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Becoming BIONIC

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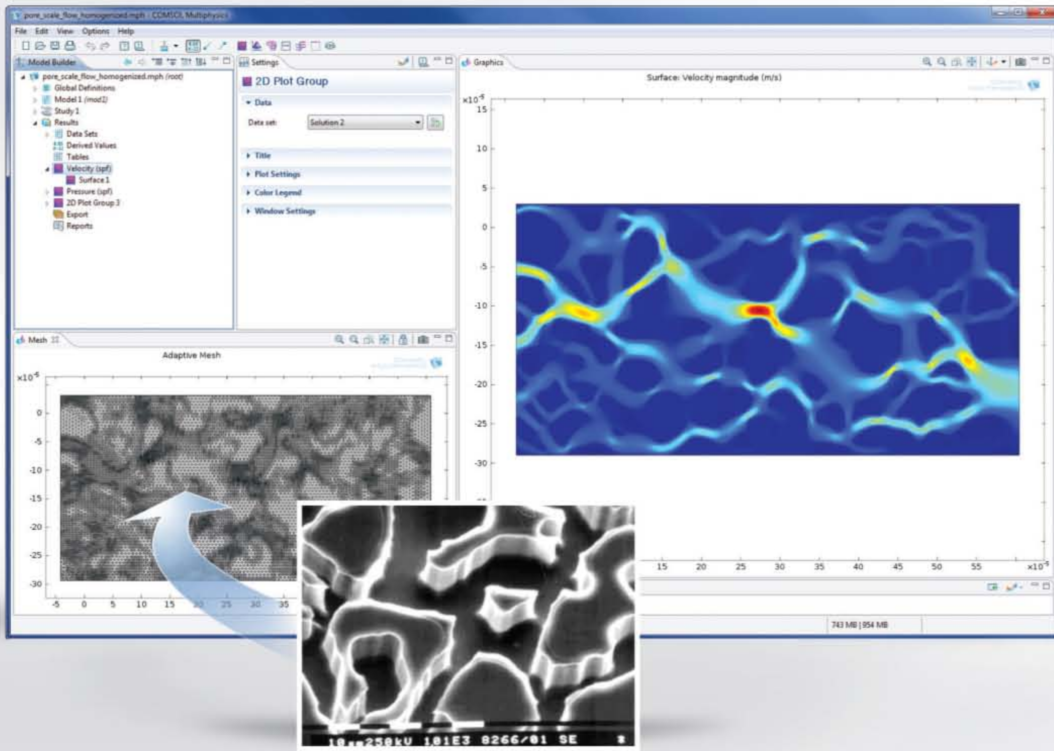
MODELING IMAGE DATA: Image data from a SEM photograph is used to represent material distribution of a porous media. This can then be meshed, using adaptive meshing, and the flow through this media then simulated.



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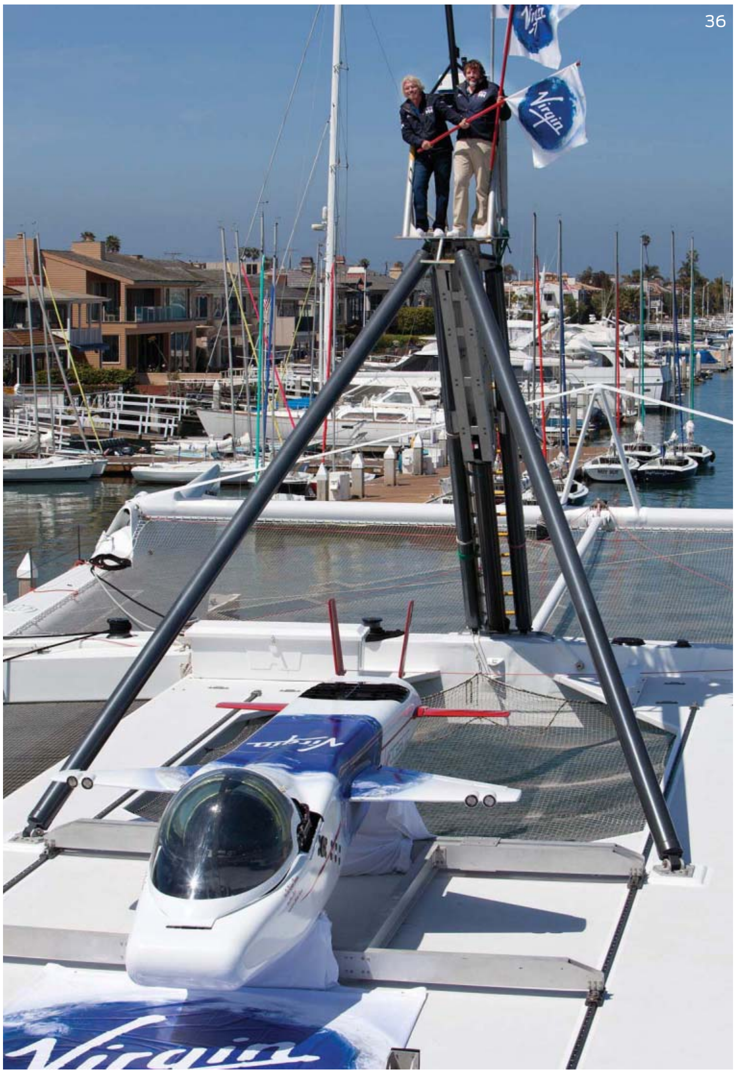

COVER: BRYAN CHRISTIE DESIGN; THIS PAGE, CLOCKWISE FROM LEFT: VIRGIN OCEANIC; JOSHUA J. ROMERO; DAVID ARKY

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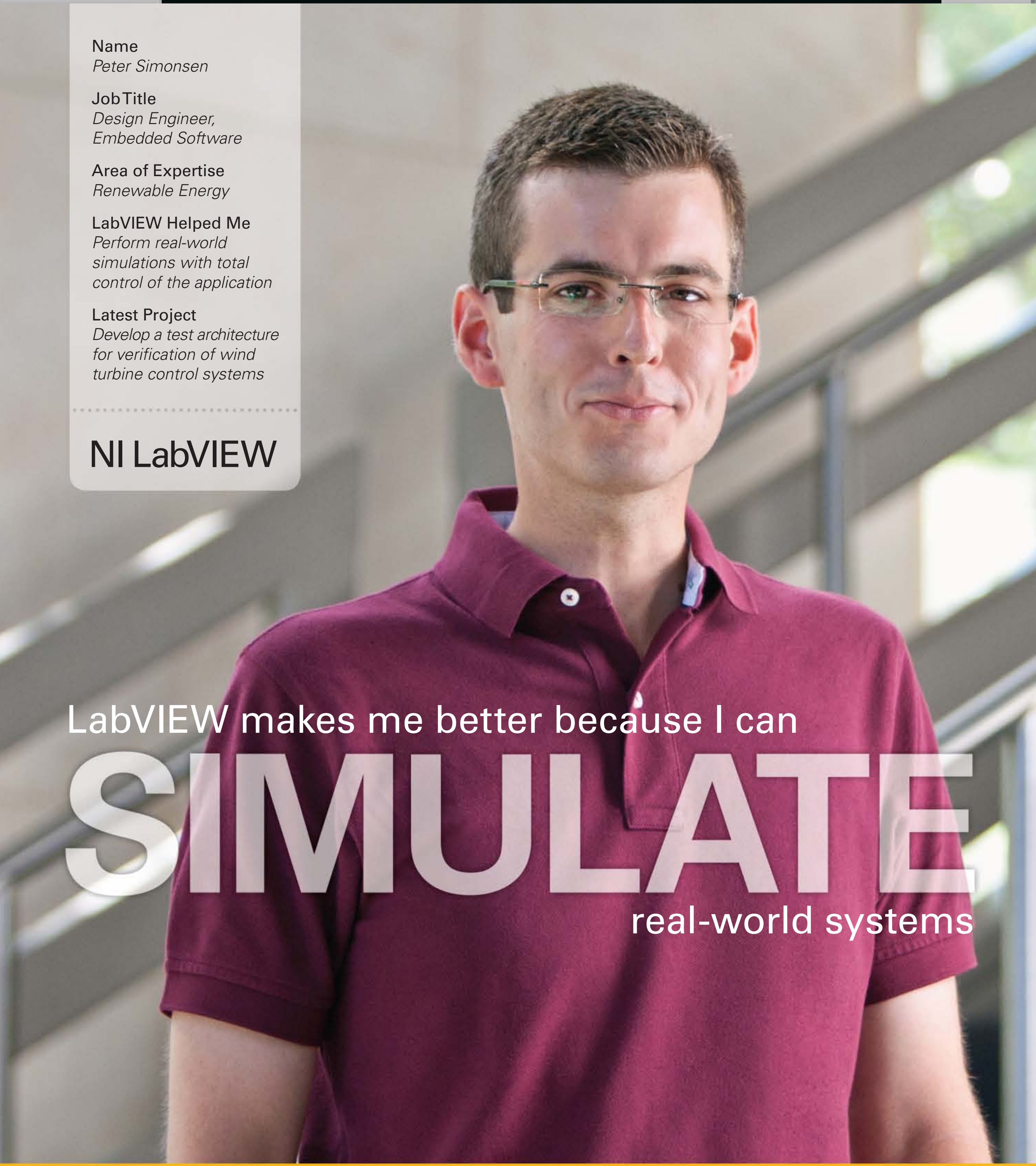
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SPECTRUM.IEEE.ORG AVAILABLE 1 MARCH

Trench Trailblazers

In 1960, two brave aquanauts made the first manned descent to the bottom of the Mariana Trench in an eccentric deep-sea vehicle called a bathyscaphe. To date, no one has repeated their journey. Listen to pilot Don Walsh [front] reminisce about his historic dive at http://spectrum.ieee.org/bathyscaphe0312.

THEINSTITUTE.IEEE.ORG AVAILABLE 5 MARCH

NEW TOOL TO HELP MONITOR THE ENVIRONMENT
Too much data coming from too many sources can be downright confusing. Such is the case with the numerous programs watching events that affect the environment. Luckily, the Global Earth Observation System of Systems is being developed to overcome this challenge.

IEEE MEDAL OF HONOR GOES TO HENNESSY
Fellow John L. Hennessy, president of Stanford University, is the recipient of the 2012 IEEE Medal of Honor "for pioneering the RISC processor architecture and for leadership in computer engineering and higher education."

HATICE ALTUG: DIAGNOSING DISEASE FASTER
When it comes to fighting off disease, early detection is key. But the technology for diagnosing some diseases can be expensive and unwieldy, and the process can be time-consuming. That's where IEEE Member Hatice Altug's portable biosensor comes in.

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CLOCKWISE FROM TOP LEFT: JACEK KADAJ/GETTY IMAGES; STEVE NICKLAS/NOS/NGS; NASA

back story

Penetrating Insight

FINDING PICTURES to accompany the feature article in this issue on LED lighting ("Driving the 21st Century's Lights") wouldn't have been a challenge for the art staff of most magazines. They would have just splashed images of colorful LED-lit homes and offices all over the page. But Photo & Multimedia Editor Randi Silberman Klett and Associate Art Director Brandon Palacio knew that wouldn't do: *IEEE Spectrum* readers don't mind nice pictures, but what they really want are insights into the technology at work under the surface. Palacio and Klett wanted to give them that—literally. So they approached David Arky, one of the few professional photographers familiar with the nuances of X-ray imagery.

Arky began taking X-ray photos more than 15 years ago, when one of his clients asked him to create pictures resembling those produced by the X-ray scanners at airports. "He asked me whether I knew anything about this technique," says Arky, who at the time did not. Undeterred, he accepted the assignment and went searching for an X-ray facility where he could get it done.

Arky soon found a nondestructive testing lab that specialized in making X-ray images of such things as pipeline segments and welds. He continues to use that lab facility, and he still uses film to record his X-ray images, even though the lab now also has the means to capture them using digital flat-panel detectors. "Film still has a little higher sensitivity and resolves a little better," Arky says.

Arky, a technophile, found *Spectrum*'s assignment satisfying on both aesthetic and technical grounds. We asked him to show the full sweep of lightbulb history, from the delicate filament of a reproduction Edwardian-era incandescent bulb to the dense ceramic base of a cutting-edge LED lamp—the Philips unit that captured the U.S. Department of Energy's L Prize. Arky found he needed to combine several different exposures to attain the results he wanted—the X-ray equivalent of the high-dynamic-range imaging that's now becoming so popular.

Arky, a native of New Jersey, always likes working with X-rays, but he confided that this assignment was special to him. "X-ray photos are a marriage of art and science," he says. "Besides, I grew up a mile from where Edison pioneered the lightbulb." ❑

BRYANT CARMONA

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. 3 (INT), March 2012, p. 60, or in *IEEE Spectrum*, Vol. 49, no. 3 (NA), March 2012, p. 68.

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contributors

JOSE M. CARMENA, who wrote "Becoming Bionic" [p. 24], is a professor of electrical engineering, cognitive science, and neuroscience at the University of California, Berkeley. While waiting for a flight at the Columbus, Ohio, airport in 1999, he came across a magazine article about the possibilities of brain-machine interfaces. "I decided I had to get into that field," he recalls. He's now codirector of the Center for Neural Engineering and Prostheses, a joint effort by Berkeley and the University of California, San Francisco.

MICHAEL JAY GEIER began repairing his neighbors' electronics at the age of 8, when he was still small and oscilloscopes were all large. Times have changed. For this issue, he critiques three handheld scopes [p. 18]. An inventor and tech writer, Geier is the author of *How to Diagnose and Fix Everything Electronic* (McGraw-Hill, 2011). He is also a conservatory-trained musician who says, "I enjoy banging out a jazz tune on the harpsichord in my kitchen."

MARK HARRIS, a British writer based in Seattle, got the idea for "A Shocking Truth" [p. 30] when he learned that one in 50 public-access defibrillators have malfunctioned within the past five years. "If 2 percent of iPhones had malfunctioned, it would be headline news," he says, "and yet these lifesaving devices are far more important." Harris wrote our August 2010 cover story about MRI lie detection. He has also covered sleep technology for *The Sunday Times* and open-source surgical robots for *The Economist*.

ROBERT NEUBECKER's whimsical illustrations appear regularly in *Time*, *Newsweek*, and *The New York Times*. For this month's Reflections [p. 23], he depicted mathematics as a museum relic. He has written and illustrated several children's books, including *Wow! City*, which won an ALA Notable Book Award. Neubecker has also illustrated books by Treat Williams and John Lithgow. A longtime New Yorker, he now lives in Park City, Utah.

JAMES TURNER and his 17-year-old son built an extended-range Wii-compatible sensor bar that they were sure other gamers would want to own. So Turner, a contributing editor for O'Reilly Media, created a Kickstarter project, whereby people pledge to buy the product if the venture goes forward. As he describes in "DIY Manufacturing" [p. 20], he quickly learned that mass production, even for 100 customers, brings a whole new set of challenges.

BERNIE WEIR, an application and marketing manager at On Semiconductor, earned his EE degree from the Rose-Hulman Institute of Technology. He began working with the electronics that drive LED lamps in the early 2000s, but only in the past few years have technical developments and industry standardization for LED lighting come together, he says. He describes the electronics that go into this new generation of lamps in "Driving the 21st Century's Lights" [p. 42].

CLOCKWISE FROM TOP LEFT: JOSE CARMENA; ROBERT NEUBECKER; JAMES TURNER; ON SEMICONDUCTOR; ADAM HEARN; BOB LASKY

spectral lines

CHUNG SUNG-JUN/GETTY IMAGES

Lessons From Korea Inc.

WHILE the United States struggles to convert scientific and engineering prowess into commercial victories and robust employment, Korea Inc. is doing exactly that. South Korea's unemployment rate is about a third that of the United States, and household income is about two-thirds of America's—on track to equal the U.S. level in a generation. For a country of roughly 50 million people, lacking in oil and other commodity resources, newfound wealth flows almost entirely from technological advances.

South Korea's ascent is often greeted with astonishment; in the 1960s, the country was poorer than Ghana. Hard work and a zeal for imitating and outdoing the high-tech triumphs of Japan—which occupied Korea from 1910 to 1945—explain some of Korea's rise. So does proximity to China's booming northeastern cities.

But location and Confucian culture is only part of the Korean story. Smart government policies have strengthened Korea's high-tech juggernauts—Samsung, LG, Hyundai, Kia, and Daewoo to name a few—raising high-skill, high-wage employment and increasing Korea's global competitiveness. The experience provides clear lessons for the United States.

Make stuff people need. The United States continues to lead the world in visionary, next-generation science and engineering. But jobs and profits flow from today's products and services. While the U.S. government tends to shun existing technologies, the Korean government lavishes money on its national champions to improve existing systems on the margins. The approach helps Samsung in its rearguard attack on Apple in smartphones, for instance. The lesson is contrarian: Don't get too visionary; avoid getting too far ahead of the market. "We were lucky to have Japan as our learning target," says Keun Lee, an economist at Seoul National University who studies innovation and rapid economic growth. "We copied Japanese policies. We became a fast follower rather than a first mover."

Change comes slower than we anticipate. The United States has directed tremendous sums at alternative energy technologies and futuristic autos. Rather than fund next-gen cars, Korea's government and its favored domestic firms have focused on making incremental improvements in old-tech autos. The result: Hyundai and Kia have posted impressive gains in market share by providing attractive value for money. When approaching electric vehicles, Korea has tackled the critical yet prosaic problem of battery recharging with its on-line electric vehicle system, which uses a wireless power supply.

Glorify engineers and harvest the science of others. Korea puts engineers at the center of its educational universe; science is a relative sideshow. While some of the brightest young Koreans attend U.S. universities, increasingly they're staying at home, fighting for places in such stellar engineering bastions as the Korea Advanced Institute of Science and Technology (KAIST), which is led by an MIT professor emeritus of engineering, Nam Pyo Suh. In areas where world-class science is required, Koreans falter: For instance, the government space agency has repeatedly failed to launch its own satellites, relying instead on Russian launchers.

Go with whom you've got. While the United States opens its doors to the world's technoscience stars, Korea depends almost entirely on indigenous talent. Korea Inc.'s dependence on natives means that Korean families pour resources into education, knowing that their own sons and daughters will win top jobs at home.

The win-now emphasis of Korea's government policies on technology isn't without critics. Some Koreans worry intensely that they have mortgaged the future to win now. The tactic of dominating established technology sectors promises fewer dramatic gains simply because the ripest areas have been taken. Growth must slow.

"We have entered into a cul-de-sac. We are trapped," says Jae-Yong Choung, a professor of management and innovation at KAIST. "How do we escape? How do we build our own unique innovation systems?"

For Koreans and Americans concerned about technological vitality, the revelation is that uniqueness—the radical breakthroughs—may be overblown as a metric of advance. Winning now—mastering everyday technologies that result in value, jobs, and growth—is more important than capturing the notional frontiers of tomorrow. —G. PASCAL ZACHARY

G. Pascal Zachary is a professor of practice at the Consortium for Science, Policy and Outcomes at Arizona State University and a frequent contributor to IEEE Spectrum. *He visited South Korea last December.*

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update

A Test Case for IP in China

Will Chinese courts finally protect foreign intellectual property?

IN THE NEXT few months, a series of lawsuits will play out in the Chinese courts that could define the risks foreign companies take when they try to make money in China's booming markets. The U.S. green energy company AMSC is suing its former customer Sinovel Wind Group Co., China's biggest wind turbine manufacturer, for breach of contract, copyright infringement, and theft of trade secrets. In total, AMSC, based in Devens, Mass., is asking for about US $1.2 billion in damages, making this the largest intellectual property case to date in China.

AMSC appears to have strong evidence, including a full confession from an AMSC employee who said he sold trade secrets to Sinovel. Yet China has a reputation as a place where intellectual property laws are routinely flouted. So the legal outcome is uncertain—and is of great interest to foreign companies.

"There are a lot of eyes on this case," says Jason Fredette, AMSC's vice president of communications and marketing. "Given all the evidence that we do have, and given that this would be an open-and-shut case in any Western court, it is important to see the Chinese courts do the right thing."

Sinovel did not respond to requests for comments, but the company previously released a statement calling the charges "completely false." The company has also filed a counterclaim regarding the contractual dispute.

As of press time, the first legal skirmish—a $200 000 copyright infringement case regarding AMSC's software—had been won by Sinovel, which

RISING POWER: Beijing's Sinovel built China's first offshore wind farm. But the company stands accused of pilfering key technology from a turbine maker in the United States. *PHOTO: PEI XIN/XINHUA/LANDOV*

512 KILOBYTES Capacity of the memory chip the Russian space agency says led to the failure of the Phobos-Grunt mission to one of the moons of Mars.

update

got a full dismissal of the case from a provincial court. But the much larger cases regarding trade secrets and contracts may fare better in the higher courts of Beijing.

AMSC (formerly known as American Superconductor Corp.) sells wind turbine designs and turbine electrical control systems through its Windtec Solutions division. AMSC and Sinovel once had a very close business relationship: Sales to Sinovel previously accounted for about 70 percent of AMSC's revenues. But in March 2011, Sinovel refused a shipment of wind turbine components. "We first thought that this was an inventory issue, and we were understanding," says Fredette. "Then in June we discovered this IP theft, and that changed things quite a bit."

The intellectual property in question is a new software package from AMSC that enables "low-voltage ride through," which allows wind turbines to continue operating during grid outages. AMSC gave Sinovel the software to test, but it had an expiration date that should have shut it down after a few weeks.

When an AMSC employee in China found a Sinovel turbine operating with "expired" software, AMSC quickly fingered an employee in Austria, Dejan Karabasevic. "We had a very limited number of employees who had access to the LVRT software and an even smaller number who had traveled in China," says Fredette. Karabasevic pleaded guilty in an Austrian court and was sentenced to one year in prison and two of probation for stealing trade secrets.

AMSC says it has further evidence, including signed employment contracts between Karabasevic and senior-level Sinovel employees that amount to more than $1.5 million.

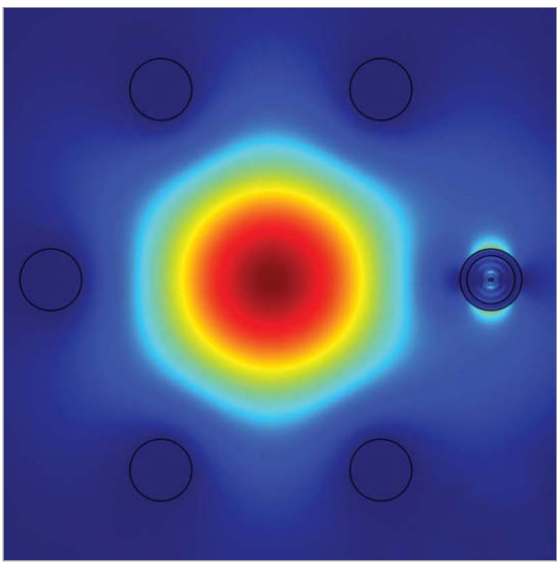
The Chinese courts that will rule on the AMSC cases are aware of the world's scrutiny, says Mark Wu, an assistant professor at Harvard Law School and an expert on intellectual property in China. He says that the Chinese government is trying to shift its economy away from manufacturing and toward research and innovation. "Stronger IP protections are necessary to achieve that policy goal," says Wu. He also notes that more patent and copyright lawsuits are being brought in Chinese courts by Chinese litigants. "So it seems like progress, because there are more Chinese stakeholders," he says.

But, Wu adds, foreign companies are still frustrated with IP theft and dissatisfied with China's enforcement mechanisms. "Often foreign companies get some form of remedy from the courts, but they say that it's insufficient compared to the value of what was stolen," Wu says. "The question really is whether IP enforcement in China is effective from a business standpoint."

AMSC suffered a serious blow when it lost Sinovel's business; since a year ago its stock price has plummeted about 80 percent, and the company has laid off nearly 40 percent of its employees. But as CEO Daniel McGahn said during an investor conference call in September, the company can't afford to withdraw from China. "It is an economic reality that we must do business in China, and I believe we can do it securely and profitably."

If AMSC wins its lawsuits in the Chinese courts, a lot of other companies will suddenly feel more secure, too.

—Eliza Strickland



Electronics in Optical Fibers

In a step toward simpler, faster telecommunication systems, researchers at Penn State University and the University of Southampton, in England, have embedded high-performance electronic devices within optical fibers. Their technique involves depositing semiconductors and metal inside ultrathin holes in the fiber. Using this scheme, they built a detector [circle at right] that converts optical data traveling down the core of the fiber [center] into electrical signals at frequencies as high as 3 gigahertz.

BADDING LAB/PENN STATE UNIVERSITY

LONELY AT THE TOP: A lack of flat land and delayed legislation means that the 10-megawatt solar farm in Osaka prefecture will probably remain one of Japan's largest for some time.
PHOTO: KANSAI ELECTRIC POWER CO.

Japan's Green Dreams Delayed

A year after Fukushima, nuclear power is still down, and renewables are far from ramping up

IN THE WAKE of the Fukushima Dai-ichi nuclear disaster, with nuclear power's future uncertain, Japan's parliament passed a bill in August aiming to boost green energy production. The bill—commonly called the feed-in tariff or FIT law—requires Japan's 10 power utilities to purchase electricity generated by suppliers of such renewable energy sources as solar, wind, and biomass and is slated to go into effect this summer. But its implementation is far from ready, and some energy experts believe it will be decades before it really helps.

The law was passed amid an antinuclear backlash that has seen the country's nuclear power generative capability come almost to a halt. At the end of January, just 3 reactors were operating out of a total of 54. Most were originally closed for maintenance and are now undergoing mandatory safety stress tests or are having test results reviewed. Yukio Edano, head of the Ministry of Economy, Trade, and Industry (METI) said recently that this summer, when electricity demand is at its highest (about 180 gigawatts in 2010), Japan may well have no nuclear reactors in operation.

Yet despite the urgent need to smooth the way for renewable energy, little progress has been made to give the FIT law teeth.

"The price rules, technical standards...money flow and so on have not been decided yet," says Keisuke Murakami, director of METI's New and Renewable Energy Division, whose task it is to flesh out the plan once such details have been decided.

There are also physical obstacles hindering the plan's implementation. With mountainous terrain covering over 70 percent of Japan, flat land for living and agriculture is at a premium. This makes it difficult to install large solar and wind projects.

According to government data, installed and planned solar farms are only around one-tenth to one-half the size of the largest sites in the United States and Europe, limiting their potential and cost competitiveness. It's a similar story for wind generation—393 of Japan's 479 wind power sites have fewer than five turbines. Worse, most wind sites are located in remote, hilly, and mountainous areas. This not only makes installation costly, it also makes turbines less efficient and prone to breakdowns from adverse wind conditions. Because the sites are small and difficult to get to, Murakami says, it usually takes many months for European manufacturers of the turbines to attend to repair requests.

Also, many such farms are set up in northeastern Japan and the northern island of Hokkaido, where good wind conditions exist, but because populations are small in these areas, the electricity grid is limited in reach. Though the FIT law obliges renewable energy plant builders to connect their systems to the grid, given the new plants' poor accessibility, this can be burdensome, and local consumers would be faced with a high surcharge to help cover the costs.

Considering all these challenges, some industry watchers don't see renewables as a near-term energy source. The Institute of Applied Energy (IAE), an independent research organization in Tokyo, estimates it will be several decades before solar and wind energy makes a significant contribution to Japan's energy needs.

"At present, nonhydro renewable energies combined is just 1 percent of Japan's power generation," says Kazuaki Matsui, executive director of IAE. Though supporters of green energy will disagree, Matsui believes it is just not possible to install solar and wind farms in the huge numbers necessary over the next 20 years to make a serious difference. "We might expect some sizable [output] from renewables, maybe in 2050."

—JOHN BOYD

update

A Faster Fast Fourier Transform

New algorithm crunches sparse data with speed

GILBERT STRANG, author of the classic textbook *Linear Algebra and Its Applications*, once referred to the fast Fourier transform, or FFT, as "the most important numerical algorithm in our lifetime." No wonder. The FFT is used to process data throughout today's highly networked, digital world. It allows computers to efficiently calculate the different frequency components in time-varying signals—and also to reconstruct such signals from a set of frequency components. You couldn't log on to a Wi-Fi network or make a call on your cellphone without it. So when some of Strang's MIT colleagues announced in January at the ACM-SIAM Symposium on Discrete Algorithms that they had developed ways of substantially speeding up the calculation of the FFT, lots of people took notice.

"FFTs are run billions of times a day," says Richard Baraniuk, a professor of electrical and computer engineering at Rice University, in Houston, and an expert in the emerging field of compressive sensing, which has much in common with the approaches now being applied to speed up the calculation of FFTs.

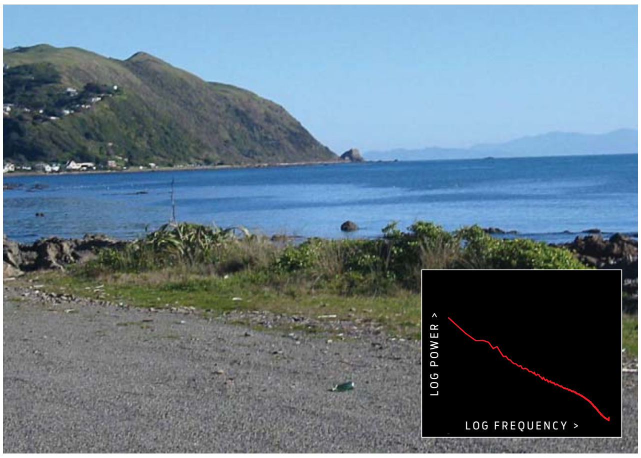
Efforts to improve the calculation of Fourier transforms have a long and generally overlooked history. While most engineers associate the FFT with the procedure James Cooley of IBM and John Tukey of Princeton described in 1965, specialists recognize that it has much deeper roots. Although he never published it, the renowned German mathematician Carl Friedrich Gauss had worked out the basic approach, probably as early as 1805—predating, remarkably enough, even Fourier's own work on the topic.

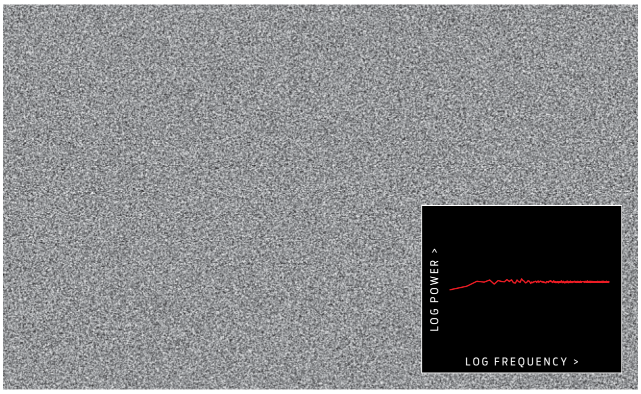
Given that great mathematical minds have been thinking about how to speed up this particular calculation for more than two centuries, how is it that progress is still being made? The fundamental reason is that the newer methods are tailored to run fast for only some signals—ones that are termed "sparse" because they contain a relatively small number of frequency components of significant size. The traditional FFT takes the same amount of computational time for any signal.

"Certainly there are applications where you need to run the full FFT because the data are not sparse at all," says Piotr Indyk of MIT's Computer Science and Artificial Intelligence Laboratory, who developed the new algorithms in collaboration with his colleague Dina Katabi and two students, Haitham Hassanieh and Eric Price. Fortunately, many real-world signals satisfy this sparsity requirement.

"Most signals are sparse," says Katabi, who points out that when you send, say, a video file over wireless channels, transmitting only a few percent of the frequency content is typically sufficient—and in line with the sparsity levels that her group's new algorithms handle well. Baraniuk adds that the frequency content of many natural signals, be they astronomical images or bird chirps, tends to be concentrated among the lower frequencies. "Sparsity is everywhere," he says.

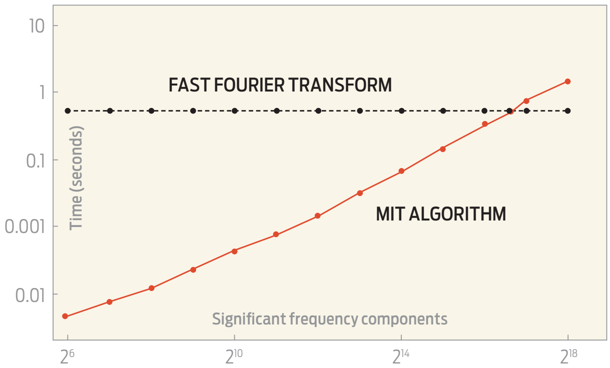
The newest MIT algorithm, which is described in a soon-to-be-published paper, beats





EVERYDAY SPARSITY: Natural signals [top] are often "sparse," which means they have relatively few frequency components of significance. A random image [bottom], however, contains significant components at all frequencies. The new fast Fourier transform algorithm accelerates calculations on sparse signals only. *IMAGES: STEVE HAROZ*

1.2 MEGAVOLTS Capacity of the highest-voltage circuit breaker yet made. Siemens plans to install it on a test transmission line in Bina, India.



SPEEDY: A new algorithm computes quickly when the signal it's working on has few important frequency components.

the traditional FFT so long as the number of frequency components present is a single-digit percentage of the number of samples you take of the signal. It works for any signal, but it works faster than the FFT only under those conditions, says Indyk.

Experts say the new algorithms coming from MIT represent considerable progress. "They've added some very smart ideas to the recipe," says Mark Iwen of Duke University, in Durham, N.C., who had earlier worked on the same problem with Anna Gilbert and Martin Strauss at the University of Michigan. The time it takes Iwen's best FFT algorithm to run increases in proportion to the fourth power of the logarithm of the number of samples, whereas the newest MIT algorithm has a run time that's proportional to just the first power of that number. "Removing those log factors is incredibly difficult," says Iwen, who also credits the MIT group for coming up with impressively fast computer implementations of their new algorithms.

Indyk points out that the library of code his group (and many engineers) uses to calculate the traditional FFT was released in the 1990s—three decades after Cooley and Tukey had worked out the basic computer procedures required. "We don't plan to spend 30 years developing a library," he says. "We plan to release our prototype code soon; researchers can just play with it and see what happens." Then, in something like six months, the MIT group should be able to provide a well-tested, portable library.

Why so long? "Developing decent code takes time," Indyk says. But there's another thing, he points out, that's bound to delay their release of a well-tested software library: "Every month or two we have a new idea."

—DAVID SCHNEIDER

Virtual Power Plants, Real Power

Five kilowatts here, a hundred kilowatts there—with a smart grid, it all adds up

THE DANISH island of Bornholm, a quiet farming and fishing community of 42 000 in the Baltic Sea, will soon be home to one of the world's smartest smart grids. Through the four-year, €21 million (US $28 million) EcoGrid project, about 2000 households there will be connected to an island-spanning network that will enable homeowners to cut back their electricity usage at times of peak demand and sell that unused wattage back to the grid at market rates. Managing all of these thousands of discrete energy trades, as well as Bornholm's other power resources—including 36 megawatts of wind power, a 16-MW biomass plant, and a new fleet of electric cars—will be a central control system that behaves very much like a traditional power generator. Only this generator will be created entirely through software—a virtual power plant.

As its name implies, a virtual power plant doesn't exist in the concrete-and-turbine sense. Rather, it uses the smart-grid infrastructure to tie together small, disparate energy resources as if they were a single generator. Just about any energy source can be linked up. And energy that's *not* used can also contribute to a virtual power plant's capacity.

Here's how that will work: Households on Bornholm will be equipped with gateway controllers, which in response to spikes in electricity prices and the homeowners' preferences will automatically be able to turn off appliances or adjust the thermostat. The unused electricity can then be aggregated by the virtual power plant, along with other actual energy resources, and sold to customers who need power during peak times. Without the virtual power plant, the utility's only other option for meeting peak loads is to ramp up production, which can get very expensive, says Kim Behnke, head of R&D and smart grid development at the Danish utility Energinet.dk, which is overseeing the EcoGrid project.

The first virtual power plants came online about 10 years ago, mainly as research projects, says Thomas Werner, a product manager in Siemens's smart grid division who oversees the company's virtual power plant projects. But

update

in the last several years, he says, energy market players have come to accept the virtual power plant as a commercially viable alternative to adding new capacity, as well as a way to handle the variability of renewables.

"Rather than having all these 5-kilowatt photovoltaic sources, you have a 100-MW virtual plant that for the utility is much more manageable," says Peter Asmus, a senior analyst at the market research firm Pike Research. "And it's temporary—you might stitch together those resources for just a half hour, to help meet peak demand." Pike Research estimates that the worldwide capacity of virtual power plants could grow from 45 gigawatts last year to as much as 105 GW by 2017, with revenues of about $6.5 billion.

A virtual power plant also lets smaller energy producers take part in energy markets from which they might otherwise be excluded. One plant set up by Siemens aggregates 1450 MW of capacity from small generators installed in hospitals, industrial facilities, and commercial buildings throughout Germany. Ordinarily, each of these units would be used only during emergencies and only to power its particular site. Hooked up via the virtual power plant, they can now be fired up whenever market rates or grid conditions make it worthwhile.

A remaining challenge, Werner says, is that there is no standard interface between the central control system that manages and optimizes the virtual power plant and the distributed energy resources out in the field, many of which may not have been designed to communicate with an IT network.

The virtual power plant concept is an obvious culmination of the decadelong push to deploy smart meters, sensors, and other infrastructure, says Amit Narayan, director of smart grid research in modeling and simulation at Stanford University. "If you think about the evolution of the Internet, it's the same thing," he says. "Somebody had to lay the wires and build the infrastructure, but once that's in place, a lot more can be done in terms of creating new applications."

And in much the same way that Google, Facebook, and Amazon troll through user data to discern subtle patterns in people's tastes and then try to influence their buying habits, Narayan says, virtual power plants give grid operators the means to study their customers' electricity usage and then try to get them to modify their behavior in a way that increases the capacity of the virtual power plant.

Indeed, changing people's habits should be one of the chief outcomes of the Bornholm project, says Behnke, because when consumers use less electricity, they'll not only reduce their electricity bill, they'll also get a bonus based on the market price for the electricity at that time. "We hope to show that even these small customers can help balance the grid, based on actual need within the hour," he adds. His company estimates that the virtual power plant should help reduce peak loads on the island by at least 20 percent.

While Denmark already has a number of virtual power plants, they're all designed to allow large electricity customers to trade energy in the day-ahead market, Behnke says. "That's what we call Smart Grid, version 1. Now we are going for Smart Grid, version 2." —Jean Kumagai

BRIGHT GREEN: Denmark's Bornholm Island will soon have the world's most advanced virtual power plant, as part of a €21 million smart grid project.
PHOTO: JACEK KADAJ/GETTY IMAGES

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the big picture

GET UP AND GO GREEN

Matevž Lenarčič, the pilot of this Pipistrel Virus SW 914, aims to fly it into the record books as the lightest-ever plane to circumnavigate the globe—and the one to make the trip on the smallest amount of fuel. During the journey, which is being called GreenLight WorldFlight, the Slovenian biologist plans to take measurements of climate-changing aerosols in areas of the sky for which climatologists currently have no data. On 8 January, Lenarčič took to the skies in the 284-kilogram plane—which can fly 4000 kilometers on 350 liters of gasoline. The 80 000-km trip is expected to take about two months.

PHOTO: SRDJAN ZIVULOVIC/REUTERS

hands on

POCKET SCOPE ROUNDUP

We put three miniature oscilloscopes to the test

Ever knelt behind a home-theater receiver, tangled in wires, trying to figure out why nothing's coming out of the stereo speakers? Is the cable bad? Is the cable box even putting out the digital audio signal? Oh, if only you could whip out a scope from your pocket and check. As it turns out, you can. Here's a look at three pint-size oscilloscopes.

Perhaps the most ambitious pocket scope yet attempted, the **DSO Quad (1)**, from Seeed Studio, is smaller than a smartphone. It offers four input channels (two analog, two digital), a gorgeous, high-contrast, active-matrix color screen, and measurements galore. Peak-to-peak voltage, duty cycle, frequency—you name it and this scope will measure it. That is, once you calibrate the thing! The Quad comes completely uncalibrated, requiring you to adjust tiny trimmer capacitors and perform a multistep firmware voltage calibration as well.

All this power is wrapped up in one of the most convoluted user interfaces I've ever seen. Eventually, you'll get the hang of its four push buttons and two multipurpose swivel controls, which move back and forth and also up and down. The interface will surely improve, because the Quad is an open-source project. Such goodies as audio frequency response plotting and fast Fourier transform analysis, as well as bug fixes, have been released or are in development.

Remarkable as it is, the Quad is still more of a hobbyist's gadget than a serious instrument. Despite its admirably fast sampling rate, the op-amp–based analog front end exhibits quirky, inconsistent response, which limits the bandwidth and accuracy. Some of the displayed measurements are wildly wrong. The Quad is great for casual waveform viewing, though, especially if you need to see multiple signals. It even includes a crude but useful function generator that outputs sine, square, triangle, and sawtooth waves.

The Quad comes with two analog probes and a USB cable for charging its internal lithium-ion battery. You can download a manual at Seeedstudio.com.

Offered through RadioShack, the **Velleman HPS140i (2)** is a much more straightforward, finished product. With only four buttons, it is easy to use. There are only two menus, and functions are logically grouped. Some key settings, including voltage scale, time, and input coupling, don't require the menus at all. The sole input channel has a standard BNC connector on top of the case, right where it should be for handheld operation. A rubber shell protects against drops and bumps.

This unit has an unusually wide and very readable screen. Available measurements include peak-to-peak, dBm (decibels referenced to one milliwatt), and Wrms (weighted root mean square) for speaker impedances from 2 to 32 ohms. Clearly, this scope is aimed at audio work, but it has enough bandwidth for low-frequency pulse and RF applications too.

The HPS140i has one fantastic feature every scope should include: fully automatic setup. It's the scope equivalent of autoranging on a digital

RANDI SILBERMAN KLETT

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multimeter, or DMM. Apply a signal and the unit quickly selects vertical and horizontal settings to show you a couple of cycles of the waveform. Nice! You can turn it off, of course, and you can save waveforms to memory, too.

This is a solid, no-frills package that slips effortlessly into a pocket or any bag of tools. It comes with a USB charging cable, a switchable 10x/1x probe, and a handy calibrator square wave terminal on the back for setting the probe compensation. The manual is brief, but there's more info at Vellemanusa.com and Hps140.com.

Calling the third oscilloscope, the **Uni-T UT81B (3)**, a pocket scope might be accurate if you've got very large pockets. While smaller than most handheld scopes of the past, it's much bigger than the other two units. It looks like an overgrown multimeter. And that's basically what it is—a digital multimeter that can display waveforms. The Uni-T offers both DMM and scope modes and can read voltage, current, resistance, diode voltage drop, frequency, and capacitance. True to its multimeter roots, it uses banana plugs for input. An optional BNC converter is mentioned in the manual but is not included. It isn't shown on Uni-T's website, either.

The user interface is well considered. Like the Velleman, this scope offers auto setup, and it can save waveforms to memory. It even includes PC software and an opto-isolated USB cable for use as a real-time PC scope. One nice DMM feature is the "relative" mode, in which the displayed reading is subtracted from the values to be measured. It's especially useful for canceling out residual capacitance when measuring capacitor values or for matching resistors. In scope mode, you can view measurements of current, something you can't do on most scopes.

Alas, even with contrast and brightness cranked way up, the screen is dim and washed out, although it looks better under a lamp. Worse, the scope is always DC coupled, even when set to measure AC. This design flaw severely limits the instrument's use as a scope, because AC coupling is a critical function for viewing signals riding on DC voltages. The only way around the problem is to build a probe with a switchable blocking capacitor in it.

The UT81B comes in a nice zippered case, with AC adapter, banana plug test leads, opto-isolated USB cable, a decent manual, and PC software on CD-ROM.

All three of these handheld scopes are intriguing, for different reasons. For pure sex appeal and as a tinkerer's delight, the DSO Quad is something to behold. As a practical, basic instrument that offers ease of use, better bandwidth and accuracy, and durability in your pocket, the Velleman gets my vote. As a bench meter or for a full-size tool kit, the Uni-T combines several instruments into one and adds some unusual, useful features. It's a viable option if you can live with its limitations.

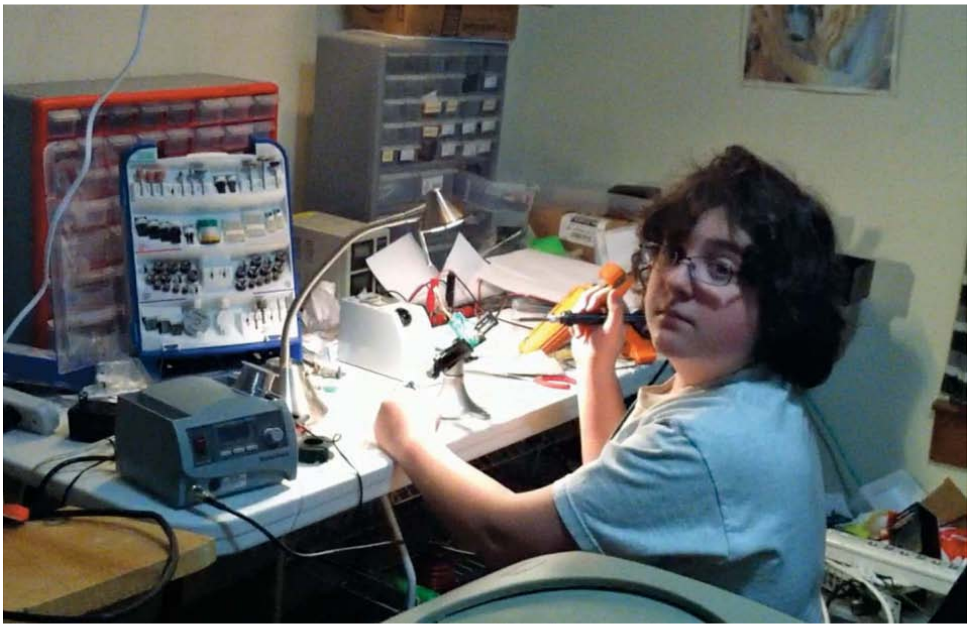
More pocket scope models are appearing almost weekly. Check eBay for the latest ones. Measure on!

—Michael Jay Geier

	SEEED DSO QUAD	VELLEMAN HPS140i	UNI-T UT81B
Dimensions	98 x 60 x 15 mm (3.9 x 2.4 x 0.6 in.)	114 x 74 x 29 mm (4.5 x 2.9 x 1.1 in.)	200 x 100 x 48 mm (7.9 x 3.9 x 1.9 in.)
Weight (with batteries)	102 grams (3.6 oz.)	200 grams (7 oz.)	498 grams (17.6 oz.)
Battery type	Lithium-ion	Nickel-metal hydride	Alkaline AA
Battery life	8 hours	6 hours	12 hours
Screen type	Color active matrix	Mono passive	Mono passive
Resolution	400 x 240	128 x 64	160 x 160
Input connector	MCX (minicoaxial)	BNC	Banana plug
Probes included	Two 10x/1x	One 10x/1x	Test leads
Tilt stand	No	No	Yes
Number of channels	2 analog; 2 digital	1	1
Real-time sampling rate	72 MS/s (144 MS/s, single-channel)	40 MS/s	40 MS/s
Bandwidth	3-11 MHz (depending on voltage range)	10 MHz	8 MHz
Fastest time base	0.1 μs/div	0.25 μs/div	0.1 μs/div
Input coupling	AC and DC	AC and DC	DC only
Most sensitive range	50 mV/div	1 mV/div	20 mV/div
Maximum safe input	80 V	100 V	1000 V
Measurement cursors	Yes	Yes	No
Internal calibrator signal	Yes	Yes	No
User-upgradable firmware	Yes	No	No
Downloads to computer	Yes	No	Yes
Real-time data to computer	No	No	Yes
Approximate price	US $200	$250	$180

MS/s—megasamples per second; μs/div—microseconds per division; mV/div—millivolts per division

hands on



SON POWER: Daniel Turner, the author's 17-year-old son, solders up one of the prototype MegaBars for testing.
PHOTO: JAMES TURNER

DIY MANUFACTURING

Making something for others, instead of yourself, is a whole 'nother project

Most DIY projects never go beyond what's essentially a prototype stage—they're one-off affairs that don't have to be cost-effective or easy to use.

But after a bunch of your friends say, "Gee, I could use one of those," it's time to consider producing your project on a larger scale. It's also time to rethink the entire project: What works for a single build often doesn't when you have to do it hundreds or even dozens of times.

I got a sense of this recently when my son and I built a high-powered replacement for the Wii sensor bar. Nintendo's own sensor bar, which is actually a pair of infrared emitters that the Wii controller uses to determine which way it's pointed, isn't much good beyond 3 meters. We created a bar that has nine high-powered IR emitters. (Actually, we built two bars, one for each of us.) We liked it so much we knew others would too, so we launched a Kickstarter project with the goal of producing at least 100 pairs. Kickstarter is a way to fund projects in which the money comes from potential customers instead of a bank (see "Getting a Kick Start" for more about it).

When you create a Kickstarter project, you need to figure out the pledge levels and exactly what the pledger gets for his or her money. Essentially, you're figuring out the selling price, as you would with any product. It turns out there's a lot to consider.

First, there's the matter of component costs. Large-scale production saves money on both unit costs and shipping. The printed circuit board for the MegaBar (as we called it) ran about US $13, using BatchPCB (which I described in an April 2010 article, "Build a Custom-Printed Circuit Board"). But for 200 (two boards per pair), the cost dipped below $2, an $11 savings. While things like switches and LEDs don't go down as dramatically, savings of 25 to 50 percent aren't uncommon.

By the way, for those off-the-shelf components, I avoided eBay as much as possible. All too often you find a bargain that's not available the next time you need it. Industrial suppliers, such as Mouser Electronics, keep large stocks of components available and will tell you how many they have on hand. Mouser, with an easily searched website and online data sheets for pretty much everything it sells, is especially nice.

Once you know your component prices, consider the packaging. This is really just another component, but because it comes last, it's often overlooked. We wanted to keep the bar small, but the device needed some extra room for thermal dissipation—the driver chips can get quite hot. We settled on cases normally used for pagers, which had the added benefit of having internal standoffs that could be used to secure the board.

It really is better to think about packaging sooner rather than later. By specifying screw holes on the PC boards that lined up with the standoffs, we were able to mount the boards directly, but we had to figure out exactly what the dimensions needed to be, which in turn required a careful study of the data sheet for the case. Typically, the one critical measure you need will not be directly available, and you'll have to infer it from other measurements that are provided.

Now is a good time to think about labor costs. For our project, each case needed to have 12 precisely positioned holes drilled (10 through the front, and 2 on the side). The holes needed to line up perfectly with the LEDs, switches, and jacks on the PC board or things wouldn't fit when assembled. Even with a template, drilling that many holes is time-consuming. Add in soldering, testing, and shipping, and I was looking at a significant cost, even at teenage-son labor rates—high enough to consider having a local machine shop drill my holes for me.

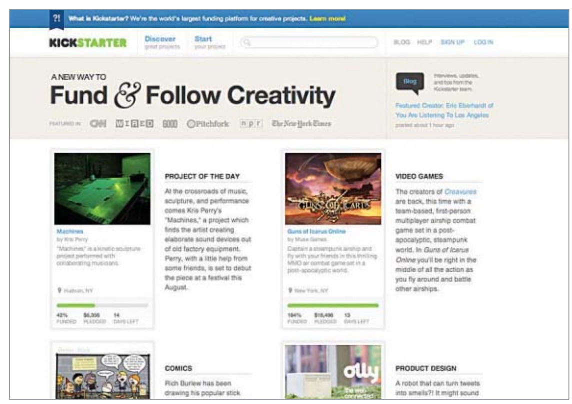
The last piece of the cost puzzle is the outbound shipping. Our unit was about 2 kilograms, which seems light but still came to $6 just to send it within the United States.

Once you have all your costs, add what you want to make as net profit, and then tack on another 10 to 25 percent for all the things that never work out the way you planned—wastage, defective units, and so on.

There's one more thing to keep in mind—liability. I'm not a lawyer, but I know that if you make something that gets ridden, heated up, or plugged in, someone will find a way to get hurt. In our case, we overengineered for safety, using parts rated well above the actual current load. We also used a DC power jack, rather than hardwiring the power leads, and a source voltage just high enough to drive the LEDs, reducing the heat that's shed by the driver chips. Even so, we were leaving ourselves open to potential trouble. It's a calculated risk.

If you plan carefully and wisely, you can scale up your one-off into a successful and profitable product. Inventing the next great mousetrap is just the first step—now manufacture it!

—James Turner



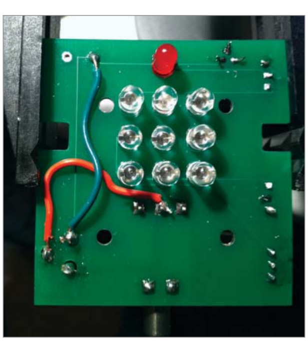
Getting a Kick Start

Traditional financing for a new product can involve digging into your life savings, maxing out your credit cards, or getting a loan from a bank. Finding investors is hard when you're talking about thousands instead of millions of dollars. But in the world of Google and Facebook, a new model is possible—crowd funding, through sites like Kickstarter.

Inventors first film a video that describes or demonstrates their idea and then write a text description. Then they set up various pledge levels. For example, as a customer on Kickstarter, I recently pledged US $410 toward a project to create a CNC (computerized numerically controlled) routing machine. For that, I received a full kit that only needed assembly. For another $100, I could have gotten it fully assembled. For our MegaBar project, we similarly set two prices: assembled and unassembled.

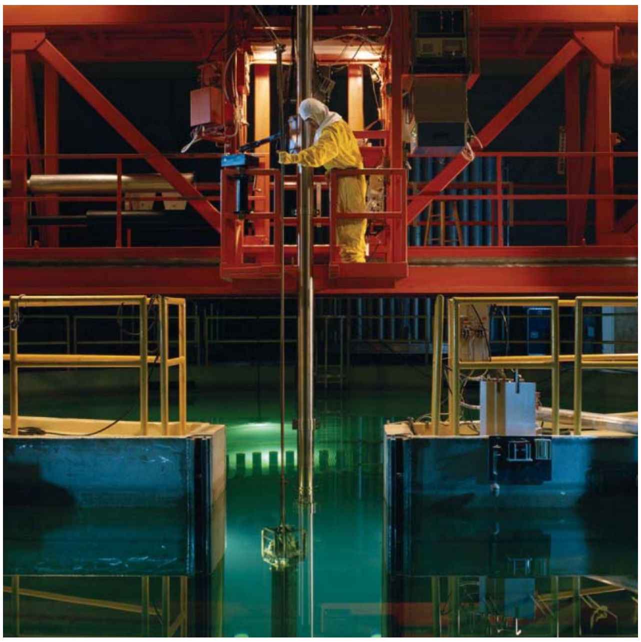
The creators also set a minimum dollar amount and a time limit. We set it at $5000 (equal to 100 people pledging for fully assembled MegaBars, or 125 people getting unassembled kits). If the project reaches its funding level before time runs out (usually somewhere between 30 and 90 days), the money is released to the creators—less 10 percent, which Kickstarter keeps.

One Kickstarter project raised over $750 000 for an iPod Nano wristband. In our case, we fell short of our level, but just getting the product ready for manufacture was a great learning experience, especially for my teenage coinventor.



MISTAKES WERE MADE: The finished MegaBar [left] consists of two IR emitter arrays packaged in cases meant for pagers. A prototype printed circuit board [right] shows the notches designed to let the board fit properly in the case, as well as a few wires I inserted to correct some design errors. *PHOTOS: JAMES TURNER*

careers



JIM KARAGEORGE/GETTY IMAGES

GOING NUCLEAR

Despite Fukushima, nuclear engineering still promises a stable career

THE CHAIRS of 47 nuclear engineering departments in North America regularly discuss concerns about their academic programs. After the Fukushima Dai-ichi incident unfolded, one question was on everyone's mind: Would nuclear engineering take a hit? E-mails were quickly exchanged among the group members, and the clear answer was no. Students were not dropping the major, and engineering freshmen were still just as interested in it.

"We're now accepting applications for 2012, and they are on track to be equivalent to last year's numbers," says Kathryn Higley, head of the nuclear engineering and radiation health physics department at Oregon State University, in Corvallis.

It has been only a year since Fukushima, but the continuing student interest is an indication that the discipline is holding its ground. The industry, bolstered by the need for carbon-free energy, is on its way up, and nuclear engineering remains a solid career path, says Arthur Motta, chair of Pennsylvania State University's nuclear engineering program. "Even if the United States doesn't build any new plants right now, 20 percent of our power is from nuclear, and that's not going away anytime soon," Motta says.

And not just in the United States. Germany and Italy have backpedaled, but many other countries are forging ahead with nuclear power. And with the Fukushima incident highlighting the need for improved reactors and better safety measures, the demand for nuclear engineers will only increase.

The contrast with the 1980s is striking. After Chernobyl, the nuclear industry buckled, and academic programs in nuclear science and engineering languished around the world. U.S. enrollments plummeted, bottoming out in 2000. But over time, the industry's reputation has healed. Concerned about both nuclear security and a diminishing workforce, the U.S. Nuclear Regulatory Commission and the U.S. Department of Energy have been supporting nuclear engineering programs through scholarships and internships.

The result is skyrocketing enrollments. In the freshman class of 2000 at North Carolina State University, in Raleigh, there were 37 nuclear engineering majors; this year there are 209. Other schools show similar trends.

This past December, the NRC approved Westinghouse Electric Co.'s new AP1000 nuclear reactor design, clearing the path for two utilities to build new plants. This has boosted confidence among academics and the industry, says Yousry Azmy, head of the nuclear engineering department at NCSU.

Nuclear engineering graduates work mostly for utility companies and for vendors such as Westinghouse, GE, and Areva. Some go to national laboratories, regulatory agencies, or into nuclear medicine. But nuclear engineers gain systems and engineering skills, along with a solid background that they can apply to other realms. "Even if the market shifts, students will have a versatile tool kit and abilities that will allow them to move around," Higley says. During the nuclear power lull in the early 2000s, many graduates went to computer chip and software companies, she points out.

Besides, Azmy says, "The future of nuclear engineering education in the United States isn't entirely held hostage to the utilities in this country." China is building 27 new reactors and expects to have another 120 operating within the next two decades. Saudi Arabia, Turkey, the United Arab Emirates, and Vietnam have new nuclear power programs. "Many jobs will materialize in the United States and Europe," says Azmy.

Recognizing the need for a talented nuclear workforce, countries such as China, Poland, and the United Arab Emirates are building their own academic programs in nuclear engineering. Many U.S. universities are making concerted efforts to connect with these countries through student exchanges and international design projects. This gives students the chance to work with people from different cultures, Higley points out. "The companies they will work for have an international footprint and will want their employees to work with people in other countries that are using their technology." —PRACHI PATEL reflections BY ROBERT W. LUCKY

ROBERT NEUBECKER

Is Math Still Relevant?

LONG AGO, when I was a freshman in engineering school, there was a required course in mechanical drawing. "You had better learn this skill," the instructor said, "because all engineers start their careers at the drafting table."

This was an ominous beginning to my education, but as it turned out, he was wrong. Neither I nor, I suspect, any of my classmates began our careers at the drafting table.

These days, engineers aren't routinely taught drawing, but they spend a lot of time learning another skill that may be similarly unnecessary: mathematics.

I confess this thought hadn't occurred to me until recently, when a friend who teaches at a leading university made an off-hand comment. "Is it possible," he suggested, "that the era of mathematics in electrical engineering is coming to an end?"

When I asked him about this disturbing idea, he said that he had only been trying to be provocative and that his graduate students were now writing theses that were more mathematical than ever. I felt reassured that the mathematical basis of engineering is strong. But still, I wonder to what extent—and for how long—today's undergraduate engineering students will be using classical mathematics as their careers unfold.

There are several trends that might suggest a diminishing role for mathematics in engineering work. First, there is the rise of software engineering as a separate discipline. It just doesn't take as much math to write an operating system as it does to design a printed circuit board. Programming is rigidly structured and, at the same time, an evolving art form—neither of which is especially amenable to mathematical analysis.

Another trend veering us away from classical math is the increasing dependence on programs such as Matlab and Maple. The pencil-and-paper calculations with which we evaluated the relative performance of variations in design are now more easily made by simulation software packages—which, with their vast libraries of prepackaged functions and data, are often more powerful. A purist might ask: Is using Matlab doing math? And of course, the answer is that sometimes it is, and sometimes it isn't.

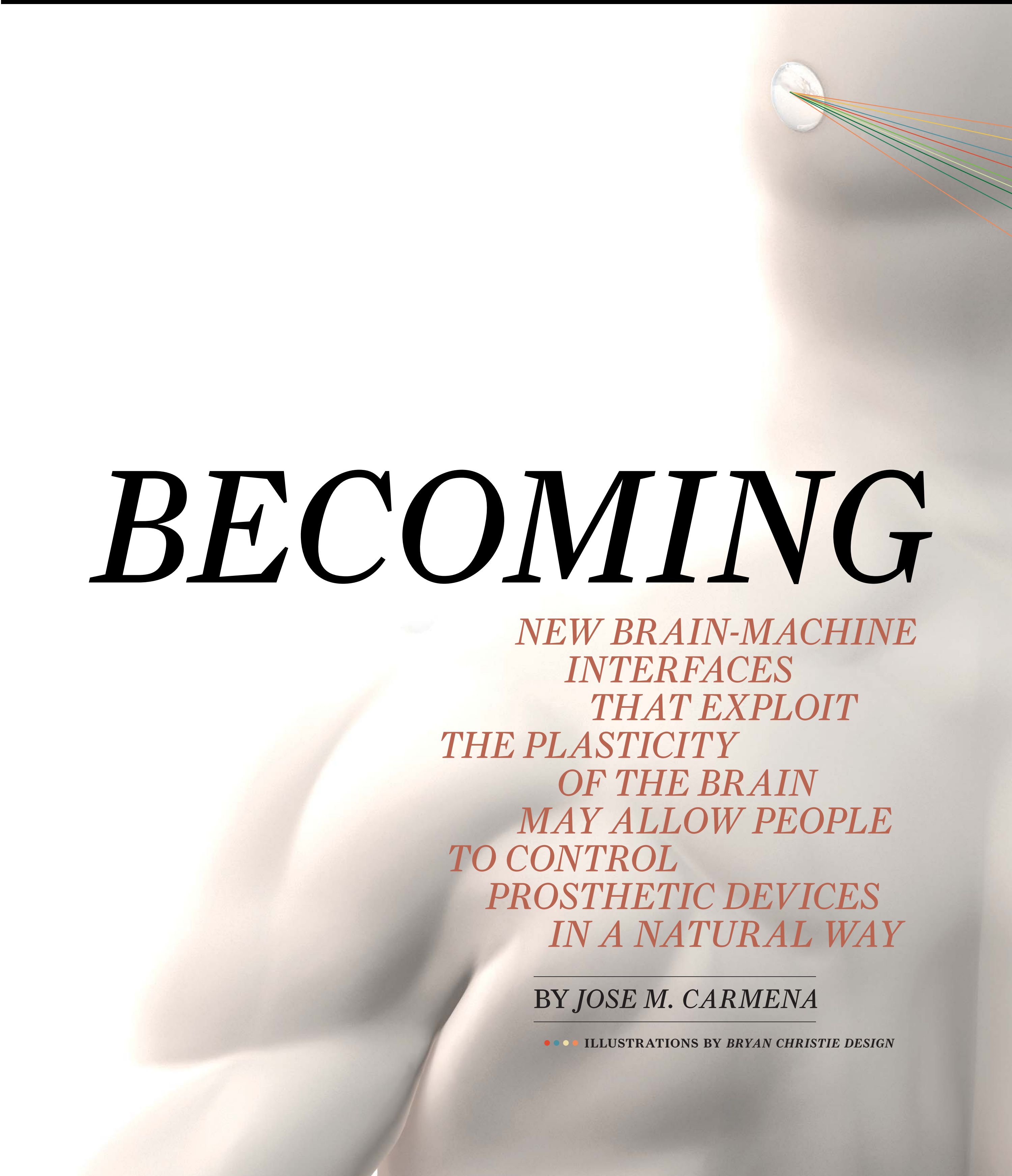
A third trend is the growing importance of a class of problems termed "wicked," which involve social, political, economic, and undefined or unknown issues that make the application of mathematics very difficult. The world is seemingly full of such frustrating but important problems.

These trends notwithstanding, we should recognize the role of mathematics in the discovery of fundamental properties and truth. Maxwell's equations—which are inscribed in marble in the foyer of the National Academy of Engineering—foretold the possibility of radio. It took about half a century for those radios to reach Shannon's limit—described by his equation for channel capacity—but at least we knew where we were headed.

Theoretical physicists have explained through math the workings of the universe and even predicted the existence of previously unknown fundamental particles. The iconic image I carry in my mind is of Einstein at a blackboard that's covered with tensor-filled equations. It is remarkable that one person scribbling math can uncover such secrets. It is as if the universe itself understands and obeys the mathematics that we humans invented.

There have been many philosophical discussions through the years about this wonderful power of math. In a famous 1960 paper entitled "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," the physicist Eugene Wigner wrote, "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift [that] we neither understand nor deserve." In a 1980 paper with a similar title, the computer science pioneer Richard Hamming tried to answer the question, "How can it be that simple mathematics suffices to predict so much?"

This "unreasonable effectiveness" of mathematics will continue to be at the heart of engineering, but perhaps the way we use math will change. Still, it's hard to imagine Einstein running simulations on his laptop. ❑



BECOMING

NEW BRAIN-MACHINE INTERFACES THAT EXPLOIT THE PLASTICITY OF THE BRAIN MAY ALLOW PEOPLE TO CONTROL PROSTHETIC DEVICES IN A NATURAL WAY

BY *JOSE M. CARMENA*

ILLUSTRATIONS BY *BRYAN CHRISTIE DESIGN*

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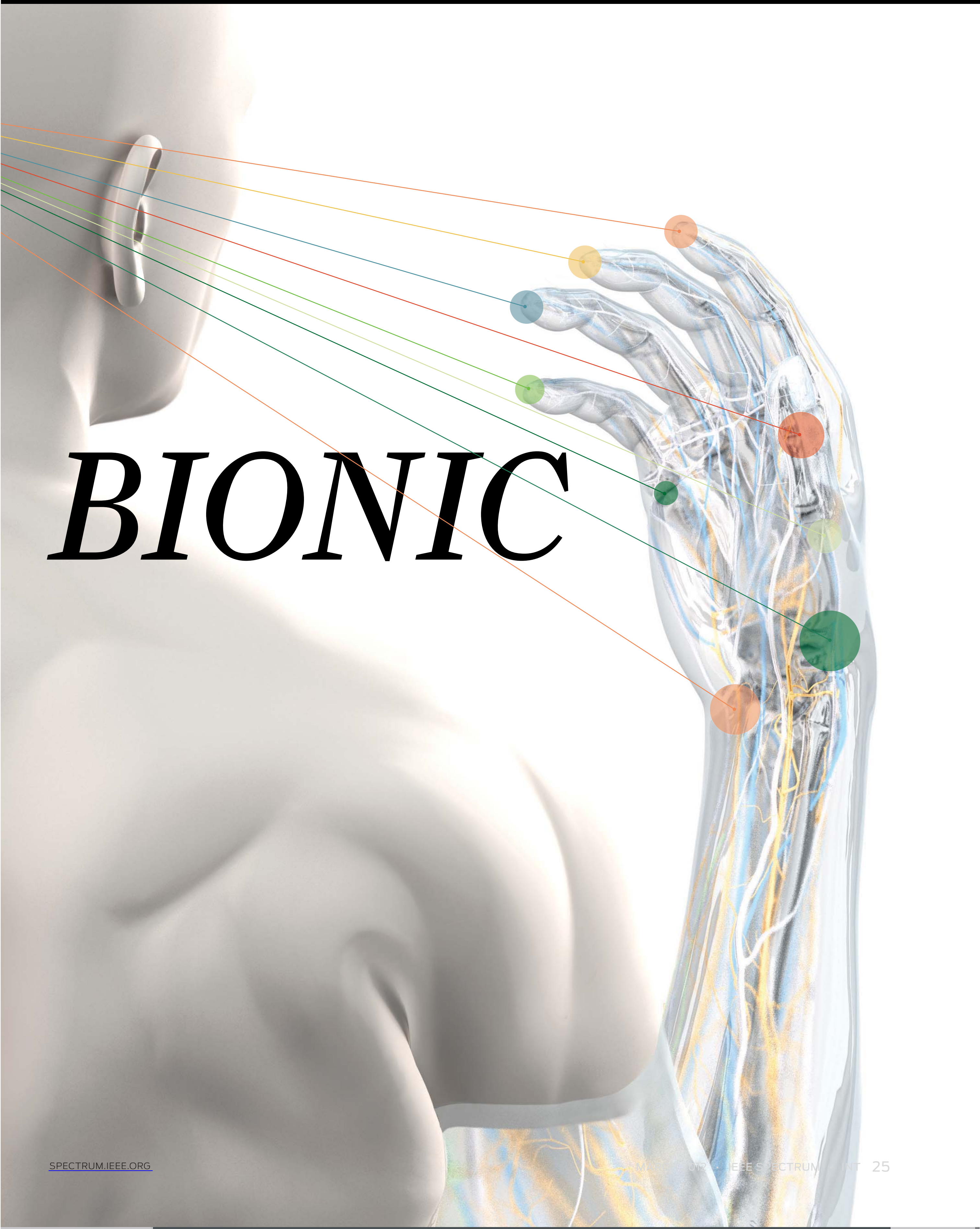

BIONIC

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Imagine a piece of technology that would let you control an apparatus simply by thinking about it. Lots of people, it turns out, have dreamed of just such a system, which for decades has fired the imaginations of scientists, engineers, and science fiction authors. It's easy to see why: By transforming thought into action, a brain-machine interface could let paralyzed people control devices like wheelchairs, prosthetic limbs, or computers. Farther out in the future, in the realm of sci-fi writers, it's possible to envision truly remarkable things, like brain implants that would allow people to augment their sensory, motor, and cognitive abilities.

That melding of mind and machine suddenly seemed a little less far-fetched in 1999, when John Chapin, Miguel Nicolelis, and their colleagues at the MCP Hahnemann School of Medicine, in Philadelphia, and Duke University, in Durham, N.C., reported that rats in their laboratory had controlled a simple robotic device using brain activity alone. Initially, when the animals were thirsty, they had to use their paws to press a lever, thus activating a robotic arm that brought a straw close to their mouths. But after receiving a brain implant that recorded and interpreted activity in their motor cortices, the animals could just think about pressing the lever and the robotic arm would instantly give them a sip of water.

Suddenly, a practical brain-machine interface, or BMI, seemed attainable. The implications were enormous for people who, because of paralysis caused by spinal-cord or brain damage, find it difficult or impossible to move their upper or lower limbs. In the United States alone, more than 5.5 million people suffer from such forms of paralysis, according to the Christopher and Dana Reeve Foundation.

The Hahnemann-Duke breakthrough energized the BMI field. Starting in 2000, researchers began unveiling proof-of-concept systems that demonstrated how rats, monkeys, and humans could control computer cursors and robotic prostheses in real time using brain signals. BMI systems have also revealed new ways of studying how the brain learns and adapts, which in turn have helped improve BMI design.

But despite all the advances, we are still a long way from a really dependable, sophisticated, and long-lasting BMI that could radically improve the lives of the physically disabled, let alone one that could let you see the infrared spectrum or download Wikipedia entries directly into your cerebral cortex. Researchers all over the world are still struggling to solve the most basic and critical problems, which include keeping the implants working reliably inside the brain and making them capable of controlling complex robotic prostheses that are useful for daily activities. At the risk of losing its credibility, the field now needs to transform BMI systems from one-of-a-kind prototypes into clinically proven technology, like pacemakers and cochlear implants.

It's time for a fresh approach to BMI design. In my laboratory at the University of California, Berkeley, we have zeroed in on one crucial piece of the puzzle that we feel is missing in today's standard approach: how to make the brain adapt to a prosthetic device, assimilating it as if it were a natural part of the body. Most current research focuses on implants that tap into specific neural circuits, known as cortical motor maps. With such a system, if you want to control a prosthetic arm, you try to tap the cortical map associated with the human arm. But is that really necessary?

Our research has suggested—counterintuitive though it may seem—that to operate a robotic arm you may not need to use the cortical map that controls a person's arm. Why not? Because that person's brain is apparently capable of developing a dedicated neural circuit, called a motor memory, for controlling a virtual device or robotic arm in a manner similar to the way it creates such memories for countless other movements and activities in life. Much to our surprise, our experiments demonstrated that learning to control a disembodied device is, for your brain, not much different from learning to ski or to swing a tennis racket. It's this extraordinary plasticity of the brain, we believe, that researchers should exploit to usher in a new wave of BMI discoveries that will finally deliver on the promises of this technology.

THE BMI FIELD started more than 40 years ago at the University of Washington, in Seattle. In a pioneering experiment in 1969, Eberhard Fetz implanted electrodes in the brains of monkeys to monitor the activity of neurons in the motor cortex, the part of the brain that controls movement. When a neuron fired at a certain rate, a corresponding electrode would pick up a small electrical discharge, deflecting a needle and emitting a chirp in a monitoring device. Whenever that happened, the animals would receive a treat. Crucially, the animals could see and hear the monitoring device, which gave them feedback about their neural activity. Within minutes, the monkeys learned to intentionally fire specific neurons to make the needle move, so that they could get more treats. Fetz showed that it was possible to teach the brain to control a device external to the body.

Today, BMI systems vary greatly in their designs. A major distinction is the location of the electrodes. In some, the electrodes are implanted inside the brain, where they monitor the firing of individual neurons. Other researchers work with electrocorticography (ECoG) systems, which use electrodes placed on the surface of the brain just under the skull, or electroencephalography (EEG) systems, which use electrodes that sit on the scalp. ECoG and EEG monitor the rhythmic activity created by the collective behavior of large groups of neurons [see sidebar, "Invasive vs. Noninvasive"].

In the case of electrodes inside the brain, which are the ones I study and the focus of this article, the neural signals captured

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by the implant are fed into a computer program called a decoder. It consists of a mathematical model that transforms the neural activity into the movements of a computer cursor or robotic arm, typically. To measure neural activity, researchers usually count the number of times individual neurons fire in a certain time span, known as a bin, which is usually about 100 milliseconds. In a 100-ms bin, you might record zero to a few firings. That number is called a spike count. The mathematical model that translates the spike counts of a group of neurons into movement might be a simple linear relationship. Increasingly, however, researchers are using models that are more complex and nonlinear in their translation of spike counts to movement.

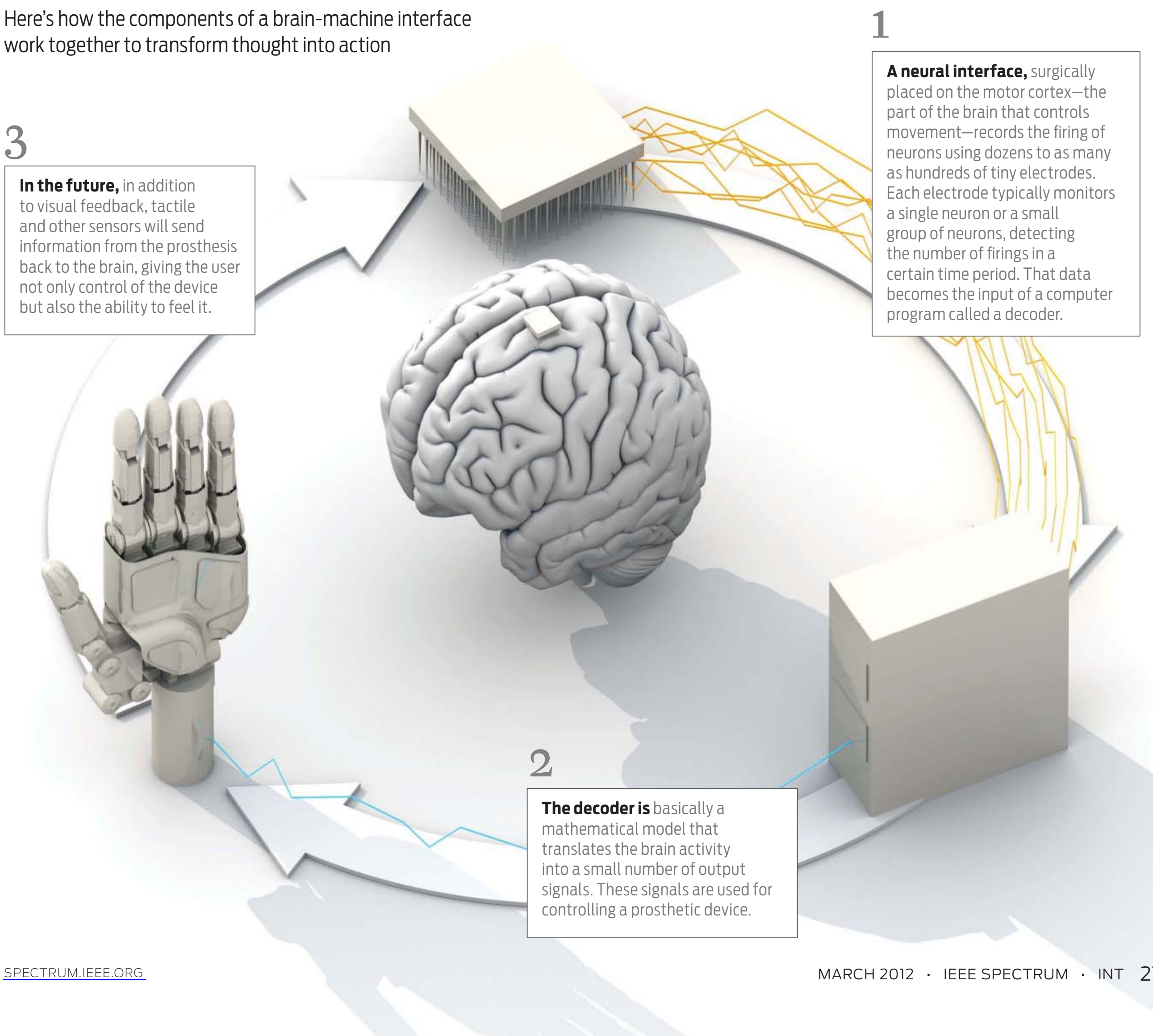
In the traditional approach to BMI, you create a decoder by monitoring the neural activity of the areas of the brain responsible for control of the natural arm. As a first step, you'd monitor those neurons while test subjects moved their arms in predetermined ways. Next you'd take the activity of the neurons and the motion of the arms recorded during that trial and compute the decoder's parameters. The decoder would then be able to transform the firings of the neurons into movements of the prosthetic device.

The decoder's function is in some sense like that of the spinal cord. The spinal cord is connected to hundreds of thousands of neurons in the brain. After these neurons fire, the spinal cord transforms that activity into a small number of signals that travel, in the case of the human arm, to about 15 muscle groups. So the spinal cord takes, say, 100 000 inputs and transforms them into about 15 outputs. The decoder does something similar, although on a much smaller scale. Current state-of-the-art BMI systems typically monitor the activity of a few dozen to a few hundred neurons and transform their firings into a small number of outputs, such as the position, velocity, and gripping force of a prosthetic device.

In the early 2000s, groups at Brown University, Arizona State University, and Duke reported more breakthroughs,

HOW TO LINK A BRAIN TO A MACHINE

Here's how the components of a brain-machine interface work together to transform thought into action



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demonstrating closed-loop BMI control for the first time. I was involved in the Duke study, conducted at Nicolelis's lab, where I was a postdoctoral researcher from 2002 to 2005. In that study, we reported that two macaques were able to use brain activity alone to control a robotic arm with two articulations and a gripper (three degrees of freedom, in robotics parlance) to reach for and grasp objects. One of the key findings was that learning to control the BMI triggered plastic changes in different brain areas of the monkeys, suggesting that the brain had even greater flexibility than previously thought. Other groups at Caltech, Stanford, the University of Pittsburgh, the University of Washington, and elsewhere followed with their own studies, further advancing different aspects of BMI control. The team at Brown spun off a BMI start-up called Cyberkinetics and succeeded in getting approval from the U.S. Food and Drug Administration for clinical trials with five severely disabled patients. The trials of their device yielded promising results, and the effort continues as part of a large research consortium called BrainGate2.

A common problem in this first batch of studies was that the BMI system had to be recalibrated for every session. Subjects were able to control the computer cursor or robotic arm to perform a task, but they weren't able to retain the skills from one session to the next. In other words, the BMI systems weren't "plug and play." And this limitation would become even more prominent as the complexity of the task increased. Another major obstacle soon became apparent, too: The electrodes' ability to read brain activity would degrade over time, and the device had to be removed from the subject's brain. With such shortcomings, a BMI system could never be practical.

BACK TO SQUARE ONE. At Berkeley, my group set out to investigate an intriguing hypothesis based on a simple question: If we're trying to control a prosthetic device that's completely different from a natural arm, why are we relying on brain signals related to a natural arm? If we want to control an artificial arm, we'd ideally use brain activity tailored to that specific arm. But could the brain learn to produce such activity for something that's not even part of the body?

The answer is a resounding yes, according to a series of experiments and trials we've done over the past five years. In this new view of BMI design, the focus isn't on using the existing nervous system to control an artificial device but rather on creating a new, hybrid nervous system that spans the biological and artificial components. This approach grew out of a series of experiments I carried out with Karunesh Ganguly, a postdoc in my lab. We implanted arrays of 128 tiny electrodes into the motor cortices of macaque monkeys. But unlike in previous studies, we chose to use only a subset of about 40 electrodes that provided reliable readings for several days. Another difference was that, rather than recalibrating the decoder every session, we kept it exactly the same during the whole time. Those differences would prove crucial for the results we would achieve.

In the experiment, the monkeys had to move a computer cursor to the center of a monitor screen and, upon seeing a circle elsewhere on the screen change color, move the cursor there. The reward was a sip of fruit juice. In an initial phase, the animals used their actual arms to operate a robotic exoskeleton and move the cursor. At the same time, we recorded brain activity from the subset of neurons. In a subsequent phase, we removed the exoskeleton and switched the experiment from manual to BMI control. In this case, the monkeys had to learn how to move the cursor with brain activity alone, irrespective of natural arm movement. And learn they did. Within a week, the monkeys had mastered the task and could repeat it proficiently day after day.

What was new here was the discovery that an animal's brain could develop a motor map representing how to control a disembodied device—in this case, the computer cursor. In past studies, researchers didn't keep track of a stable neuron group, and they inevitably had to recalibrate the decoder to adapt it to the new activity the neurons were producing in every session. But that recalibration resulted in a serious problem: It meant that the brain wasn't being allowed to retain the skill learned in the previous sessions and thus wasn't able to develop a cortical map of the prosthetic device. In our study we left the decoder unchanged, allowing the brain to assimilate the prosthetic device as if it were a new part of the body.

After two weeks, we performed two follow-up experiments with one of the monkeys. In the first, we started with a decoder that the animal had never used for BMI control. Within a short period of time, the monkey had mastered this new decoder, just as before. The interesting thing this time was that we could switch between this new decoder and an earlier decoder and the monkey's brain would correctly choose the motor map that corresponded to whichever decoder was active. In the second experiment, we went further and created a shuffled decoder by completely scrambling its parameters. To our surprise, the animal was again able to learn this decoder and operate the computer cursor just as skillfully as before.

These findings highlight the brain's remarkable plastic properties and suggest that a newly formed prosthetic motor map meets the essential properties of memory. Namely, the map remains unchanged over time and can be readily recalled: Every day the monkeys could promptly control the device; it seems to be a BMI that's truly plug and play. The map was also resistant to interference from other maps comprising the same set of neurons—just as learning to play tennis doesn't erase your ability to ride a bicycle.

And in our most recent study, with my students Aaron Koralek and John Long, and my colleagues Xin Jin, of the U.S. National Institutes of Health, and Rui Costa, of the Champalimaud Centre for the Unknown, in Lisbon, we went one step further. Our results showed that other brain areas that had not been explored in a BMI context—including neural circuits between the cortex and deep-brain structures such as the basal ganglia—are actually key to the learning of prosthetic skills. This means that in principle, learning how to control a prosthetic device using a BMI may feel completely natural to a person, because this learning uses the brain's existing built-in circuits for natural motor control.

SO IS A TRULY PRACTICAL BMI system at hand? Not quite. There are many challenges and obstacles, some obvious, others less so. In the obvious category are the basic parameters of the implants: They need to be tiny, use very little power, and work wirelessly. Another conspicuous challenge is the reliability of all the subsystems of a BMI, including the biophysical interface, the decoder, and also the feedback loop that allows the brain's error-correcting mechanisms to kick in and improve performance. Each component would have to work for the user's entire lifetime, of course.

Even after those challenges are met, there is a whole category of other obstacles involved with making the BMI system more sophisticated and capable. Ultimately, we want to build a BMI that can control not only primitive systems but also complex bionic prostheses with multiple degrees of freedom to perform dexterous tasks. And we want the BMI to be able to transmit signals from the brain to the prosthesis as well as from the prosthesis to the brain. That's BMI's holy grail: a system that's part of your body in the sense that you not only control it but also feel it.

Most BMI studies today rely only on visual feedback: A monkey's brain can form a motor memory for a given task because the animal can see how it is performing during the task and adjust its brain activity to improve its performance. But when we learn a task—riding a bicycle, playing tennis, typing on a keyboard—we're not using just visual feedback; we're also relying on our tactile senses and our proprioceptive system, which uses receptors on muscles and joints to tell you where a certain part of your body is in space. Could BMI systems do something similar? Could you use tactile and position information from a robotic gripper and stimulate the brain to allow a user to find a glass of water on a nightstand in the dark, for example?

We've begun trying to answer that question in our lab, and we've had some promising results already. We're using a technique known as intracortical electrical microstimulation to attempt to induce tactile sensations. In a recent study, Subramaniam Venkatraman, a graduate student in my lab, used rats with electrodes implanted in their sensory cortices. He placed the rats in a cage and used a motion-tracking system to precisely monitor the position of one of their whiskers in real time. When the whisker hit a virtual target—a line located at one of various possible positions—the BMI system delivered a precise pulse of stimulation into the rat's cortex, giving the animal the illusion of touching an object. Whenever the animal was able to consecutively hit the correct target four times, it received a drop of fruit juice as a reward.

The study demonstrated that the rats were able to combine natural signals from their proprioceptive system with artificially delivered tactile stimuli to encode object location. This result suggests that in addition to readout functions, we can also perform write-in operations to the brain, a capability that will be useful in providing feedback for future users of neuroprostheses. In fact, Nicolelis and his team at Duke recently described an experiment in which monkeys could control a computer with their minds and also apparently "feel" the texture of virtual objects. The interface was both extracting and sending signals to the brain—a bidirectional BMI.

Finally, another research area that BMI needs to advance in is that of the prostheses themselves. Advances in biomechatronics toward exploiting compact sensor, actuator, and energy-storage technologies will play a big role in the development of these systems. The good news is we're already seeing major progress in this realm: Take Dean Kamen's Deka Research and Development Corp., which built a robotic arm so advanced that it was nicknamed the "Luke arm," after the remarkably lifelike prosthetic worn by Luke Skywalker in *Star Wars*.

BMI research is entering a new phase—call it BMI 2.0—thanks to work at universities, companies, and medical centers all over the world. (These include a recently launched Center for Neural Engineering and Prostheses, which I codirect, based at Berkeley and at the University of California, San Francisco, and which will focus on motor and speech prostheses.) There is a palpable sense that we are quite close to cracking several of the fundamental problems standing in the way of clinical and commercial use of BMI systems.

INVASIVE VS. NONINVASIVE

A perennial question among brain-machine-interface researchers is whether we should focus on invasive or noninvasive approaches. In other words, should we design BMI systems that rely on electrodes inserted inside the brain, sitting on its surface just beneath the skull, or on those that simply rest on the scalp? This debate always emerges at meetings and conferences. To me, however, it's a pointless discussion.

Almost every disease can benefit from more than one type of treatment. You can treat cancer with, among other things, surgery, chemotherapy, radiotherapy, or all of them together. Also, there are other factors that affect the choice of therapy to follow, such as the physical condition of the patient. So why can't BMI systems work in a similar fashion? Some people may require electrodes inside the brain to get the most benefit—for controlling a robotic arm in a natural way, for example; for others, a simple electrode cap on the scalp may suffice—say, for steering a wheelchair.

Some BMI systems record brain activity at a microscopic level, producing a signal with two components. The high frequency part, related to the firing of individual neurons, is known as single unit activity, or SUA, and the low frequency part represents local field potential, or LFP, which consists of aggregate currents from neurons surrounding the electrode. Another type of invasive implant records cortical field potentials via electrocorticography. The fields can also be recorded from the scalp via noninvasive electroencephalography, although the result is a noisier signal.

In the long term, BMI systems may very well become a hybrid of different kinds of neural signals, able to benefit from local, high-resolution information (for generating motor commands) and more global information (arousal, level of attention, and other cognitive states). Society can only benefit from the availability of both approaches, so let them both thrive. And as many of my colleagues would say, at the end of the day the decision of which to adopt is entirely in the hands of two people: the patient and the physician. *—J.M.C.*

The initial applications of BMI, in helping patients suffering from paralysis due to spinal cord injury or other neurological disorders, including amyotrophic lateral sclerosis and stroke, are still probably a decade or two away. But after this technology becomes mainstream in health care, other realms await in the augmentation of sensory, motor, and cognitive capabilities in healthy subjects—a fascinating possibility for sure, but one that promises to unleash a big ethical debate. The world where we're able to do a Google search or drive a car just by thinking will be a very different place. But that's a BMI 3.0 story. ❑

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A Shocking Truth

The defibrillators in airports, malls, and offices can save your life—but too many have failed at the crucial moment

BY MARK HARRIS

In November 2007, Anna Malofiy awoke in her Southampton, Pa., home to find her husband, Eugene, shaking and unresponsive. She called 911 and attempted cardiopulmonary resuscitation. A few minutes later, a police officer arrived with an automated external defibrillator (AED), the Powerheart model, made by Cardiac Science Corp. By administering an electric shock, such devices can save your life if your heart stops beating.

When the officer turned on the device, Anna's lawyers claim, it displayed an error message and failed to operate. Officers and paramedics attempted to save Eugene Malofiy without the device but were ultimately unsuccessful.

Eugene's nephew, Francis Malofiy, a lawyer practicing in Philadelphia, is suing Cardiac Science, based in Bothell, Wash., for construction and design defects, a failure to warn consumers about the problems, breach of contracts, and negligence. A jury trial is scheduled for July 2012.

If It *Can* Go Wrong…

it will—unless engineers can design AEDs that work without fail after sitting in a box for years at a stretch

1. **USER INTERFACE** Controls can be confusing; voice prompts may refer to buttons that are not visible.
2. **LCD** Information on displays can be difficult to read, particularly in bright light or from a wide angle.
3. **STATUS INDICATOR** An unexpected shutdown can result from component failures or poor design.
4. **CABLES AND CONNECTORS** Incompatible or damaged cables can lead to serious malfunctions.
5. **CASING AND CONSTRUCTION** Cases may not sufficiently protect the device from humid conditions and minor knocks.

"We went deep into police records and found a smoking gun," Malofiy says. "Cardiac Science had 114 complaints of these specific relay-switch failures but failed to do any real corrective action. Rather than a recall being issued, rather than anything happening, the situation had to present itself many, many times."

Cardiac Science did eventually recall about 280 000 of the Powerheart and other models. This is only one of many failures reported of AEDs, first-aid devices that have become increasingly common in the public spaces of the United States, where they are designated by the symbol of a heart and a lightning bolt. There are now 1.5 million AEDs deployed nationwide, five for each of the 300 000 people in the country who need them every year.

When a policeman, shopkeeper, or passerby uses an AED promptly and correctly, it can help keep the suffering person alive until professionals can provide treatment, increasing survival chances up to tenfold. Yet despite the enormous investment in these AEDs, the death rate from sudden cardiac arrest is no better than it was 20 years ago. It still kills more Americans than lung, breast, and prostate cancers and AIDS combined. Worldwide, it kills about 7 million people a year.

• • •

So what's going wrong? Are too many AEDs badly designed or prone to malfunction? Are they just not numerous enough to be found and used in time? Or are there other reasons they aren't saving lives, reasons that would render public AEDs a waste of money?

First, a primer on the problem. Sudden cardiac arrest is not a heart attack. In a heart attack, blood can't flow properly to the heart but the muscle itself keeps beating, so sufferers typically remain conscious. In cardiac arrest, the heart's pumping mechanism—an electrochemically choreographed affair—becomes deranged, so that the many motions of the various parts no longer work together to pump any blood. With no blood flowing to the lungs or brain, victims rapidly lose consciousness.

From that moment on, time is of the essence. For every minute that passes without a heartbeat, the patient's chance of survival drops by up to 10 percent. Even if a properly trained bystander immediately starts cardiopulmonary resuscitation (CPR), rapidly compressing the patient's chest to force blood around the body, survival rates will still decline 5 percent per minute. To actually save the person, you must restore the heart's normal sinus rhythm, and this is where AEDs come in.

Sudden cardiac arrest is most often caused by ventricular fibrillation, when the heart's lower chambers stop beating and instead quiver rapidly and irregularly. AEDs detect this distinctive quivering and then deliver one or more electric shocks. The shocks cause the heart's muscle cells to contract simultaneously, interrupting the disorganized spasms and, if all goes well, rebooting the malfunctioning organ.

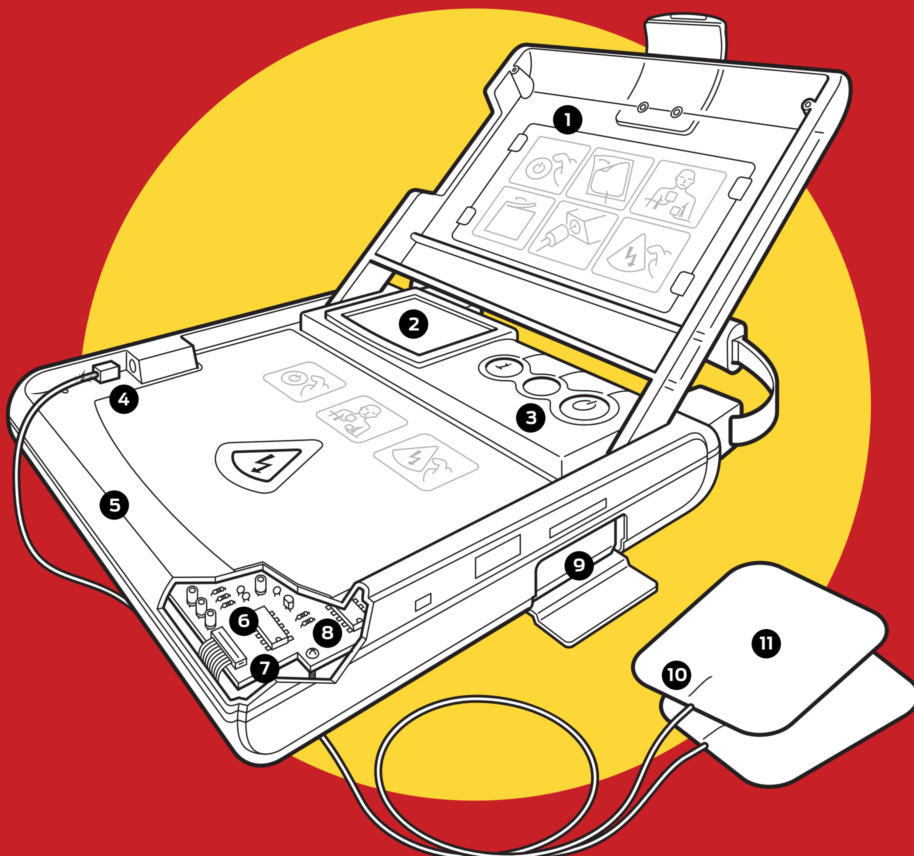
The first successful use of defibrillation on a person was in 1947, by Dr. Claude Beck of Western Reserve University School of Medicine, in Cleveland. His experimental device required a large transformer and delivered AC current directly to the exposed heart of a 14-year old boy, who was undergoing surgery when he suffered cardiac arrest. The boy survived. Closed chest systems followed in the mid-1950s. Eventually, defibrillators moved to DC current supplied by banks of capacitors, so that defibrillators could be made portable and even battery powered.

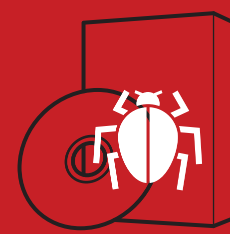
Until the 1990s, AEDs delivered what are termed monophasic shocks—jolts so energetic they could damage heart tissue and inflict burns. Modern AEDs take a leaf out of the alternating-current playbook by employing a biphasic waveform: The pulse travels in alternate directions between the paddles, allowing for lower energy levels and providing higher survival rates. In hospitals, biphasic defibrillators can now restore a regular pulse in up to 99 percent of patients.

• • •

Today, however, the majority of these machines are situated not in hospitals but in public places, which is pretty much without parallel among medical devices. A public-access AED spends endless days, months, and even years hanging on a wall, gathering dust. Most AEDs reach the end of their expected 5- to 10-year lifetimes without ever having been used. Yet they must remain fully charged,

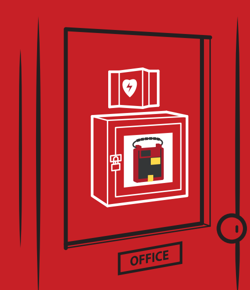
PREVIOUS PAGES: PHOTOGRAPHER: DAN SAELINGER; PROP STYLIST: ARIANA SALVATO





12 SOFTWARE Bugs cause error messages or malfunctions.

13 POWER-UP SELF-TEST If tests miss component defects, the device may fail.



6 VOLTAGE MONITORING CIRCUIT If this draws power from the source it monitors, a false alert can cause a shutdown.

7 CIRCUIT BOARDS Faulty circuit boards are the main cause of repairs on malfunctioning AEDs.

8 RESISTORS The wrong resistor can lead to misdiagnosis of the ECG waveform.

9 BATTERIES Problems with power management, recharging, or accidental discharge can make AEDs cancel shocks.

10 ELECTRODES These can dry out if not maintained and regularly replaced.

11 PADDLES Skin burns may occur at the electrode sites, particularly during repeated defibrillation attempts.

14 LOCATION AND DISPLAY Many units are inaccessible or marked "For use by trained personnel only."

JAMES PROVOST

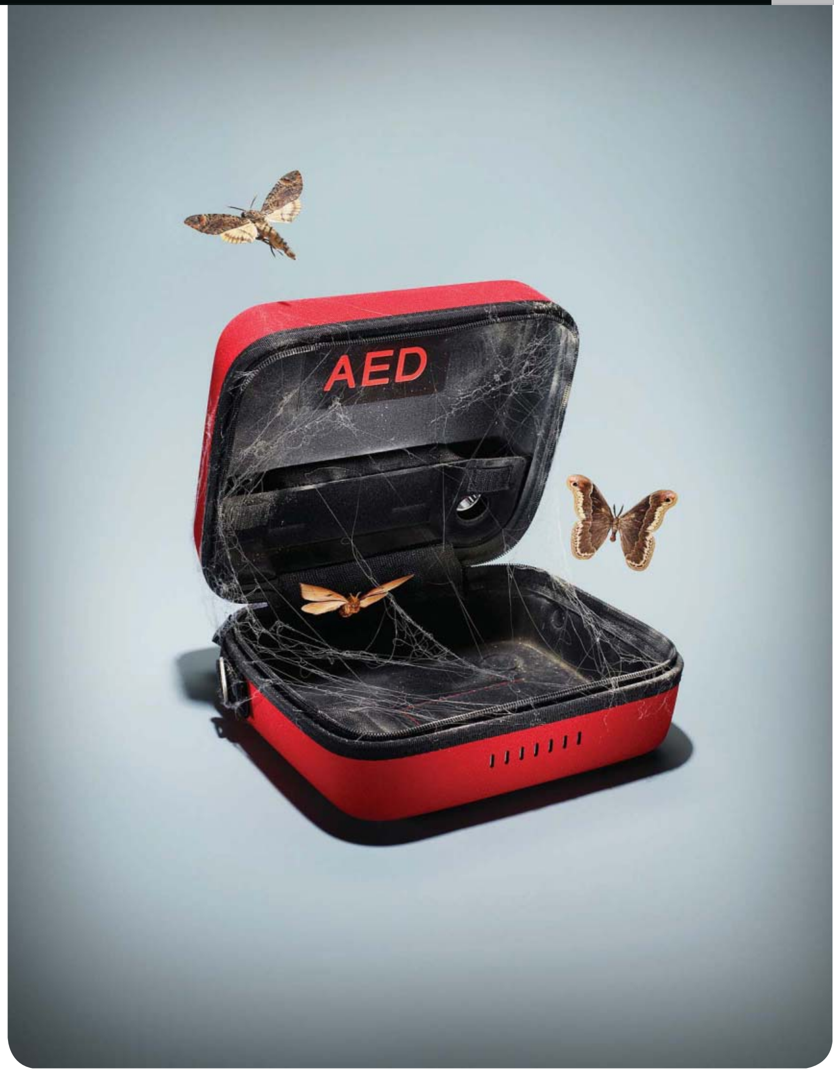
functional, and ready to operate at a moment's notice, often by people who have never seen a defibrillator outside of a TV hospital drama.

"It was a really daunting technical challenge," says Carl Morgan, who developed some of the first public AEDs at Heartstream (now part of Philips). "We helped pioneer the concept of self-test, where the device wakes up every day and performs extremely comprehensive tests on itself. These are supplemented by other tests done weekly and monthly to conserve the battery."

In modern AEDs, he adds, twice as much software code is dedicated to self-testing as to signal processing (for analyzing heart rhythms), and the bulk of the device's battery power is also reserved for tests. Even so, things occasionally go wrong.

Last year, officials at the U.S. Food and Drug Administration (FDA) noticed a disturbing trend. Between 2005 and 2009, the annual number of problems reported with AEDs increased by 85 percent. Medical-device reports are issued by manufacturers whenever they think one of their units may have malfunctioned, contributing to a death or serious injury. In that five-year period there were more than 28 000 such reports—one malfunction for every 50 devices in the country. More than 750 of the reports followed a death. Problems included the AED displaying error messages, being unable to power up, and failing to deliver shocks. In the same period, up to 70 kinds of AEDs were recalled, including models from every AED manufacturer in the world. Of those recalls, 17 fell into the most serious category, in which there was a reasonable probability that the problem would have led to serious injury or death.

"This opened our eyes," says Mitchell Shein, who oversees the regulation of pacemakers, defibrillation devices, and the electrical leads attached to both for the FDA. "Was the approval process providing us with adequate control so that devices making it to market were safe and effective? We needed to make an assessment."



PHOTOGRAPHER: DAN SAELINGER; PROP STYLIST: ARIANA SALVATO

The FDA discovered that manufacturers had evaluated barely a third of the malfunctions and had identified the problem in only a third of those cases. Some 90 percent of the failures were thus unexplained. Worse, because the manufacturers had declined to reveal their sales volume to the FDA, the agency couldn't nail down the rate of malfunction or tell whether it had risen over time.

"I was stunned to hear this," says E. Magnus Ohman, a physician on the FDA's oversight panel for AEDs. "We're in the era of transparency. If I go to a restaurant, I get the hygiene rating." Another physician on the panel, Frank LoGerfo, complains, "If these devices can self-report after an incident, it's almost inexplicable that we don't have very detailed data for each device where it failed."

Eventually, the agency set its own engineers to work on the job. "We found some pretty egregious design errors," says Al Taylor of the FDA's Office of Science and Engineering Laboratories. "There were many situations where deficient product design and—let's put it bluntly—poor engineering were a cause or a contributory factor to an adverse event."

One AED, the brand name of which the FDA would not disclose, was found to occasionally misdiagnose the heart's electrical rhythm. It delivered some shocks that weren't needed and failed to deliver others that were. The culprit was a resistor that could vary in resistance by up to 10 percent of its stated value. "When our engineer looked at this design, it was an instant 'uh-oh,' " says Taylor. "We would have to do analysis to decide if it needed a 1 percent or a 0.1 percent resistor, but this was clearly off the scale." The reason? Only at that higher tolerance can the noise-canceling circuitry isolate the cardiac signal from environmental sources of radiation, such as the oscillating electric fields of fluorescent tubes.

In another device, a voltage-monitoring circuit drew power from the very source that it was checking. Because of this, a momentary drop in voltage would cause a false signal to shut down the AED, and the device would be unable to deliver a shock. Still another recalled AED—made by MRL, of Buffalo Grove, Ill.—would work perfectly until somebody dropped it. The impact could cause a circuit board connector to perforate an insulation shield, creating a short circuit and generating RF interference that would prevent analysis of the patient's arrhythmia. Again, the unit would not deliver a shock.

The companies put some of the blame on a manufacturing environment they say has become increasingly globalized in the past 15 years. "Most of the risk today is in the supplied material, the commercial off-the-shelf components; these are the components that go in your iPhones and your laptops, and we don't control their specification," says Brian Webster, president of Physio-Control, a division of Medtronic. "We're prisoners of that supply chain."

Beyond failures in design and purchasing control, the FDA found that many AED manufacturers were practicing a "fix on fail" philosophy. William Maisel, deputy director for science at the FDA, explains: "Fix on fail means identifying and trending problems on a case-by-case basis, repairing individual devices rather than communicating the problem to all users. In one example, a firm tracked hundreds of complaints tied to a known defect. They serviced each device when it failed but did not systemically notify other users so that their devices could proactively be evaluated and repaired."

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How did the AED industry get into this state? It has to do with a quirk in the law regulating medical devices. If you count AEDs as Class III devices—those intended to support and sustain life—then manufacturers must produce extensive efficacy, safety, and reliability data, usually provided by large-scale clinical trials. This process can cost upward of US $800 000 and take two years.

Manufacturers can, however, get around those requirements, thanks to what's called the 510(k) process, which effectively removes AEDs from Class III. The process requires merely that a new AED be "substantially equivalent" to any AED on the market. The 510(k) system was originally intended as a temporary measure to grandfather in devices already on the market in 1976. More than 30 years later, the process is still being used to clear AEDs, as well as 25 other high-risk products, including implantable pacemakers, ventricular bypass devices, and systems for electroconvulsive therapy. Meanwhile, external defibrillators have graduated from manual operation that requires some degree of skill to complete automation. They have also been upgraded to administer a biphasic shock, use rechargeable batteries, and incorporate LCD screens, CPR pacing systems, voice prompts, and self-testing circuits. These features add to the things that can go wrong—and as they were introduced, they were grandfathered in.

In a recent report, the Institute of Medicine of the National Academies noted that "Prior 510(k) clearances are legally binding on the FDA when making clearance decisions. Thus, any unsafe or ineffective devices are embedded in the system." Dr. Michael Carome, a physician with the consumer advocacy group Public Citizen, goes further: "The entire category of AEDs has been insufficiently regulated by the FDA. The status quo essentially represents ongoing, uncontrolled human experimentation with no ethical oversight," he says.

The FDA is now considering whether to remove the 510(k) loophole for AEDs and classify them as full Class III products. Despite claims from manufacturers that reclassification will double or triple the development time for new devices, the change seems likely to proceed.

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Not everyone favors reclassification. "AEDs are fine, technologically," says Gust Bardy, a physician who helped to found the Seattle Institute for Cardiac Research (and is a consultant for Cardiac Science). "You can always find engineering problems, but patients in cardiac arrest are predominantly going to die. There seems to be an unrealistically high expectation that these machines can reverse the process of death. The more restrictions one puts on AEDs and the more demands for AED perfection, the fewer lives will actually be saved. Innovation will be pushed overseas, and we'll be stuck with AEDs that are older and more expensive."

The FDA's Shein agrees that the vast majority of today's AEDs are effective. "There is room for improvement, but it would be a poor choice to leave an AED hanging on the wall rather than applying the therapy to a patient," he says. Rare failures, like that of the unit used on Eugene Malofiy, are of course distressing. But a much bigger factor in the poor survival rate from sudden cardiac arrest is the difficulty of getting access to an AED in the first place. In the United States, AEDs are used in just 4 percent of sudden cardiac arrests that occur in public places. One reason is that AEDs are not always easily located; more on this later. Another deterrent is that many AEDs are labeled "For use by trained personnel only." These labels arose because virtually all AEDs are prescription-only devices, bought under the authority—and responsibility—of a medical officer at the airport, mall, or school. If an AED were somehow misused—or even correctly used by someone not explicitly authorized by the prescribing physician—that doctor could be held legally liable and theoretically even lose his or her medical license.

In fact, modern AEDs are safe and simple enough for anyone to operate: A 1999 study found that even untrained sixth graders could use them nearly as effectively as trained paramedics. Also, Good Samaritan laws cover the well-intentioned use of public AEDs by lay people nationwide. But discouraging "trained use" labels persist—even for public AEDs found within buildings of the FDA itself.

Worse still are stories of bystanders vainly seeking AEDs that were locked away in offices or languishing in unmarked closets. The solution appears to be education and openness. In 1998, Washington state began a citizen defibrillation program that included advertising, public training sessions, and the creation of a detailed registry of AED locations around the state. The survival rate for witnessed sudden cardiac arrest in Seattle is now more than 45 percent, compared with less than 0.5 percent in Detroit and 4 percent nationwide.

If regional health authorities have much to learn from Seattle, manufacturers could do with some inspiration, too. Critics complain that AEDs lack the plug-and-play simplicity of today's consumer electronics. "Each manufacturer has different electrodes that attach to the AED differently," says Robyn Silverman of the ECRI Institute, a nonprofit organization that researches medical technologies. "When the next level of care arrives, they might have another brand of AED. Paramedics have to rip off the first electrodes and put on new ones, which takes time. It would be nice to have universal electrodes for any AED."

Then there's the AEDs' price: up to $2000. "If companies were able to produce low-cost AEDs that could be purchased by nearly everybody, then you'd have mass dissemination, like cellphones," says Bardy. "But under the current regulatory, legal, and engineering burdens, it's nearly impossible to produce an AED that can be bought at Costco."

Ideas abound. BT Group (formerly British Telecom, the United Kingdom's communications leader), has replaced obsolete wired telephones in some of its iconic red phone boxes with public AEDs. And the San Ramon Valley Fire Protection District, in California, has released one of the world's first bystander CPR apps, for the iPhone. Users of the app receive an alert when anyone within 500 feet reports a sudden cardiac arrest, along with a digital map pinpointing the location of both the victim and the nearest public AED.

Future AEDs might be integrated into a program called Next-Generation 9-1-1, a federal initiative to expand emergency communications to include wireless and voice-over-IP devices, text and video messaging, and geolocation data. Tomorrow's AED could automatically summon paramedics the moment it's activated.

But the companies seem reluctant to invest the necessary money. Says Brian Webster, of the AED maker Physio-Control: "The public access market is only about 15 percent penetrated. The economics of the market today do not support our industry doing core technology innovation."

Clearly, the AED industry is not in the best of health. It's ready for a good shock to the system. There are two on the way: reclassification by the FDA and a potentially industry-shifting lawsuit. Whether these jolts will prove fatal or therapeutic remains to be seen. ❏

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Voyage to the Bottom of the Sea

VIRGIN OCEANIC HOPES TO LAUNCH A NEW ERA OF MANNED DEEP-SEA EXPLORATION

BY ELIZA STRICKLAND

As the battered little boat slides down a 3-meter ocean swell into the next trough, Chris Welsh grits his teeth and peers out into the storm. Sheets of rain pummel the dark windows of the bridge, and a Micronesian sailor wrestles with the wheel. It's past midnight on a July night and we're bobbing over the almost 11 kilometers of water that fill the deepest abyss on Earth, the Mariana Trench. Welsh is leading a small party of engineers, scientists, and adventurers under the banner of Virgin Oceanic; they've chugged out here aboard a 20-year-old ferryboat to test some unmanned deep-diving probes. It's the first step in what they hope will be a glorious high-tech adventure, in which a man—Welsh, specifically—will visit the bottom of the trench before the end of this year.

But right now, most of us would be happy just to make it back to Guam, 130 km (81 miles) to the north. Another wave breaks over the boat and crashes down on the cabin house, dousing the upper deck. I recall a plaque mounted on a table in the main cabin that admonishes, "No passengers more than 20 miles from shore." This 20-meter-long vessel is what oceanographers call a "ship of opportunity," which means it was pressed into service for the mission basically because it was available. Welsh turns to the captain, who lives in the Mariana Islands, and asks, "In your experience, what usually happens in a storm like this? Does it get better? Does it get worse?"

DEPTH SEEKERS: Chris Welsh [left] and Sir Richard Branson perch atop the sub that will take Welsh down to the bottom of the Mariana Trench. If Welsh and the sub survive that adventure, Branson will pilot the sub to the bottom of the Puerto Rico Trench, in the Atlantic. *PHOTO: VIRGIN OCEANIC*

The captain keeps the boat's prow pointed firmly into the waves. "I don't know," he says. "I've never seen it like this." It occurs to me that if the boat sinks, it will take 3 hours to reach the seafloor.

Of course, it wouldn't be real adventure if there wasn't any danger. Like the South Pole, the peak of Mount Everest, and the moon, the Mariana Trench is a singular place that looms large in the human psyche. Countless ordinary people have imagined what it would be like to be there, and a very few extraordinary people have actually managed to go. Of all those singular places, the bottom of the Mariana Trench has had the fewest visitors—precisely two. In 1960, U.S. Navy lieutenant Don Walsh and Swiss engineer Jacques Piccard rode down in a primitive vehicle called a bathyscaphe (essentially a small metal sphere attached to an enormous bag of buoyant gasoline). No one has been there since, although three unmanned vehicles took the plunge in the 1990s and 2000s.

If Walsh and Piccard's bathyscaphe was a dirigible, the sleek experimental vehicle being built for Welsh is a fighter jet. Welsh plans to pilot it on the world's first solo dive to the trench bottom. He'll be accompanied by an entourage of robotic landers, the prototype of which we're now testing in this stormy sea. We dropped the lander 6 hours ago, and by now it has completed its round trip to the seafloor and is bobbing somewhere out there on the dark waves. The researchers on board dearly want it back, with its payload of deep-sea water samples. But the radio beacon attached to the probe isn't sending out its location signal, and there's no sign of the instrument's flashing strobe light in the storm. If an unmanned probe carrying only electronics can run into this much trouble in the Mariana Trench, what difficulties will confront the actual sub, with its cargo of human life?

Welsh doesn't seem too worried. He's a firm believer in calculated risk; he does the math and then forges ahead. "I think one of the stupidest phrases in the English language is 'He died doing what he loved,'" Welsh told me before we set out from Guam. He's figured out the possible health consequences of drinking eight Diet Cokes a day and found them acceptable. He flies planes and helicopters and sails racing boats because he trusts his abilities and finds the rush to be well worth the risk. And he has no intention of dying on a crummy old ferryboat bobbing on the surface of the Pacific—or in the sub that will take him to the nadir of the world.

SO WHAT'S A GUY LIKE WELSH doing musing about his mortality on a creaky ferryboat? The answer begins with a half-finished submersible built by the radical sub designer Graham Hawkes, who creates what he calls "underwater flying machines." In 2010, Welsh bought a sub that came with a grim history and three years' worth of dust. Hawkes had been building the vehicle for Steve Fossett, a wealthy adventurer who wanted to add the record for the first solo Mariana Trench dive to his achievements in ballooning, flying, and sailing. But in September 2007 Fossett took off in a single-engine plane from a ranch in Nevada and never came back. His bones were found a year later in the mountains of eastern California, near the wreckage of his crashed plane.

Welsh previously got his thrills with sports cars, planes, and sailboats, but around 2010 he started toying with the idea of setting some kind of world record. He wasn't too particular—the fact that he'd never parachuted didn't deter him from thinking about attempting the highest-altitude skydive. Then, while inquiring about Fossett's up-for-sale yacht, he learned that the boat had been modified to launch a sub from its deck and that the sub was also for sale. He'd never piloted a submersible before either, but once he saw the sub he was hooked. "Buying the sub was enormously consistent with my past history," Welsh declares. "Each aircraft that I bought, I wasn't licensed or qualified to fly when I bought it. But I learned."

At around US $10 million, the Mariana expedition is beyond the capacities of the lower order of rich people. So Welsh, who made his pile in real estate, approached Sir Richard Branson, the chairman of Virgin Group and No. 4 on *Forbes*'s list of British billionaires. Branson founded Virgin Galactic, a company that plans to rocket wealthy tourists to the edge of space; an oceanic venture seemed like the perfect complement. Branson signed on, agreeing that Welsh would pilot the

PRECEDING PAGE: BRYAN CHRISTIE DESIGN

sub on the first Mariana Trench dive, while Branson will plunge the sub into another deep ocean trench.

Sending anything more complicated than a rock to the bottom of the trench, where the pressure is 1100 times as great as at sea level, is a momentous engineering challenge. Ever try to build a sleek hydrodynamic enclosure that can withstand a pressure that's equivalent, over its entire surface, to the weight of four pickup trucks pressing on an area the size of a postage stamp? Didn't think so.

Most governments long ago gave up on trying to send people to the bottom of the deepest ocean trenches, citing the challenges and the seeming pointlessness of the endeavor. After all, a sub like Japan's *Shinkai 6500*, currently the deepest diving manned submersible, can reach 98 percent of the world's seafloor, although it can't make it even two-thirds of the way down into the Mariana Trench.

To probe deeper, down to the other 2 percent, engineers have built autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs). Just as space explorers have come to rely on rovers and unmanned probes to survey our solar system, oceanographers have chosen robotic vehicles and ocean observatories to be their proxies in the deep. But for true believers like Welsh and the Virgin Oceanic team behind him, there's nothing like having a human brain down there to see, experience, think, and improvise.

Welsh and Virgin aren't the only private explorers in this race to the bottom. Decades after governments abandoned the deep, deep sea, a crop of entrepreneurs have taken up where the world's research institutions left off. No fewer than four private companies are designing or building manned submersibles capable of reaching the lowest of the low. James Cameron, the director of blockbuster movies like *Avatar* and *The Abyss*, is financing the construction of a one-person vehicle that will likely be studded with cameras. Triton Submarines, located in Florida, has designed a sub that would bring three people down to the seafloor in an innovative glass pressure vessel, which would certainly give passengers a great view. Deep Ocean Exploration and Research, a California company with funding from former Google CEO Eric Schmidt, is also designing a three-person sub.

Using exotic materials, these new marine trailblazers are promising to build vehicles that are much faster and cheaper than the old-style government models. Hawkes's 5-meter-long sub, for example, is a far cry from the plump, pod-like submersibles operated by the world's research institutions, which rely solely on ballast to descend straight down. Think of Hawkes's machine as an underwater flyer, one whose stubby wings generate hydrodynamic forces to pull the vehicle down into the abyss rather than up into the air. The institutional subs are robust and reliable, but Virgin's sub is sexy. Hawkes calls his vehicle the *DeepFlight Challenger*. Welsh wants to rename it *Scarlett*, and has contacted the actress Scarlett Johansson about modeling for the Virgin Oceanic mermaid logo.

The sleek craft also breaks with the tradition of using a sphere—the most inherently pressure-resistant shape—for the crew capsule. Instead, the pilot will lie inside a cylindrical pressure hull made of carbon fiber. "It's the strongest, lightest material we know on the planet," says Hawkes, and it's the main reason why the sub weighs only 3600 kilograms. A full-ocean-depth sub built around a steel sphere would weigh about 10 times as much, says Hawkes. The six manned deep-sea submersibles operated by government agencies around the world are so heavy that they require specially equipped and enormously expensive mother ships to launch them, while Hawkes's sub is designed to be hauled atop, and launched from, any reasonably large boat.

The entrepreneurs now at the forefront of manned deep-ocean exploration don't justify their projects in terms of benefits to science. Some, like Welsh, say they'd like to investigate the bizarre life-forms in the dark deeps and the geological forces that undergird Earth's mantle. But the motivations also have to do with thrills, ego, bragging rights, and the possibility of a financial return in the future. If all goes well with Virgin Oceanic's solo sub, the company plans to build a two-seater to hold a tourist in addition to a pilot.

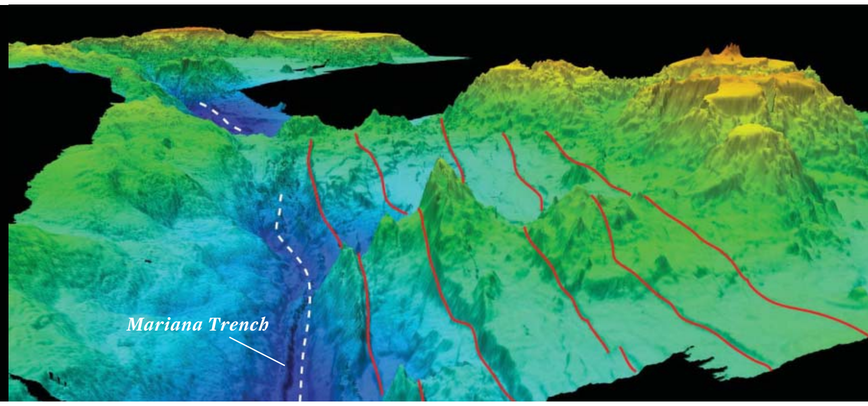
For Hawkes, though, the ultimate payoff would be if his lightweight, inexpensive craft leads the charge into a new era of exploration. "In my view, the existing manned submersibles are almost an extinct species," says Hawkes. "You do need the wild, experimental craft to unlock the future, to show that it can be done. Unless we can break

LANDER AWAY: During the July expedition to the Mariana Trench, marine engineer Kevin Hardy [top] prepares the seafloor lander's sample tubes. Researchers hope that water samples from more than 10 000 meters down will contain strange new life-forms. Once the lander begins its plunge [bottom], it takes 3 hours to reach the seafloor.

PHOTOS: TOP: ROXIE J. CIRINO; BOTTOM: ELIZA STRICKLAND

How Deep?

Remarkably, there is no definite measurement for the Challenger Deep, the deepest part of the Mariana Trench. Measurements taken from the surface using sonar are calculated using the speed of sound traveling through water—but that speed varies depending on the water's temperature and salinity. The best sonar reading to date, taken in 2011, put the trench's lowest point at 10 994 meters.



through to a different kind of manned craft that is dramatically different from existing vehicles, marine exploration in the future won't be manned—it just won't be economically feasible. It will all be done with robots, and we won't have access to our own planet."

For the past few days we've been nervously tracking Tropical Depression 11, a nasty squall south of Guam. Around midnight, just when the lander is supposed to bob to the surface, the storm finds us. "Visibility just went from across the universe to 10 feet," says Kevin Hardy, the marine engineer who designed and built the lander.

We had dropped the seafloor lander over the side of the boat around sunset, sending it down into a patch of the Mariana Trench called the Sirena Deep, which at about 10 640 meters is not quite as deep as the trench's absolute bottom, the 10 994-meter Challenger Deep. Hardy had watched fondly as its cheerful orange flag disappeared beneath the waves and kept tabs on its descent with a sonar communication system. When the probe finally reached the bottom, he transmitted an acoustic command that sent electricity through a "burn wire" to disconnect the anchor (a 50-kg engine block picked up in a Guam junkyard), and he started tracking his lander all the way up through kilometers of black water. On the surface, however, the swells were getting rough, pushed to greater heights by the strengthening wind. In the Pacific night sky, the dazzling glory of the Milky Way began to disappear behind ominous clouds.

The heart of the lander is a hollow glass sphere that protects the electronics and provides buoyancy; that sphere is encased in sturdy orange plastic. Below that is a second sphere for additional buoyancy, and then two long sample tubes to collect water and tiny organisms from the bottom of the trench. The scientists on board are particularly interested in any piezophiles—pressure-loving critters—that may live in the Sirena Deep.

Such landers will play an important role in the Virgin Oceanic mission because Welsh wants the project to be more than just an ego trip. "From the very start I thought, if we're going down there to look around, then it's critical that we bring back samples and data to help scientists understand what we've seen," he says. To avoid weighing down the sub with heavy instruments, he and his engineers decided to use an entourage of landers that will descend in advance of the sub. The landers will drop down and collect water samples; the sub, meanwhile, can cruise between them to observe their environment. The landers will also capture on video the sub's historic arrival on the bottom.

When the storm winds begin to rage, Hardy asks Welsh to come up to the bridge to consult on the status of the mission. The two men struggle across the rain-lashed deck as the boat pitches and lurches. Lightning bleaches the sky, illuminating the two pathetic life rafts with mesh-net bottoms. Hardy scans the dark waves, but there's no sign of the lander's strobe. A lightning strike may have fried the lander's electronics, he tells Welsh. Improbable though it may be, such a strike would also explain why the lander's radio beacon isn't working either—the radio receiver hasn't picked up a single chirp. Without those two systems, the lander is gone for good, unless somebody just happens to spot the little orange globe out there in 10 or 20 square kilometers of storm-tossed Pacific.

Under sunnier skies, on the shore of San Francisco Bay, I paid a visit to Hawkes's marina workshop, where the sub sat in a dozen pieces inside a small storage unit. The wings were stacked to one side, oxygen canisters for the life-support system were boxed up in the front, and the thick steel plates that form the sub's ballast lay on the floor. Jay Tustin, the lanky and unflappable technician who's overseeing the sub's preparations for the Mariana Trench, surveyed the pressure hull, a black cylinder with 13-centimeter-thick walls, and said, "We just don't know how happy it's going to be at full-ocean depth. It's the big unknown."

To survive the dive into the highest pressure environment on Earth, the sub is relying on an exotic material with exciting but untested capabilities. The carbon fiber material that forms the hull is some of the toughest stuff on Earth, but it's never been used in quite this way before. The carbon fibers, which are wound around an epoxy matrix, are fantastically strong in tension when the pressure is applied from inside. But when external pressure causes compression, the material doesn't have quite the same strength.

Tustin noted that the original owner of the sub, the late Steve Fossett, was "very much an adventurer, very much used to taking risks." Tustin explained that with human-occupied vehicles, Hawkes's team typically designs with a 2-to-1 safety factor; in this case, that would mean designing a hull that could withstand the pressure at the purely hypothetical ocean depth of 21.8 km. "We got this to a 1.4 safety factor, and we wanted to do more testing, but Steve cut it off," said Tustin. I asked Tustin if Welsh was comfortable with the 1.4 safety factor. "He's pushing ahead," Tustin replied. "I think that tells you all you need to know."

THE CENTER FOR COASTAL AND OCEAN MAPPING/JOINT HYDROGRAPHIC CENTER

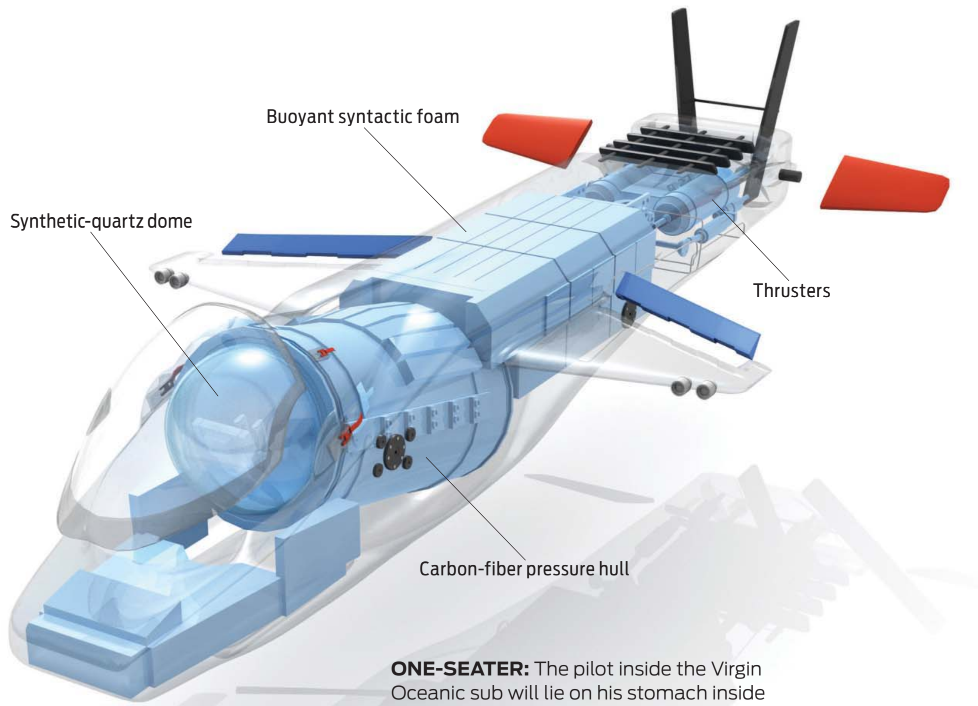
The bulk of the sub—the cylindrical pressure hull and the fuselage around it—was intact, and Tustin invited me to clamber in. The glass dome attached to the front of the pressure hull swung open with a resonant creak, allowing me to slide in feet first. Inside the hull, I lay on my stomach in a modified Superman-in-flight pose, propped up on my elbows so I could grip the two joysticks that control both the thrust and the plane-type parts that allow the pilot to steer: ailerons in the wings and elevators and rudders in the tail. With a combination of the hydrodynamic forces and about 270 kg of ballast, the sub will get to the bottom of the Mariana Trench in 2 hours, Tustin says, leaving plenty of battery time for an exploration of the seafloor.

Tustin and other members of Hawkes's team began building the sub in 2005. The time was right to go for full-ocean depth, Tustin says. The team used light and powerful lithium-ion batteries developed by the auto industry for electric cars. The back half of the sub holds blocks of a buoyant material called syntactic foam, composed of hollow glass microspheres embedded in an epoxy matrix; the newest type of this material can stand up to the deepest sea pressures. Once the sub drops its ballast, that buoyant foam will bring the pilot home.

The acoustic communication system isn't finalized yet—Virgin Oceanic's current system works only to depths of about 5 km. The company's engineers are looking for a replacement system, but Tustin says that during Welsh's dive, he shouldn't count on advice from the surface. "My feeling about it is that once Chris gets down there he's on his own," Tustin said. "It's the dark side of the moon."

The pilot's head will be within the pressure-resistant transparent dome on the front of the pressure hull. This will give him a much better view than researchers get in government subs, which sport just a couple of small portholes. The original plan was to use high-strength glass for this component, but when the glass dome was tested in a pressure chamber, it cracked under the pressure it would experience at just 5000 meters. The thick glass is now fissured all around the edges where it meets a titanium ring.

In the trench, such cracks wouldn't be just a disappointment, they'd be deadly. So Virgin Oceanic hired a company to make a new dome out of a 1270-kg ingot of synthetic quartz. Then a company that makes lenses for NASA telescopes spent one year hollowing it out into a hemispherical shape. This new dome will be tested in a pressure chamber at Pennsylvania State University this spring.



ONE-SEATER: The pilot inside the Virgin Oceanic sub will lie on his stomach inside the cylindrical pressure hull. It's a tight—some might say claustrophobic—fit.

BRYAN CHRISTIE DESIGN

I've never been as happy to see daybreak as I am the morning after the storm, with our ferry pushing through thick fog over a gray sea. On the bridge, Welsh and Hardy scan the horizon, looking for the little orange flag atop the lander's orange spheres that would signal unlikely victory. "We're mowing the ocean," said Hardy as the captain steers us through a slow search pattern around the site where we dropped the lander. But even if the lander survived the storm, it had all night to drift away.

The radar shows an even bigger patch of storm barreling toward us from the south, and the harbor authorities in Guam are advising all ships to head back to port. "The storm is moving at about 13 knots. Our boat travels at 10," Hardy tells us, and there is nothing to do but abandon the search and motor back to Guam. Hardy insists that the mission hasn't been a failure, though. He likens his lost lander to the earliest moon missions, when the Soviet Union sent probes crashing into the lunar surface. "We learned a lot," says Hardy, "but we didn't get the craft back."

So we flee before the storm, which will turn into Super Typhoon Muifa over the following days, and we kiss the $30 000 lander good-bye. But that's the price you pay for trying to explore the mysterious deep—sometimes the deep claims your emissaries. Standing on the bridge, staring into the empty gray sea, Welsh vows to press on. "We'll do it better next time. We'll build four more. We've just got to learn how to overcome the obstacles, and we will."

This year, while Hardy builds new and improved landers, Welsh will oversee tests of the sub's pressure hull and its new quartz dome. If all that goes well, before the end of this year the team will be back out here over the trench, attempting a much more ambitious mission with much higher stakes. Welsh says that when he pilots the sub on its long, long dive into the Mariana Trench, he'll be thinking about the pressure, of course, and trying not to dwell on the fact that any weakness in the hull means implosion and instant death.

"I don't have the appetite for roulette," he says, "but there is a need for gumption in science and exploration." Virgin Oceanic is bringing the gumption back. ❑

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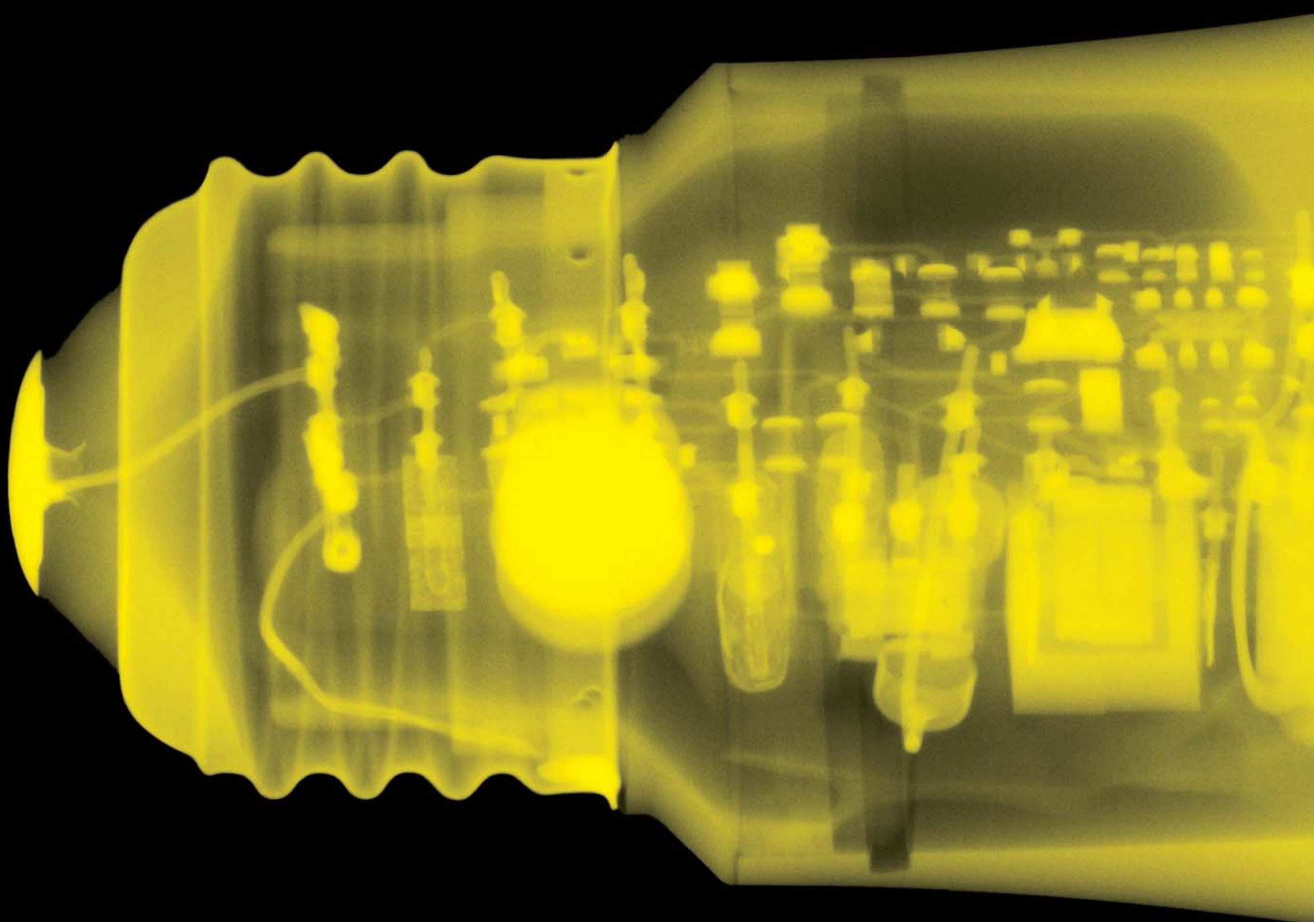

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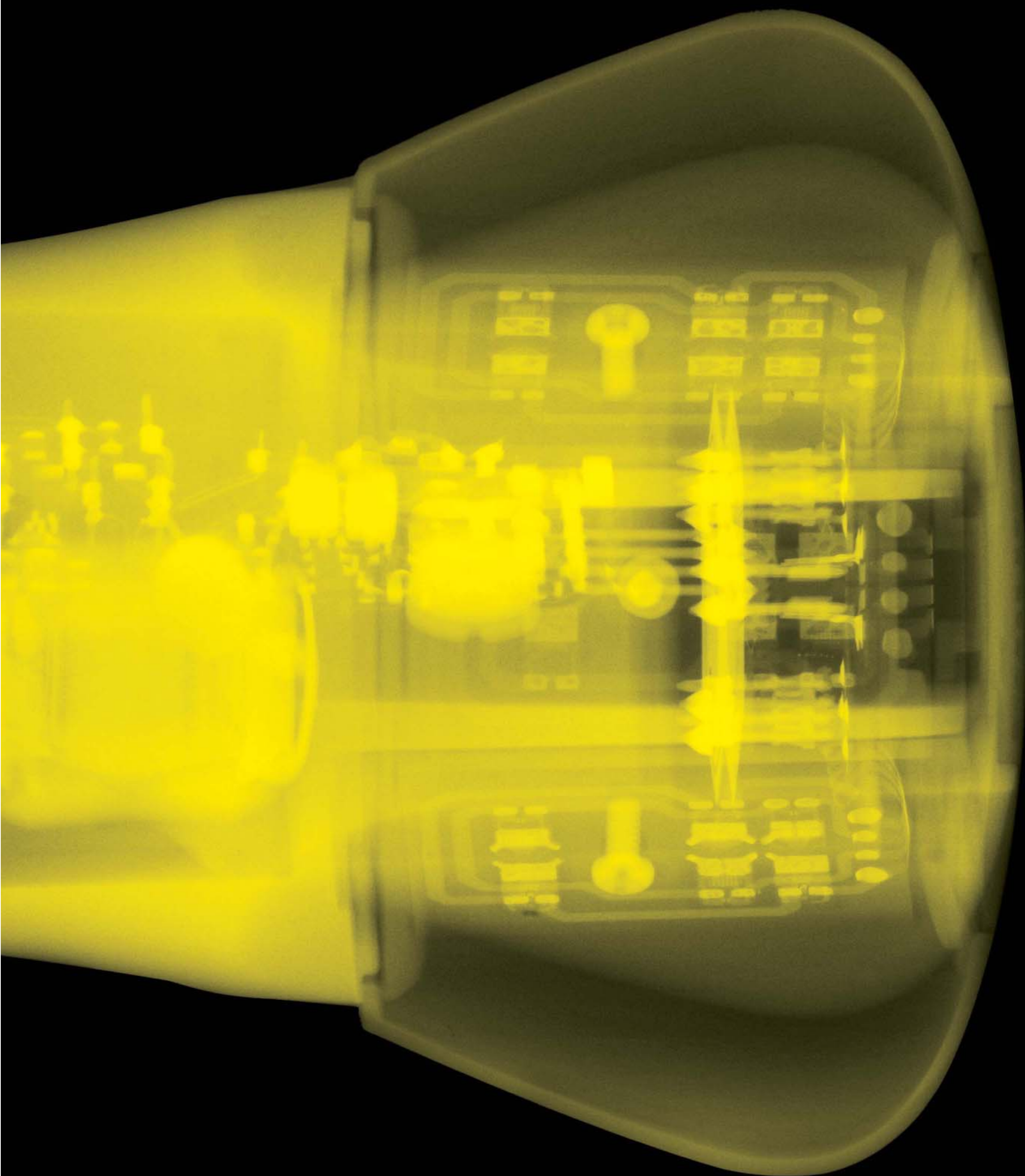
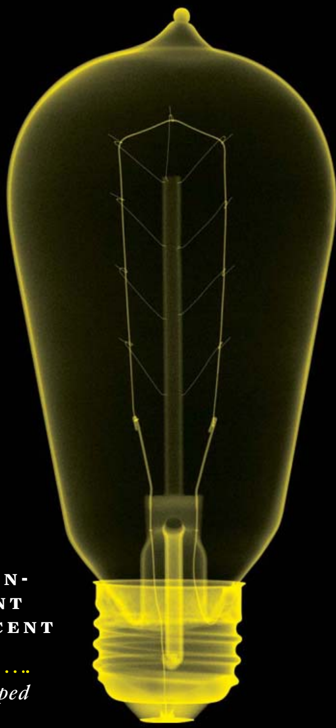


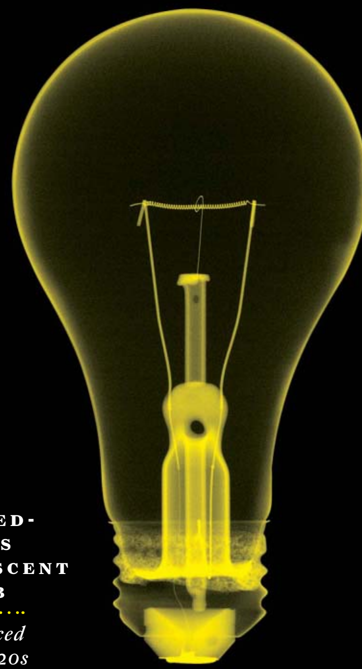
The circuitry behind LED lighting poses tricky challenges

by BERNIE WEIR



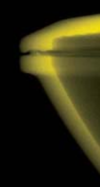
TUNGSTEN-FILAMENT INCANDESCENT BULB

First developed in 1906



FROSTED-GLASS INCANDESCENT BULB

Introduced in the 1920s



HALOGEN-FILLED INCANDESCENT BULB

First patented in 1959

LAST AUGUST, the U.S. Department of Energy announced the first winner in its ongoing competition to encourage lighting that's more efficient—the Bright Tomorrow Lighting Prize, or L Prize. The DOE awarded Philips Lighting North America US $10 million for coming up with a lamp that's equivalent to a standard 60-watt incandescent bulb in size and brightness but lasts at least 25 times as long and runs on less than 10 W.

Although lamps that are almost as efficient have been available for more than a year, the prizewinning design is just now going on sale. Like the backlights in modern cellphones and computer monitors, these lamps use light-emitting diodes to generate white light. They offer long lifetimes, pleasing colors, and most important, phenomenal energy efficiency.

Is it now time to throw away the incandescent bulbs still lurking in your light fixtures—and even the compact fluorescent lamps (CFLs) you've been switching to—and replace them all with LED superlights? With costs often hovering around $25 a pop, few homeowners are rushing to take that plunge. But prices are dropping, and performance is improving fast. So it's clear that the day when LED lamps will dominate lighting in both residences and businesses is not far off.

Why are LED-based lamps superior, and what makes them so tricky to engineer, anyway? You might imagine that the answers would hinge on the subtleties of solid-state semiconductor physics that govern high-brightness LEDs. They do, but only up to a point. The practicality of these new lights also depends on a more mundane part of the package that's often overlooked: the circuitry required to drive them. Here I'll explain what the requirements are for that circuitry and why designing the appropriate electronics can be a challenge, although not one that should slow the adoption of this fantastic new form of lighting.

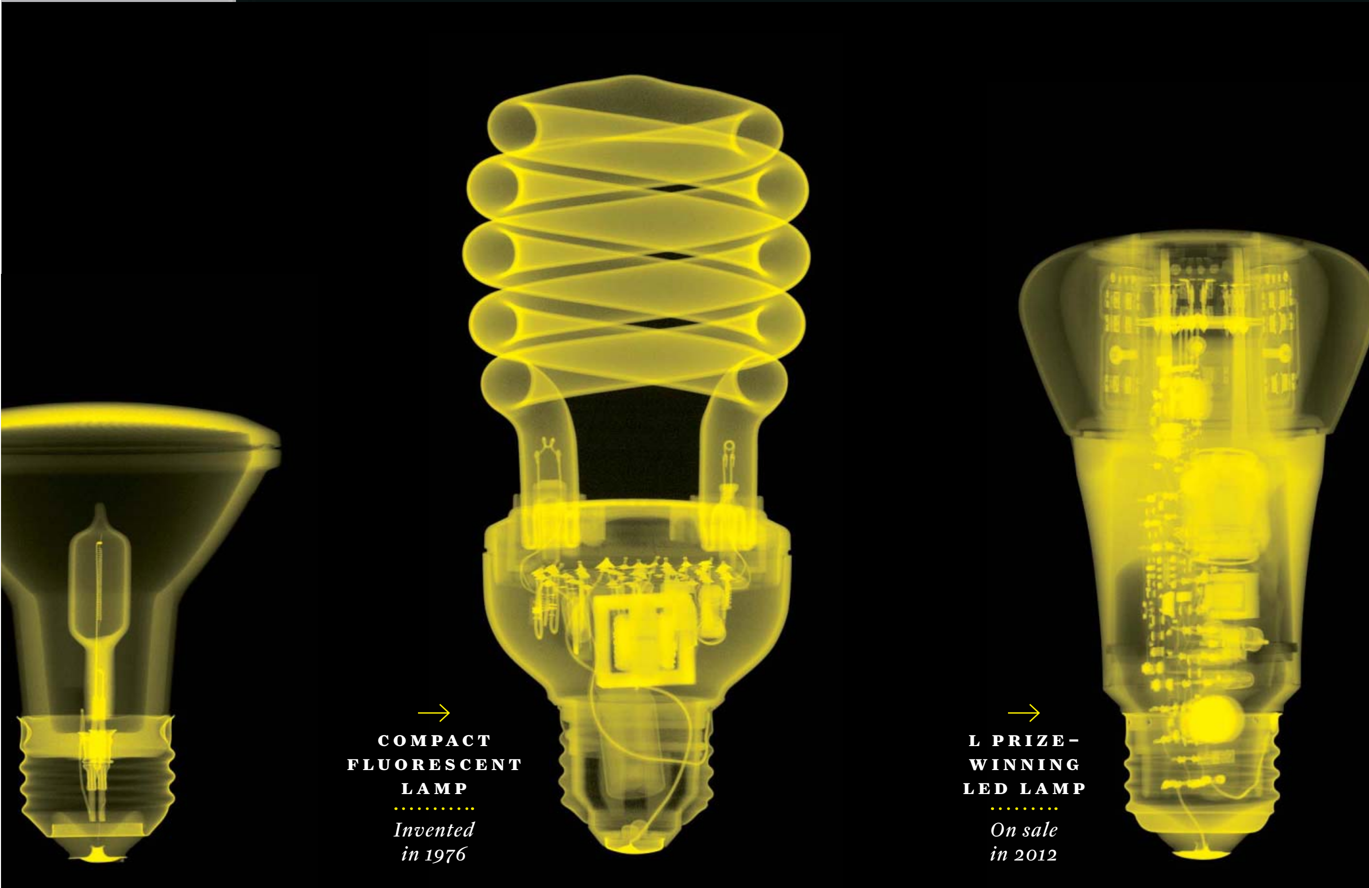
LIKE IT OR NOT, incandescent bulbs are a dying breed. Australia and the European Union started phasing out traditional incandescents in 2009. The United States is haltingly moving in the same direction, and China is aiming to eliminate incandescent bulbs by 2016. The reason is simple: Old-fashioned lightbulbs squander enormous amounts of electricity.

A full 90 percent of the energy you put into an ordinary incandescent bulb goes into making heat, not light. A standard 60-W bulb generates approximately 850 lumens of light, which comes out to about 14 lumens per watt. Halogen lamps (a more sophisticated kind of incandescent with a higher temperature filament) can provide about 20 lm/W. CFLs are considerably more efficient, producing around 60 lm/W, but they have other problems.

One common complaint is that you can't dim them. (In truth, some can be dimmed, but their range is usually limited.) Also, CFLs are slow to light up, and because their bulbs contain mercury vapor, they present an environmental hazard. Even with recycling opportunities available, millions of these bulbs end up in landfills every year.

LED-based lights have none of those drawbacks, and they are far more efficient, some offering more than 100 lm/W. These nominally white lights, in fact, contain blue LEDs, along with a phosphor coating that converts the narrow wavelength light they emit into something the human eye perceives as white. With the appropriate mix of phosphor materials, designers can set the tone of

ABOVE AND PREVIOUS PAGES: DAVID ARKY



the light from cool to warm, depending on the application they have in mind.

Next to their high energy efficiency, the most attractive quality of LED lights is their longevity. Exactly how long one will last depends on how it's designed and operated, but most will work for 25 000 hours or more while maintaining at least 70 percent of their initial light output. And many manufacturers advertise 35 000-hour lifetimes. So if you used an LED lamp for 10 hours a day, you could expect it to last from 7 to almost 10 years. That's a far cry from a standard incandescent bulb, which on average goes dark after only about 1000 hours of use. It also beats CFLs, which typically last from 6000 to 10 000 hours.

Such long lifetimes reduce one of the hidden costs of lighting, especially for commercial and industrial users: maintenance and replacement costs. That, and the energy savings that accrue, explains why large-scale users have been the early adopters. For example, the city of Los Angeles is now in the process of replacing 140 000 high-pressure sodium streetlights with LEDs. Major retailers, like Walmart and McDonald's, are also switching to LED lighting in some places. Really, the only thing holding such businesses back is the high up-front costs—and the prospect that LED lighting technology will soon improve and become an even better deal.

ONE DRAWBACK of the LED, however, is that, unlike an incandescent bulb, it can't just run straight off the electric mains. The operating voltage of a standard white-light LED is usually in the range of 3 to 3.6 volts, about the same voltage as the lithium-ion battery in your cellphone. Although this makes LEDs easy to use in mobile devices, most lighting fixtures get power from the grid. So conversion circuitry is required to transform the AC line voltage into a form that can drive individual LEDs.

The necessary circuitry is similar to that in a cellphone charger or laptop adapter, with some key differences. First, because LEDs can operate for many years, the power electronics that drive them must either last just as long or be configured so that any failure-prone circuits can easily be replaced. Also, because the drive electronics must often be embedded within a screw-in light source, the circuitry must be very compact. It should also be energy efficient, because any losses from the drive electronics increase the total power that must be drawn from the wall outlet. Lastly, and rather surprisingly, the drive circuitry must be able to withstand relatively high operating temperatures.

That last statement requires some explanation. As I've noted, incandescent bulbs turn only 10 percent of the electrical energy they consume into light, with the rest wasted as heat. LEDs transform about 50 percent of the energy fed to them into light, making them far more efficient. But there's a complication: Incandescent bulbs radiate their waste heat into the space around them as infrared waves, whereas LEDs radiate only visible light. Also, the ceramic bases of screw-in LED lamps act as insulators. So their waste heat, modest as it is, tends to remain at the source. That spells trouble, for a couple of reasons.

For one, the heating causes the temperature of the LEDs to rise—and here, hotter isn't better. Light output drops as the temperature of the lamp increases (just the opposite of what happens with fluorescent lights). Worse, high temperatures shorten the life of LEDs. Another problem is that as the drive circuitry heats up, various electronic

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Internal Affairs

LED lamps contain an assortment of highly engineered components. The generic example shown here includes an array of white-light LEDs and the electronic circuitry to drive them, all packaged in a compact screw-in unit.

components—particularly electrolytic capacitors—wear out faster.

One way system designers combat those problems is to use a metal heat sink, allowing convection to shed heat into the environment. Another is to avoid creating any more waste heat than is absolutely necessary by designing drive circuitry that's highly efficient.

Although specialized circuits are sometimes attached to individual LEDs, more often than not one set of drive electronics powers multiple LEDs wired together. Indeed, some LED manufacturers mount an array of LEDs in an integrated package to achieve higher light output, although single high-output LEDs are also common.

In most instances, the individual LEDs in each group are wired in series. Connecting them this way ensures that the same amount of current flows through each one, even if there are minor differences in their electrical characteristics. And that's exactly what you want, because drive current determines their light output and color. So you need to do all you can to maintain the specified current level.

This need for a constant current does not exist in most electronic devices. A microprocessor, for example, accepts a fixed voltage and, depending on what task it is performing, draws more or less current. You can't, however, just apply a fixed voltage to an LED and expect a set amount of current to pass through it. That's because the voltage across the diode varies with temperature and also with the amount of current it draws. Also, there can be considerable manufacturing variation between LEDs, not to mention variation between similar devices from different suppliers.

Often, though, it's not practical to wire all the LEDs you need into one big series-connected chain. For the desired amount of light, you might need so

EMILY COOPER

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many LEDs that the voltage to drive them would become excessive if you had them all wired in series. The obvious solution is to limit the number of LEDs in each string and to power several strings in parallel if need be.

That's straightforward if each string has its own drive circuit, but if several strings share the same power source, life gets more complicated. For one thing, putting LEDs in parallel requires that the components be well matched—otherwise the current (and light output) in each string won't be the same. And there's the danger that one LED will fail and cut off the flow of electricity through the string it's in, like what used to happen frustratingly often with old-fashioned Christmas-tree bulbs. That's bad, of course, because the whole string goes dark. Also, it will send more current into the parallel strings, which increases their temperature and will damage them if the current is too high. Designers can avoid such cascading failures, however, by cross-connecting the LEDs in parallel strings. A single point of failure would then affect only a few other LEDs.

Ideally, though, each series-connected string would have its own regulated driver, providing just the right amount of current needed. LED manufacturers carefully document the amount of current required for a given light output, so it's not hard to decide what current to provide. The voltage needed to maintain that current level might vary from, say, 3 to 3.6 volts. So if, for example, eight LEDs are wired in series within one lamp, the drive circuitry for it must provide the desired current level at voltages that range from 24 to about 29 volts.

The drive electronics must include two basic functional elements: a power conversion circuit (essentially a transistor switch that rapidly turns on and off) and a sensing circuit, which monitors the average current through the LEDs and provides a feedback signal to regulate the proportion of time that the power-conversion switch remains turned on. In many cases, a transformer is used to change voltages and to isolate the LED from the high-voltage electrical mains. In such designs, the feedback signal is often communicated optically from the sensing electronics to the power-conversion circuitry, so as not to compromise the electrical isolation between these two stages.

Arranging all this is easy enough for engineers versed in designing switched-mode power supplies, like those inside cellphone chargers or desktop computers. One looming challenge with LED lighting, though, is that it promises to make switched-mode power supplies even more widespread than they are now. This is great for companies like the one I work for, On Semiconductor, based in Phoenix, which builds ICs for use in such supplies. But it could present a headache for electric utilities, unless additional measures are taken to ensure that these power supplies are grid friendly. Let me explain.

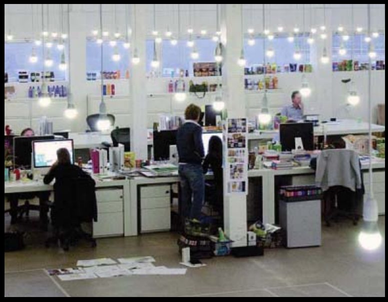
The amount of current an ordinary incandescent lightbulb draws at any given instant is proportional to the voltage applied across it. As the magnitude of this AC voltage oscillates, so does the current flowing through the bulb, along with the energy expended. As a result, the power that the local utility company generates flows smoothly into the bulb where it's converted to light and heat.

Many electrical loads, however, contain capacitors or inductors, which can store energy and thus alter how the device draws current from the electrical mains. Substantial capacitance or inductance will push the timing of the voltage and current oscillations out of whack, allowing energy to flow back and forth between the load and the grid. Another problem is the generation of harmonics of the grid's fundamental frequency.

Power companies can deal with these disruptions, but they are nevertheless troublesome. This is why regulatory authorities are attempting to limit the problems LED lighting might create. The usual gauge for judging that is called the power factor, which varies from 0 (when energy just flows back and forth without being consumed) to 1 (when all the energy flows smoothly into the load). In the United States, for example, any LED bulb that draws more than 5 W, or any LED-based lighting fixture intended for residential use, must have a power factor greater than 0.7 to qualify for an Energy Star rating. And LED fixtures intended for commercial use must have power factors greater than 0.9 to qualify.

THE ADOPTION of LEDs for general lighting will no doubt be both evolutionary and revolutionary. On one hand, many people will shift to LEDs bit by bit, using the lamps they have always used and simply purchasing replacements for their screw-in incandescents and CFLs. On the other hand, LEDs present designers with ways to create much more innovative forms of lighting, ones that take advantage of the long lifetime, directionality, and fine-grain scalability of light that LEDs offer. Lighting designers for homes and businesses will need time to discover the possibilities, but once they do, fantastic new kinds of lighting will surely start to illuminate our homes and offices. And if the circuits that operate them are built right, those lights will prove just as reliable as they are attractive. ❑

POST YOUR COMMENTS *online at* http://spectrum.ieee.org/powerled0312



LED-ING EXAMPLES [from far left]: Phoenix Children's Hospital; the Audi A8; McDonald's Amsterdam Southeast; a solar-powered streetlight in the Netherlands; a Walmart freezer case; the office of Reggs, an Amsterdam design agency.

PHOTOS, FROM FAR LEFT: PHILIPS; AUDI; PHILIPS (2); WALMART; PHILIPS

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INDIA'S *Big Bet on* IDENTITY

THE WORLD'S LARGEST BIOMETRIC AUTHENTICATION SYSTEM REACHES ITS FIRST MAJOR MILESTONE, BUT LOTS OF CHALLENGES REMAIN

BY JOSHUA J. ROMERO

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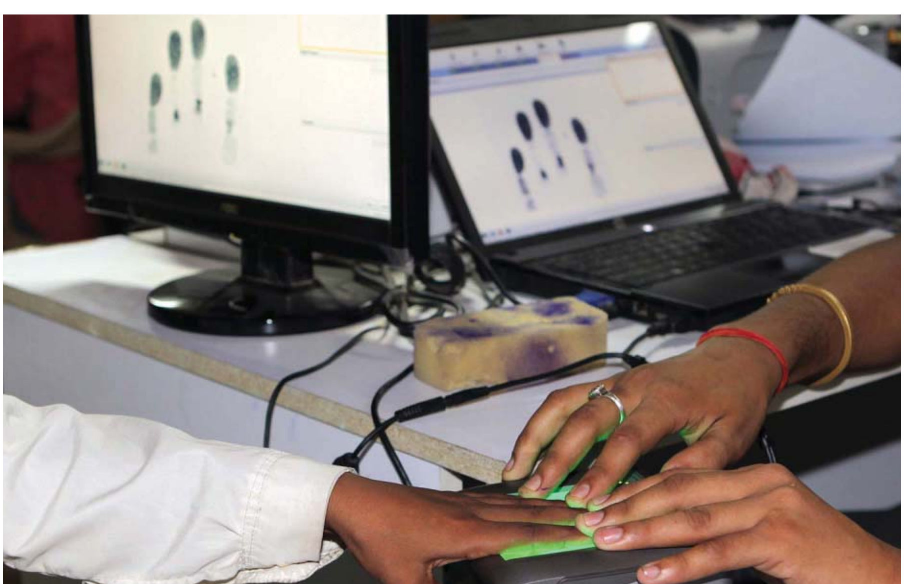

BY THE NUMBERS

Throughout India, people (like these residents of Bangalore and Delhi) are providing fingerprints, iris scans, and facial photos to obtain a unique 12-digit number. The government hopes to eventually collect biometrics from everyone in the country.

PHOTOS: JOSHUA J. ROMERO

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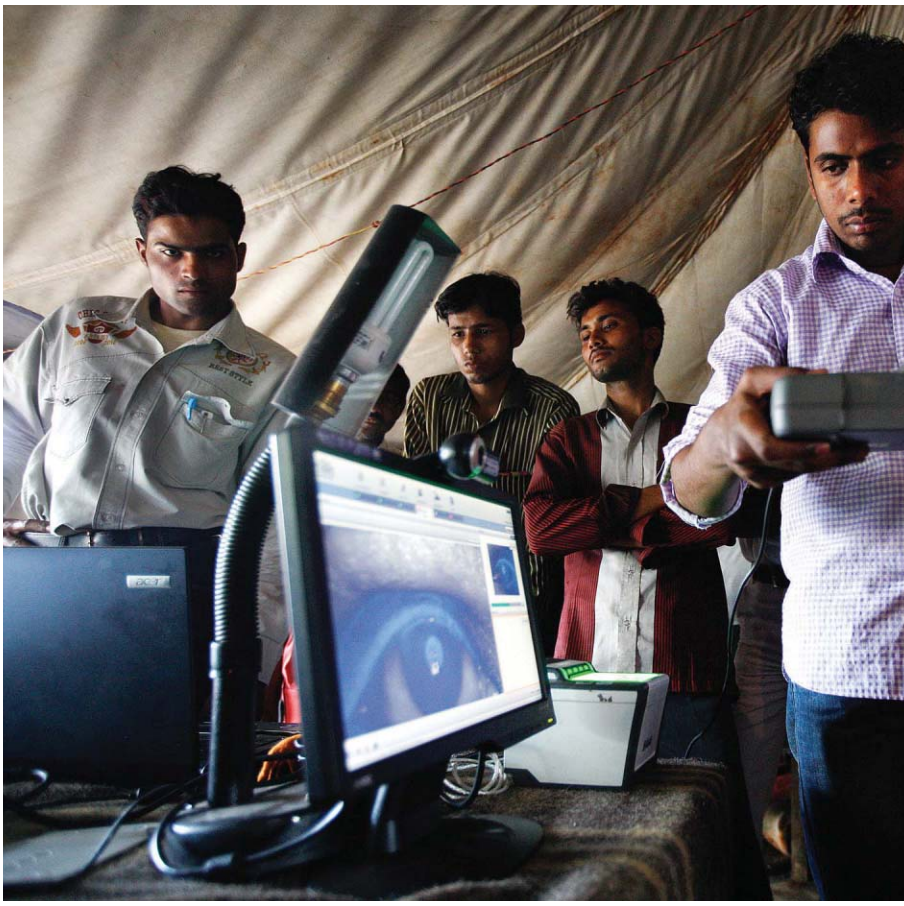


DRIVING AROUND Bangalore, it's immediately clear that the infrastructure hasn't kept up with the IT boom in this once-sleepy South Indian city. Auto rickshaws, scooters, and motorcycles squeeze into a tight phalanx at each red light and choke the air with exhaust. Construction, such as the concrete supports of the new metro rail line that looms overhead, causes detours everywhere, and in spots the entire road abruptly disintegrates into gravel.

But something miraculous happens as you make your way south, past the outer ring road. A ramp lifts a select few vehicles out of the weaving traffic and onto an elevated tollway, where you suddenly have a bird's-eye view of the urban landscape. This is the road to Electronic City, an oasis of glass and steel high-rises overlooking pristine black asphalt paths that snake through the perfectly manicured lawns of tech companies like Wipro, IBM, and Infosys Technologies.

"If you can have such good roads in the Infosys campus, why are the roads outside so terrible?" That's the common question foreign visitors would ask Nandan Nilekani, one of the company's cofounders. "Politics" was his usual reply, according to Nilekani's 2008 book, *Imagining India*. Now the man who has been called the Bill Gates of India has jumped into politics to try to use what he learned at the IT giant to transform the dysfunctional country that lies beyond the borders of Electronic City.

Since July 2009, Nilekani has been a cabinet minister, leading hundreds of engineers and entrepreneurs as chairman of the Unique Identification Authority of India (UIDAI). By the most conservative estimates, at least a third of the country's 1.2 billion citizens live below the poverty line and outside the formal economy. The UIDAI is expected to connect those hundreds of millions of people to government programs, save public money, reduce fraud and corruption, and foster new business opportunities—all by creating an unprecedented biometric system.

2% OF INDIA'S GDP IS SPENT ON SOCIAL PROGRAMS

59% OF THAT SPENDING DOESN'T REACH THE POOR

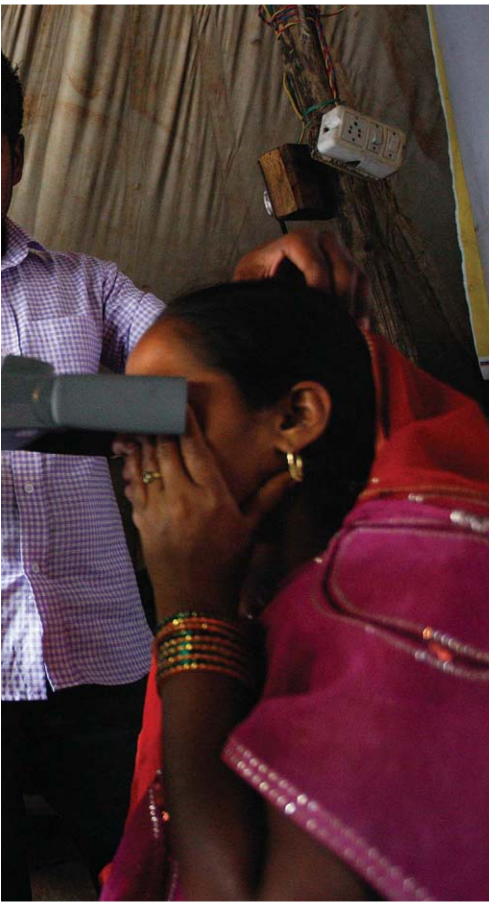
"On the one hand, within India and across the world, people of Indian descent have done some remarkable work," says Nilekani. "And on the other hand, here is a country that needs to solve some very basic problems. This project marries these two worlds." UIDAI plans to use fingerprints and iris scans to assign every person in the country a unique 12-digit ID number that can be verified online. It's one of the biggest IT projects in the world, and getting bigger: By early February, the UIDAI had issued 130 million ID numbers, and it can issue up to a million more IDs every day. The agency has set up 36 000 enrollment stations staffed by 87 000 certified enrollment operators. In India the project is called Aadhaar, which means "foundation" or "support," because it's meant to be a fundamental technology platform that will enable dozens of new public and private services to be created.

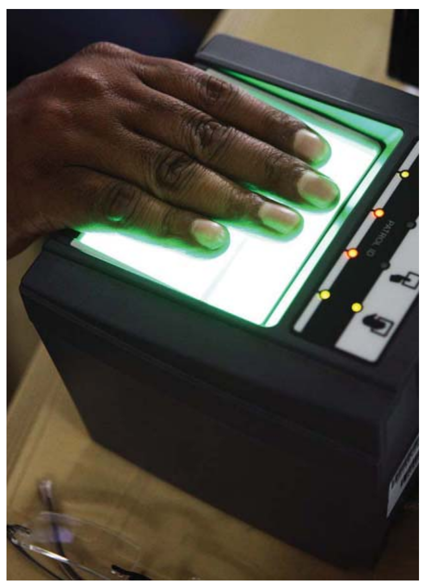
That's if it all works. It's easy to list major challenges: How exactly do you collect biometrics from every single person in the world's second most populous country, especially those living at the margins? How do you keep bad data from getting into the database in a country rife with corruption? And how can you build the entire system around online authentication in a country where fewer than one in 20 people have access to the Internet?

The answers to these questions are getting more than the usual amount of scrutiny, because a lot of political fortunes are riding on the UIDAI.

The program has been heavily supported by the ruling Indian National Congress party; Nilekani was appointed by the prime minister himself, Manmohan Singh. But Singh and his Congress party have had a difficult time enacting many of their biggest policy goals, and the UIDAI has increasingly become the target of criticism.

Earlier this year, the whole scheme seemed in imminent danger of collapse, when a parliamentary committee killed the bill that would have given the program statutory authority, and a political turf war erupted between the UIDAI and the National Population Register, another government project collecting biometrics for the national census. But by late January the two sides had reached an agreement to share biometric data collection, and Aadhaar is once again moving full steam ahead with a new mandate and an estimated budget this year of 15 billion rupees (about US $300 million).





NECESSARY GEAR: Each enrollment station has the same basic set of equipment, including an iris scanner [left], a fingerprint scanner [bottom], a webcam and light [top], a laptop, a second monitor for the resident to view, and a scanner and printer to handle documents.

PHOTOS, CLOCKWISE FROM LEFT: RUTH FREMSON/ THE NEW YORK TIMES/REDUX; JOSHUA J. ROMERO (2)

To understand why the government has invested so heavily, it helps to know the current state of affairs in India. Aadhaar is meant to provide a form of identification that's free, national, impossible to counterfeit—and available to everyone. "There's an ID divide," Nilekani explains, between people who have multiple official IDs and the hundreds of millions who have none. Only about 60 million people in India have passports, he says, and only about 100 million have photo ID bank cards. The most prevalent document is a voter ID card, which has been issued to about 700 million people, covering just over half of the country. But these and the rest of the official IDs created by the country's vast bureaucracy all have shortcomings.

The primary reason for creating a biometric ID system is to give India's poorest citizens better access to an array of welfare programs. India spends about 2 percent of its gross domestic product on social programs like the Public Distribution System, which provides subsidized rice, wheat, and other staples, and a rural employment scheme that guarantees 100 days of work. But all such programs suffer from severe "leakage": According to the World Bank, corrupt officials and middlemen siphon away 59 percent of the money before it reaches the intended recipients. Eventually, the government hopes to provide funds directly to each person who needs them.

Most states issue ration cards, but they usually aren't valid in other states. An official ID that can be used throughout the country is increasingly important as more and more people move away from their hometowns to follow employment, Nilekani says.

Complicating the problem further, existing ID cards are easy to duplicate. Some states have more names on their food ration lists than there are people living in the state. To fight counterfeiting, the Aadhaar team decided to use biometrics instead of issuing just another ID card. From the beginning, they consulted biometric experts, used existing standards when they could, and studied similar systems like the U.S. Visitor and Immigrant Status Indicator Technology program, run by the U.S. Department of Homeland Security.

One thing the team realized early on is that a single biometric measurement wasn't enough to guarantee uniqueness. In proof-of-concept studies, researchers determined that only by using all 10 fingerprints and a scan of both irises could error rates be kept manageable. Adding iris scans also makes the program more inclusive for people whose fingerprints have been worn down by manual labor.

Getting an Aadhaar number is not a quick process. One Friday after midnight, I watch dozens of families wait patiently in a municipal building where only half the lights are on and there's always a baby crying. While Anurodh Kanchan waits, he explains that he came at this hour because he'd heard the lines were even longer during the day. He'd already been once before to schedule this appointment. Now his 7-year-old daughter dozes on his wife's shoulder as the whole family waits another half an hour for the enrollment agent to return from a break.

Hiring and training people to work as agents has been one of the project's biggest logistical challenges. The UIDAI outsources enrollment to "registrars"—often state governments or banks—which in turn hire accredited agencies to actually set up and staff the centers. The agencies get paid a flat rate for each successful enrollment, as do the agents they hire. A coordinator for one of the largest agencies told me that his organization had significantly overestimated how many enrollments an agent could complete in a day. UIDAI says that an average station (see photos, "Necessary Gear") can process each enrollment in under 10 minutes, but in the days I spent observing, it wasn't uncommon for the process to take twice as long. And if you're an agent looking at a line of people stretching out the door, it's easy to see how you might begin to rush through your tasks.

That's why enforcing quality is left to a piece of software known as the enrollment client, installed on each agent's laptop. The program manages every step of the process and was developed jointly by engineers at UIDAI and MindTree, an Indian IT company. Because enrollment often takes place in remote locations with no Internet access, the client must be fully independent and be able to run off a single laptop. The developers also had to make sure that the enrollment client could work seamlessly with any of the 11 biometric devices from various manufacturers that had been certified for use. And the initial version had to be built fast: MindTree won the contract at the end of April 2010, and the UIDAI wanted to enroll the first resident by that August.

100 trillion
PERSON MATCHES ARE REQUIRED TO GENERATE 1 MILLION AADHAAR NUMBERS PER DAY

MindTree met the deadline, and the client it designed now manages to prevent and correct most errors an enrollment agent might make. In addition to a simple quality check, the software looks for self-consistency—for instance, verifying that each fingerprint isn't coming from the operator or another recently enrolled resident and that all 10 fingerprints and two irises are distinct from each other. If something goes wrong in a biometric capture, the software tells the operator how to correct it—for instance, it can distinguish between a facial photo that's too dark and one in which the person was photographed at the wrong angle.

Still, over the last 21 months, the software engineers have had to continually improve the program to address new challenges encountered in the field. For example, when the UIDAI began enrolling people in the Punjab region of North India, where many men wear long beards and large turbans, enrollment agents had a hard time taking a photo that the software considered acceptable: The turban would be interpreted as an unacceptable background, or the automatic cropping feature would crop around the turban instead of the face. The software team was able to quickly tweak the parameters and release a new version of the client so that enrollment could continue.

It isn't just the biometric collection that's tricky. A resident must also supply basic demographic data—name, age, gender, and address. Residents can fill out

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paper forms in any of the 16 official Indian languages, which agents must first transfer to the computer and then translate into an English version of the form. This is by far the most time-consuming part of the process, and MindTree has tried to speed it up by building transliteration into the client software. But Indic languages have many variations—some are written right to left, and many use unique character sets. Still, the agent is expected to check the results and clean up minor mistakes.

There are obviously both privacy and security concerns when you're collecting personal data from more than a billion people. "You can't change your biometrics," points out Sunil Abraham, the executive director at the Center for Internet and Society, in Bangalore, so if they become compromised, it's a difficult problem to fix.

Among the precautions the UIDAI takes is to encrypt all data as soon as they're collected. The data can be decrypted only by UIDAI servers, so the records aren't even accessible to the operator or enrollment agency that collected them. At the end of each day, all the encrypted enrollment data are stored on USB flash drives, and the drives are transported to a place with Internet access so the data can be uploaded to UIDAI's servers. It's in the best interests of the enrollment agencies to safeguard the data, because otherwise they won't get paid.

From the enrollment centers the action moves to the racks of servers at the UIDAI Central Information Data Repository, which is also in Bangalore. Here is where deduplication—checking each new enrollment against every other record in the database—will arguably make this identity scheme rise above the rest. Ensuring that no person can get two numbers is key to making biometrics a worthwhile investment. A few years ago, one Indian state collected biometrics for everyone below the poverty line, but it didn't have the technology or a plan to prevent duplicates. It ended up capturing 1.2 times the population, which resulted in a significant leakage of benefits.

Many critics, including members of Parliament, have doubted that it's even possible to deduplicate records from the entire Indian populace. It's certainly a big task. In order to issue 1 million Aadhaar numbers in a single day, the current maximum rate, the data center must conduct 100 trillion person matches. To improve this process, the UIDAI came up with an unusual arrangement. Rather than hiring a single firm for the job, it awarded the project to three contractors, each responsible for processing a portion of the enrollments, with the overlapping records used to compare performance between the systems. This arrangement lets the UIDAI know if a system isn't working correctly and also gives the companies a financial incentive to improve their software—they'll get to process more records, and get paid more, if their products perform better. The vendors were even required to use the same kind of hardware to build their systems, so the agency isn't tied to any one company.

In late January, the UIDAI released a report that for the first time detailed the results of this deduplication effort. There are two primary factors that determine the accuracy of a biometric system: the false-positive rate, which in this case is how often a newly registered person is incorrectly judged to be already enrolled, and the false-negative rate, which is how often true duplicates are not recognized as such. To measure the false-positive rate, the

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UIDAI tested 4 million unique records against a subset of the enrollment database containing 84 million records: Of the unique records, 2309 were falsely rejected, for a false-positive rate of 0.057 percent. The agency also tested 31 399 known duplicates. The system caught all but 11, for a false-negative rate of 0.035 percent.

The false-positive rate applies to the total number of records in the database. As that number grows, the rate should increase in a linear fashion, because there are more opportunities for false matches. The false-negative rate, on the other hand, applies only to the small minority of enrollments that really are true duplicates (the UIDAI estimates that these make up only 0.5 percent of all incoming enrollments). Because the false-negative rate doesn't depend on the total number of records, it should remain steady unless more people try to enroll multiple times.

R.S. Sharma, the director general of UIDAI, says that preventing all duplicates with technology alone is impossible. There are some people who just can't be uniquely identified through biometrics, because the data for them aren't good enough—children under age 5, for instance, and people with multiple disabilities. That's why the responsibility for accuracy and uniqueness isn't all left up to the software. Several full-time employees manually review the roughly 0.2 percent of cases that the software can't handle, resolving errors and looking for evidence of fraud.

Even if the system isn't perfect, it's likely to be much better than any existing alternative, simply because it will eliminate "ghost identities," says M.R. Madhavan, who works at the Centre for Policy Research, in New Delhi. "At least people who died in 1995 or 2005 will not get into the system," he says.

Now that the UIDAI has shown it can collect biometric and demographic data and eliminate duplicate enrollments, much of the attention will shift to the authentication system, where people can prove their identity with just the swipe of a finger. Such systems are still under development, so most residents I met weren't clear about the benefits of the program. When I asked people why they were enrolling, they often had vague reasons: "It might make it easier to get my benefits," said one middle-aged woman in Bangalore. "I heard you'll need it to buy heating gas," said another woman. "I think it's mandatory," an elderly man told me. Nilekani thinks that getting authentication services up and running will be the best way to demonstrate the power of the entire project.

Here's how such a futuristic system might work: Walking up to a wirelessly connected terminal at a local shop, a person will type in his name and Aadhaar number, and then he'll scan his fingerprints. The data will be sent to a central database, where the Aadhaar number will be used to locate his record. The submitted name and biometric data will be compared to those on file, and the software will determine whether they match.

The UIDAI imagines that such biometric terminals will eventually be ubiquitous. The first devices deployed will likely be micro-ATMs in rural shops. These machines process transactions electronically, just like a full-size ATM, except they don't store and dispense cash—that gets handled from the shopkeeper's till. The hope is that such systems will deliver financial services to the 40 percent of the Indian population who have never had bank accounts. When people enroll for Aadhaar, they simply need to check a box and an Aadhaar-enabled bank account will be created for them.

In January, the UIDAI began a pilot project in the state of Jharkhand, where workers in the rural employment program could collect cash payments by scanning their fingerprints at a micro-ATM. Another pilot program in Maharashtra transferred small amounts of money to individual Aadhaar numbers, showing that bank servers could be easily linked with the UIDAI system.

The authentication system is already available as an application programming interface (API), which means it won't be limited to just government programs and banks. Private service providers could use it to verify new customers as well. Take India's vaunted mobile-phone culture: Phone companies are currently required to collect and retain significant documentation for every person they sell a SIM card to, as I found out in the two days I spent collecting the photos and local references I needed to get one myself. "If you look at any service provider, they're not going to offer the mobile-phone service unless they verify who you are," says Bala Parthasarathy, an entrepreneur who worked in Silicon Valley but came back to India to volunteer on the project for a year. Parthasarathy says that using Aadhaar for identity verification could provide the telephone companies with major savings.

Still, setting up a nationwide network of biometric terminals has plenty of its own challenges. First, India will need better connectivity. Wireless voice networks now cover most of the country, but wireless data networks have trailed behind. Current penetration of 3G is mostly just in the cities, says Debabrata Das, an IEEE member and a professor of electrical engineering at the International Institute of Information Technology, Bangalore, who has been studying the network challenges of authentication as a technical advisor for the state of Karnataka.

The API will also need to be flexible enough to handle variations in the demographic data that are submitted. The system can't enforce strict matches: Many Indians use initials in their names, and there is no guarantee that they will always spell their names the same way in English. Further, sometimes a married woman will use her father's family name instead of her husband's. Because of the ambiguity in names and addresses, the database must be able to perform partial and fuzzy matches. Eventually, Sharma says, the UIDAI hopes to be able to do database matching for all the Indian languages as well, so the API will continue to undergo revisions.

Now the UIDAI must wait for its partners to begin taking advantage of the system, and Nilekani admits that starting up such services is largely beyond his control. Cooperation with other agencies and industries is all part of Nilekani's approach to how government initiatives should work. "The big thing to my mind has been, How do you create a model of change, and how do you carry a lot of people with it? How do you think this through in a way that everyone comes on board?" he says. In building the project to this point, he's managed to bring, if not everyone, then certainly a pretty diverse crowd: technical experts; national, state, and local officials; banks and businesses; and all those millions who willingly wait in line for hours.

"Everyone puts their own aspirations on it…like Obama," he jokes. But the downside of being so inclusive is that as the project matures, it may be difficult to keep all the interested parties happy, and there's bound to be disappointment if the project fails to achieve all its lofty ambitions.

The project has made it this far by adapting quickly as problems arise. "Think of it as multigeneration, continuous improvement," Nilekani says. "You launch and get feedback and you get criticism. You need to build a rapid feedback loop, which is what we've built." ❑

AUDIO SLIDESHOW *at* http://spectrum.ieee.org/indiaid0312

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INL INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

INL-MIT Program

INL – International Iberian Nanotechnology Laboratory (INL), based in Braga (Portugal), is the first fully international research organization in Europe in the field of nanoscience and nanotechnology. As part of a collaboration with the Massachusetts Institute of Technology, the INL is currently seeking candidates for **two Group Leader positions**. The first position will focus on research in the area of **biological approaches to templated self-assembly and nanopatterning.** The second position will lead the effort on **graphene-based nanoelectronic sensor devices** at INL.

Candidates with outstanding CVs and demonstrated excellence in these scientific topics will be especially considered. Candidates with an excellent research track record are sought. Previous industrial laboratory experience will be valued. The work location is Braga (Portugal), but candidates must show availability for temporary relocation between Massachusetts (US) and Braga (Portugal). The start-up package and remuneration scheme is in line with those offered by other International Organizations and according to candidate experience and background. Applicants should forward the application material indicated to the INL directly, with a copy to *inl-mit@mtl.mit.edu.*

The detailed position announcement can be found at http://inl.int/job_offers

INL-MIT-2012-05, Nanotemplating of Biomolecular Structures (Group Leader)

INL-MIT-2012-06, Graphene Based Nanoelectronic Sensor Devices (Group Leader)

DEADLINE: April 9th, 2012

BAYLOR UNIVERSITY

The Electrical and Computer Engineering Department of Baylor University seeks senior faculty applicants in all areas of electrical and computer engineering, with preference in the areas of cyber-physical systems (i.e., embedded systems, computer/network security, and sensor networks) as well as power and energy. Applicants must have an earned doctorate and a record of achievement in research and teaching at the rank of associate or full professor including a demonstrated record of research funding. The ECE department offers B.S., M.S., M.E. and Ph.D. degrees and is poised for aggressive 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 15,000 students and is a member of the Big XII Conference. Baylor's mission is to educate men and women for worldwide leadership and service by integrating academic excellence and Christian commitment within a caring community. The department seeks to hire faculty with an active Christian faith; applicants are encouraged to read about Baylor's vision for the integration of faith and learning at **www.baylor.edu/about/vision**.

Application reviews are ongoing and will continue the positions is filled. 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 three professional references.

Additional information is available at **www.ecs.baylor.edu.** Applications should be sent by email as a single pdf file to **Robert_Marks@baylor.edu**, or mailed to

Dr. Robert Marks
Baylor University
One Bear Place #97356
Waco, TX 76798-7356

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the data

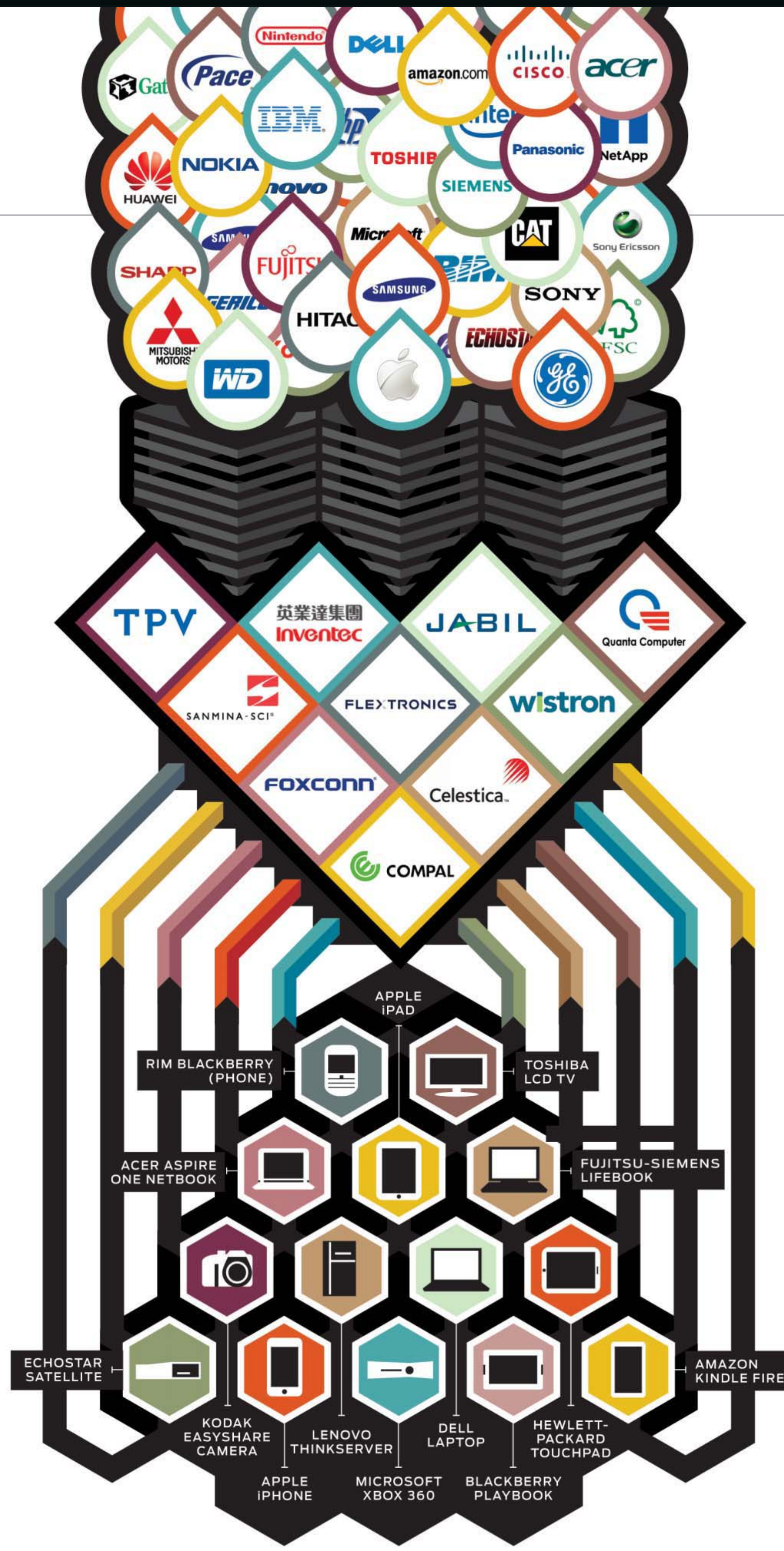
Made by Apple in Name Only

THE WORLDWIDE consumer electronics marketplace might appear to be a vast jungle of different brand names and product lines. But this diversity is deceiving. Even though every major brand around the world outsources some—and in some cases all—of its manufacturing, there are just 10 major players in electronics contract manufacturing. Industry leader Foxconn Technology Co. (based in Tucheng, Taiwan) makes not only Apple's iPods, iPhones, and iPads but also computers and components for Dell, Hewlett-Packard, and Acer; phones for Sony Ericsson and Nokia; and other electronics for Intel, Cisco, Nintendo, and Amazon.com.

It's a business high in revenue but low in profit. According to a recent report by the United Nations Conference on Trade and Development, those 10 top electronics original equipment manufacturers (OEMs) made US $196.5 billion in 2009 (the most recent year for which data are available). But Foxconn, even with its booming iPhone and iPad lines, actually lost money in 2010, according to its annual report.

Despite all that revenue, Foxconn isn't about to become the next Apple or Cisco, says Timothy J. Sturgeon, senior research affiliate at MIT's Industrial Performance Center. He notes, however, that "over time, the center of gravity for electronics manufacturing will certainly shift to China." In fact, he says, with 6 of the top 10 electronics OEMs in China and Taiwan, "that process is already well under way."

—*Mark Anderson*



APPLE iPHONE

In May 2010, iPad and iPhone manufacturer Foxconn famously installed nets at its Chinese plant in Shenzhen to stem the rash of overworked factory employees jumping to their deaths. Foxconn has since embarked on plans to replace 500 000 Chinese workers with one million factory robots. With these and other investments, Foxconn lost money in 2010.

MICROSOFT XBOX 360

Microsoft's mammoth footprint in the gaming world, the Xbox 360, originates in the Chinese factories of 2 of the world's top 10 original equipment manufacturers (OEMs): Celestica and Flextronics. Microsoft had originally hired a third company, Wistron, but in 2007 falling Xbox prices squeezed the Taiwanese firm out of the Xbox-making business.

HEWLETT-PACKARD TOUCHPAD, BLACKBERRY PLAYBOOK, AND AMAZON KINDLE FIRE

When a product dies, the pain passes down the value chain. Last year, HP discontinued its iPad-imitation TouchPad—and the TouchPad's manufacturer, Inventec, laid off 400 workers. When Research in Motion's PlayBook tablet proved a dud in the marketplace, PlayBook's OEM, Quanta, laid off as many as 1000. To be sure, the markedly similar Amazon Kindle Fire appears to be taking off. Quanta makes that, too.

LUKE SHUMAN