal arts college of 2,400 undergraduates. Our 110-acre campus is located one and a half hours from both New York City and Philadelphia. Degree programs are offered in the liberal arts, sciences and engineering.*

Lafayette College is currently seeking applicants for 2 positions available within our Department of Electrical and Computer Engineering for the 2013-2014 Academic Year.

Visiting Faculty Position – Electronics

The successful candidate will teach undergraduate electrical and computer engineering courses primarily in the electronics area, but ability to teach semiconductor physics preferred. Applicants should possess a Ph.D. degree in Electrical and Computer Engineering or closely related field and must demonstrate a strong commitment to undergraduate education and research.

Tenure-Track Faculty Position – Computer Engineering and Embedded Systems

Applicants should possess a Ph.D. degree in Electrical or Computer Engineering and must demonstrate a strong commitment to undergraduate teaching, mentoring, and research along with potential for multidisciplinary collaboration. The successful candidate will teach courses covering digital systems, microcontrollers, FPGAs, embedded systems, computer organization/architecture, and other courses that contribute to the College's Common Course of Study. Exceptionally qualified candidates may be considered at the Associate Professor level.

Lafayette College's ABET-accredited ECE program features small class sizes, hands-on laboratory experiences, and strong faculty-student interaction. **Applications should include a cover letter, curriculum vitae, and the names of three references and should be submitted by email (preferred) at ecesearch12@lafayette.edu. Consideration of applications will begin in January 2013.**

Lafayette College is committed to creating a diverse community: one that is inclusive and responsive, and is supportive of each and all of its faculty, students, and staff. All members of the College community share a responsibility for creating, maintaining, and developing a learning environment in which difference is valued, equity is sought, and inclusiveness is practiced. Lafayette College is an equal opportunity employer and encourages applications from women and minorities.

國立交通大學
National Chiao Tung University

The College of Photonics, National Chiao Tung University

invites outstanding researchers for faculty positions for the Assistant / Associate / Full / Professor ranks. The starting date of faculty positions is **Aug. 1st, 2013**. The applicants with demonstrated strength in research, commitment to teaching in graduate level, and ability to teach in English, can choose one of the following Institutes of interests:

- **Institute of Photonic System**
- **Institute of Lighting and Energy Photonics**
- **Institute of Imaging and Biomedical Photonics**

National Chiao Tung University has long-lasting been a leading research university in Taiwan. *For more information, please see the website of*

***http://www.nctu.edu.tw/** and* ***http://www.cop.nctu.edu.tw/**.*

Interested applicants should send a cover letter, curriculum vitae, copies of representative publications, photocopy of diploma, research summary and teaching portfolio, and an application form (***http://www.cop.nctu.edu.tw***) with 3 letters of recommendation sent to

Faculty Recruitment Committee, College of Photonics, National Chiao Tung University, Tainan Campus (No.301, Gaofa 3rd Road, Guiren District, Tainan City 711, Taiwan (R.O.C.)) before **Jan. 25th, 2013**.

Contact: Ms. Alva Hsu (***alvahsu@nctu.edu.tw***)

IEEE JobSite

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Take the next steps to finding your ideal job.

The IEEE Job Site can help you explore the engineering career opportunities that may be right for you.

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IEEE

Visit the IEEE Job Site at www.ieee.org/jobs

ROSE-HULMAN INSTITUTE OF TECHNOLOGY

Rose-Hulman Institute of Technology's Electrical and Computer Engineering Department invites applications for tenure-track position(s) that will begin in the Fall 2013. For details, please see our IEEE Job Site Posting at ***http://www.ieee.org/jobs***

Applications must be submitted online at: ***https://jobs.rose-hulman.edu*** and must include: 1) a CV/resume, 2) a cover letter, 3) a statement of teaching that describes your teaching philosophy, and 4) a statement of professional development/research. Screening will begin January 2013. **EEO/AA**

The University of Minnesota – Twin Cities invites applications for faculty positions in **Electrical and Computer Engineering** from individuals with a strong background in core areas of ECE, particularly (1) power and energy systems and (2) systems, communications, and controls, with interests in bio- or medical-imaging, big data, information processing, or systems biology. Women and other underrepresented groups, and those with strong interdisciplinary interests, are especially encouraged to apply. An earned doctorate in an appropriate discipline is required. Rank and salary will be commensurate with qualifications and experience. Positions are open until filled, but for full consideration, apply at ***http://www.ece.umn.edu/*** by January 4, 2013. The University of Minnesota is an equal opportunity employer and educator.

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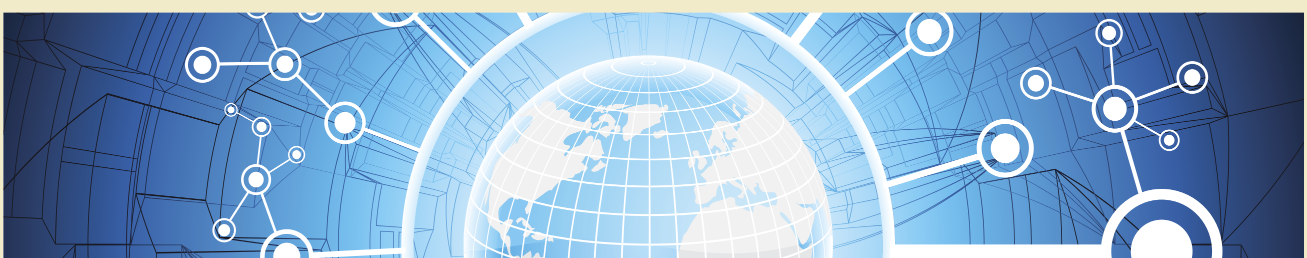

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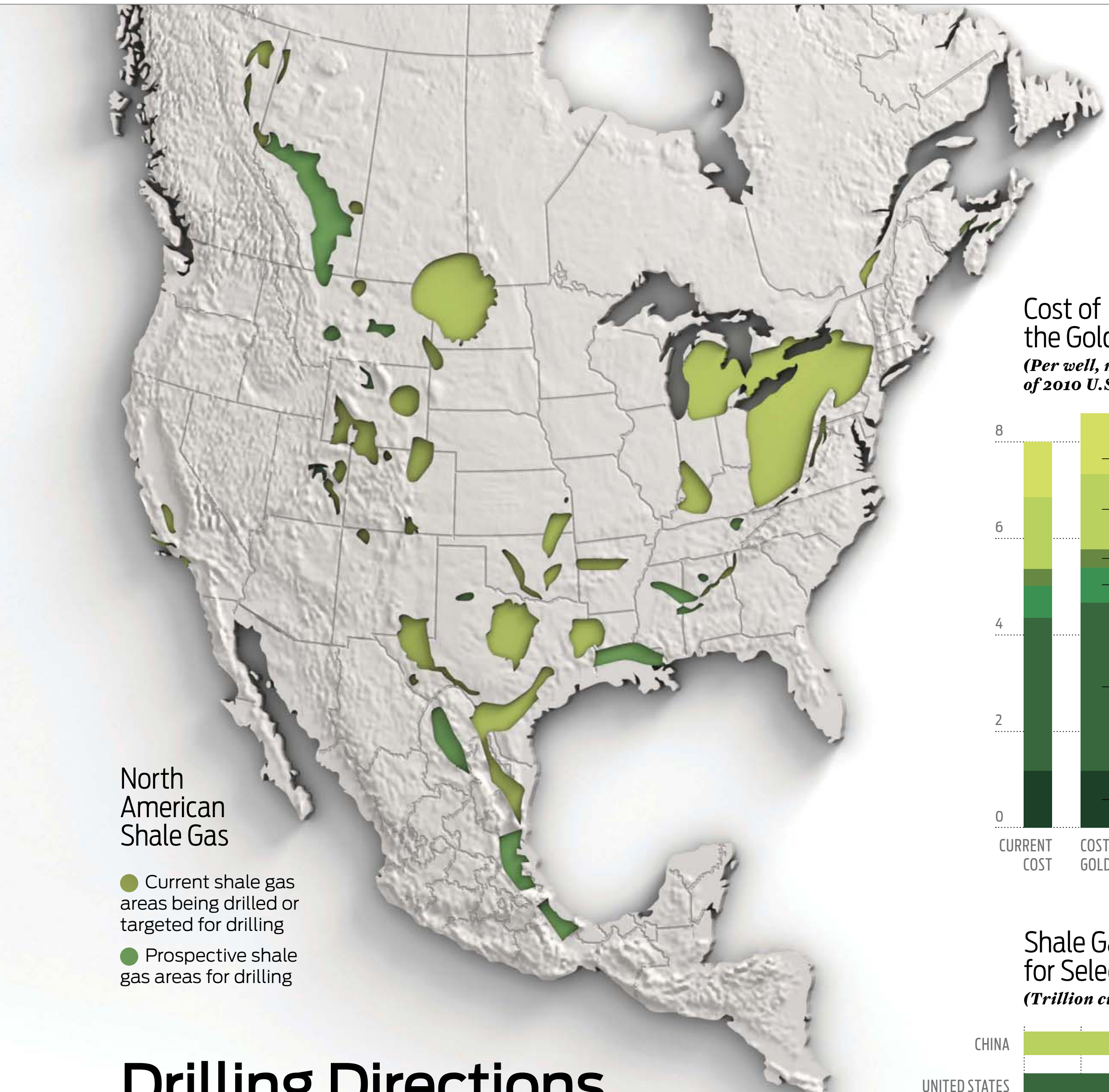
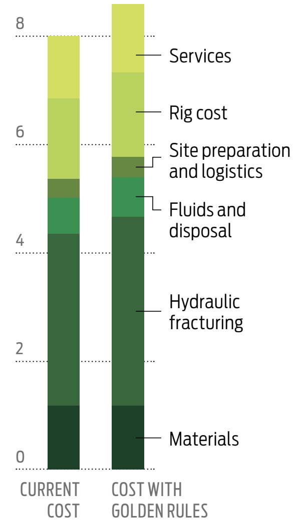


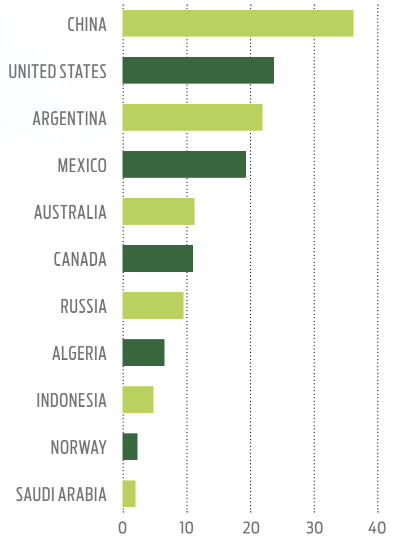
Cost of the Golden Rules

(Per well, millions of 2010 U.S. dollars)



Shale Gas Reserves for Selected Countries

(Trillion cubic meters)



EMILY COOPER

Drilling Directions

THE DISCOVERY and exploitation of vast shale gas reserves has revolutionized the U.S. energy outlook and may soon do the same in parts of Eurasia and China. But the International Energy Agency (IEA), headquartered in Paris, believes the full potential of these reserves will be realized only if "golden rules" for drilling and operating wells are adopted. Otherwise, the industry is likely to incur the ire of citizens worried about environmental damage and could face crippling restrictions.

The rules the IEA proposes are for the most part common sense: Be meticulously careful about where you drill; work closely with local communities and be open with them; don't let wells leak—recycle water and dispose of it correctly; avoid venting and flaring (burning off excess gas).

The IEA estimates that following the rules increases the cost of the average well by just 7 percent, and the payoff is enormous. A golden rules scenario could allow global production of natural gas to triple to 1.6 trillion cubic meters per year by 2035. This would let natural gas, with its lower carbon footprint, come close to a tie with oil as the world's leading primary fuel.

—William Sweet

Sources: U.S. Energy Information Administration, September 2011 (map); "Golden Rules for a Golden Age of Gas: World Energy Outlook Special Report on Unconventional Gas," International Energy Agency, 29 May, 2012 (charts)