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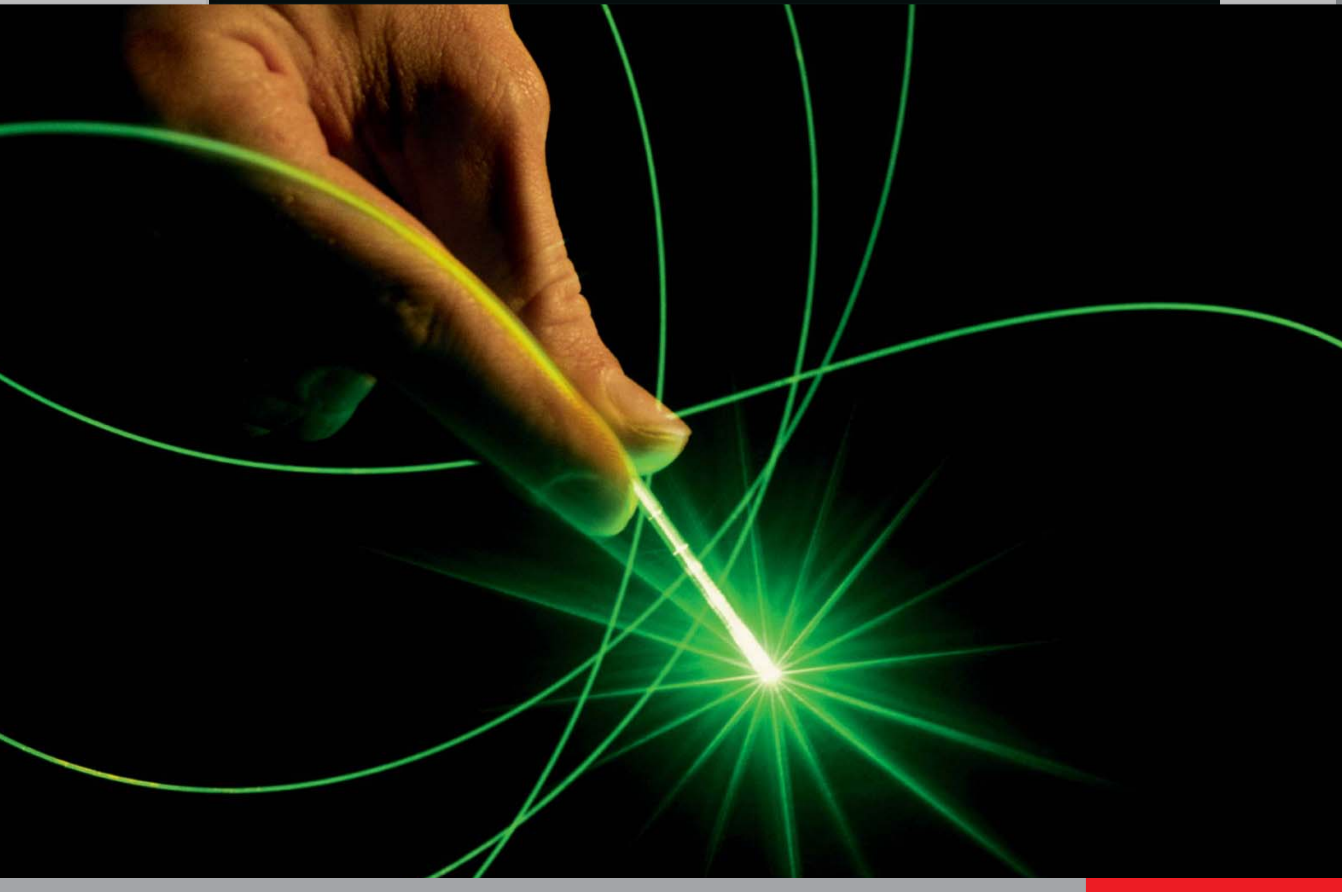

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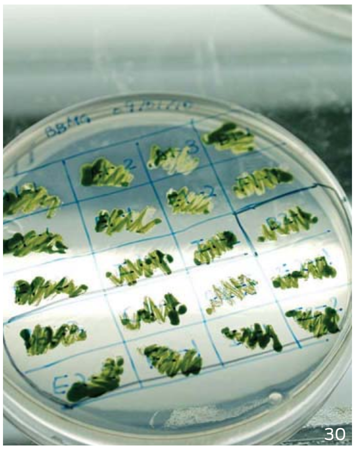

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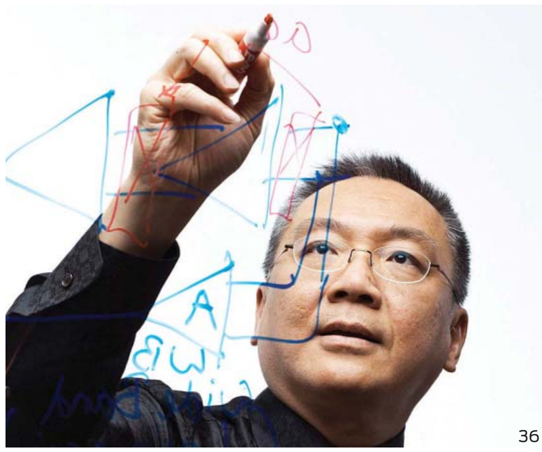

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COVER: DR. KEITH WHEELER/ PHOTO RESEARCHERS
THIS PAGE, CLOCKWISE FROM TOP LEFT: E.J. CARR; GABRIELA HASBUN; RANDI SILBERMAN KLETT

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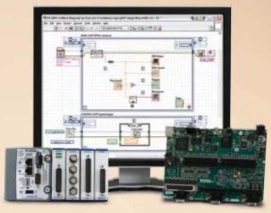

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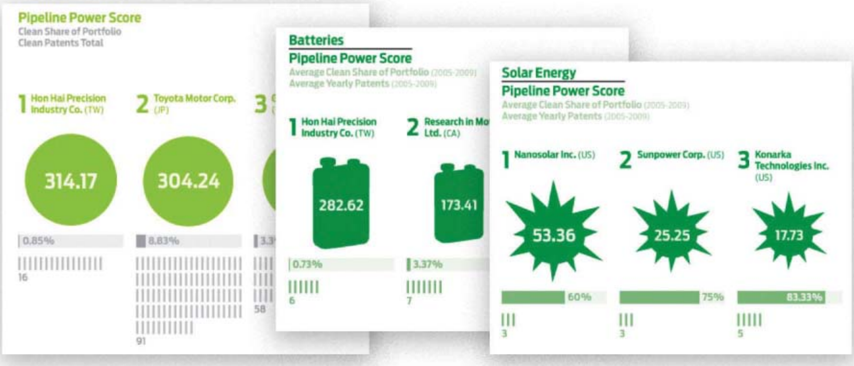


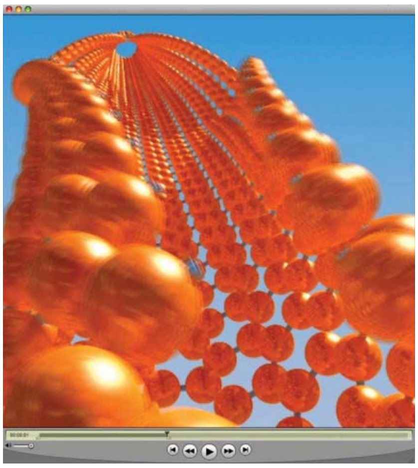
AVAILABLE 1 NOVEMBER

Introducing the Clean Tech 50

Check out the debut edition of the *IEEE Spectrum* Clean Tech 50. Our partners at 1790 Analytics have rated the world's patent portfolios according to which companies have the most valuable patents in batteries, clean coal, fuel cells, and five other categories. To see where your company ranks, dive deep into our interactive charts, created by the Dutch firm Information Design Studio, and discuss the rankings in our new commenting system.

TUBULAR ACTION!

WATCH A NANOTUBE UNZIP in the animation accompanying this month's story on graphene, the recently discovered flat, atom-thick form of an element that scientists *thought* they fully understood: carbon.



CLOCKWISE FROM TOP LEFT: INFORMATION DESIGN STUDIO; BRYAN CHRISTIE DESIGN; NASA

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AVAILABLE 5 NOVEMBER

MEMBER PROFILE: ASTRONAUT RICK MASTRACCHIO
IEEE Member and NASA astronaut Rick Mastracchio recently flew into space on board the space shuttle *Discovery*, in one of NASA's last scheduled shuttle missions. Read about the work he did for the mission to the International Space Station, his career, and his future space travel plans.

FROM BOOTSTRAPS TO BILLIONS
A recent five-part webinar series shows entrepreneurs how to use alternate financing sources to grow their companies. Topics include how to find the right financial resources and how to make better financial decisions.

CHANGING ELECTRICAL SAFETY CULTURE
The Electrical Safety Workshop, sponsored by the IEEE Industry Applications Society, will explore ways to prevent workplace injuries and reduce risks from electrical hazards. Learn about some of the topics to be covered at the workshop, taking place 25 to 28 January 2011 in Toronto.

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back story

For the Love of Lightbulbs

One of the great delights of living in New York City is that if you are looking to buy a very particular or obscure thing—a pair of ox-bone chopsticks, say, or a button for a World War II bomber jacket—you can almost always find a shop that specializes in that kind of thing. Italian sporting rifles, vintage bathroom fixtures, animal skeletons, Asian textiles, French spectacles—Manhattan seems to have a shop for every conceivable consumer craving.

Many of these shops have proprietors who are as singular as their wares. So last year, when *IEEE Spectrum* intern Ariel Bleicher [above] was asked to produce a radio profile for a graduate journalism course, she thought of David Brooks. She had read about Brooks in a newspaper article covering a speech he'd given to a New York state energy panel. The panel was drafting new policies to rid office buildings of incandescent lightbulbs, and Brooks had come to defend some of the more indispensable varieties. "Wonderful bulbs that enhance your mood, make it easier to see, improve your decor," he rhapsodized. His deep affection for those simple glowing globes touched Bleicher and piqued her curiosity. "He had me at 'I love lightbulbs,'" she says.

Brooks owns a tiny shop on East 60th Street called Just Bulbs, which has been in his family for three generations. It's crammed to the ceiling with exotic bulbs, funky holiday lights, rare collector's lamps, and plain old 60-watt frosted whites. Bleicher spent an afternoon with Brooks, recording his interactions with customers and listening to fond descriptions of his favorite bulbs.

Months later, she mentioned Brooks at a staff meeting, when we were casting about for creative ways to cover the scheduled demise in many developed countries of the incandescent bulb, one of the most successful technologies ever. So on a bright morning this past August, she paid another visit to Just Bulbs, this time with *Spectrum* photo editor Randi Silberman Klett. The two of them collaborated on a photo feature, "Bright Lights, Big City," which appears in this issue. "By the end of the shoot, we just couldn't help ourselves—we'd both fallen in love with the lightbulb," Bleicher says. ❑

RANDI SILBERMAN KLETT

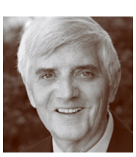
CITING ARTICLES IN IEEE SPECTRUM

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 first page of Update is in *IEEE Spectrum*, Vol. 47, no. 11 (INT), November 2010, p. 11, or in *IEEE Spectrum*, Vol. 47, no. 11 (NA), November 2010, p. 13.

contributors

SALAH M. BEDAIR, JOHN M. ZAVADA, and **NADIA EL-MASRY** are professors at North Carolina State University, in Raleigh. In "A Spin to Remember" [p. 42], they explain how the weird world of semiconductors collides with the weirder worlds of quantum mechanics and ferromagnetism to forge the weirdest world of all: spintronics, which relies on electron spin for data storage and manipulation. Though Bedair found writing about spintronics daunting—"I even had a nightmare one night!"—he hopes reading about it will be enjoyable.

E.J. CARR avoided learning anything about algal biofuels before shooting the photography for "Green Gold" [p. 30] so that he could approach the subject with fresh eyes. Even more fascinating than the energy-packed vats of pond scum, he discovered, were the scientists who cultivated it. "They were the coolest geeks I've ever met," he says. Well known as a fashion photographer, Carr is now finishing a pet project to photographically depict King Arthur's courtiers. He was inspired, he says, by the mythic roots of Ireland, where he lived for three years before recently moving to Denver.



ROBERT W. LUCKY can find stochastic wonder in information theory, a computer's LEDs, or as in this month's Reflections [p. 17], the swans he periodically sees from his backyard. Lucky, an IEEE Fellow and holder of 11 patents, worked for many years at Bell Labs before becoming vice president for applied research at Telcordia Technologies, in Piscataway, N.J. He retired in 2002, to better reflect on life—and wildlife.

RICHARD MIA, of Toronto, translates broad concepts into visual metaphors. Take, for instance, the stimulus plan. Mia's vision of a bedridden world globe about to be defibrillated became an illustration for *Business Week*. His collages start as scanned drawings, inspired by traditional silk-screening and his 200-piece stamp collection. For "Black Swan" [Reflections, p. 17], he tackled the idea that "it's unwise to think certain things are improbable, because they just might happen."

PHILIP T. PIENKOS, ERIC JARVIS, and **AL DARZINS,** all veterans of biotechnology start-ups, are now molecular biologists at the National Renewable Energy Laboratory, in Golden, Colo. In "Green Gold" [p. 30], they assess the potential of algae-based biofuels. The authors would like "to see algae biorefining follow the meat packers' principle, where everything is used except for the oink." Every molecule in an algal cell could be made into useful products, including nutritional supplements, animal feed, and fertilizers. Says Darzins, "The final chapter hasn't been written for algae."

ALEXANDER SINITSKII and **JAMES M. TOUR,** who wrote "Graphene Electronics, Unzipped" [p. 24], specialize in the science of the exceedingly small at Rice University, in Houston. Their main interests are the microstructures—nanotubes, sheets, and cages—that carbon atoms tend to form. Tour trained as a synthetic organic chemist, but his work in electronics has led to an extraordinary range of appointments: He's a professor of chemistry, computer science, mechanical engineering, and materials science, as well as the founder of several companies. Sinitskii, a postdoctoral researcher, earned his doctorate in materials science at Moscow State University.

CLOCKWISE FROM TOP RIGHT: RICHARD MIA; STEPHEN LACKO; CHLOE AND E.J. CARR spectral lines

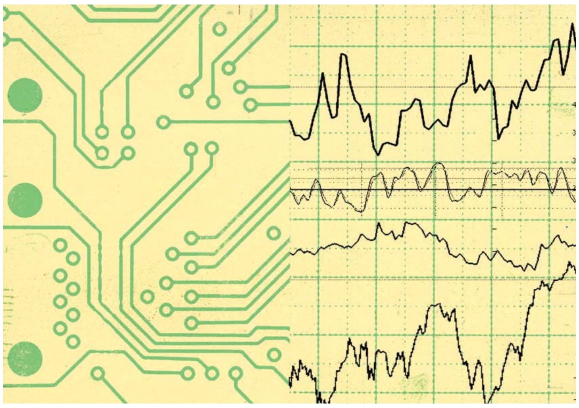
The Winners Write the History Books

SOME OF THE WORLD'S greatest fortunes were built on the back of technology. Legions of millionaires, and the occasional billionaire, owe their all to Oracle, Apple, Intel, Google, or Microsoft. Yet you should no more judge success in tech investing by Microsoft than you'd use Mick Jagger as the gauge of a successful career as a rock musician. Microsoft is a survivor—indeed a major winner of the technology wars—as are Apple, Intel, Oracle, Google, and so it seems, Facebook. To fairly judge technology as a whole you'd have to give equal consideration to Kaypro, Wang Laboratories, Fairchild Semiconductor, Digital Equipment Corp., AltaVista, and all the other mighty fallen.

Or you could delve into the statistics, as we do in this month's The Data. It turns out that US $100 spread among the 118 tech stocks listed by Standard & Poor's in 2002 would now be worth $138, a return that *barely edges out inflation*. If that money had gone instead into S&P's first 118 nontech stocks *as listed in alphabetical order*, you'd have a 25 percent better return. And remember, this eight-year period comes after the bursting of the dot-com bubble, so it measures the tech sector not from a prior high but from a prior low. It therefore ought to show technology to its best advantage.

Why do tech stocks stink? Technology is, after all, one of the things that separates developed countries from less developed ones. And technology cultures and establishments that are robust, creative, and highly advanced are what distinguish the highly productive economies—those of the United States, Japan, Germany, and China. In a world of uncertainty and disappointment, semiconductor performance, with its regular doubling, is the one thing that can be counted on to improve without fail.

However, as any economist will tell you with gimlet-eyed glee, the market value of a thing reflects not its intrinsic worth but relative scarcity. Just because you're in a business that provides goods that double in performance every 18 months doesn't mean that their price will rise, that your profit margin will hold steady, and that your job won't disappear. Just because your invention has sparked a revolution—the kind that produces qualitative changes in the way people live—doesn't mean that it will make you a nickel.



RICHARD MIA

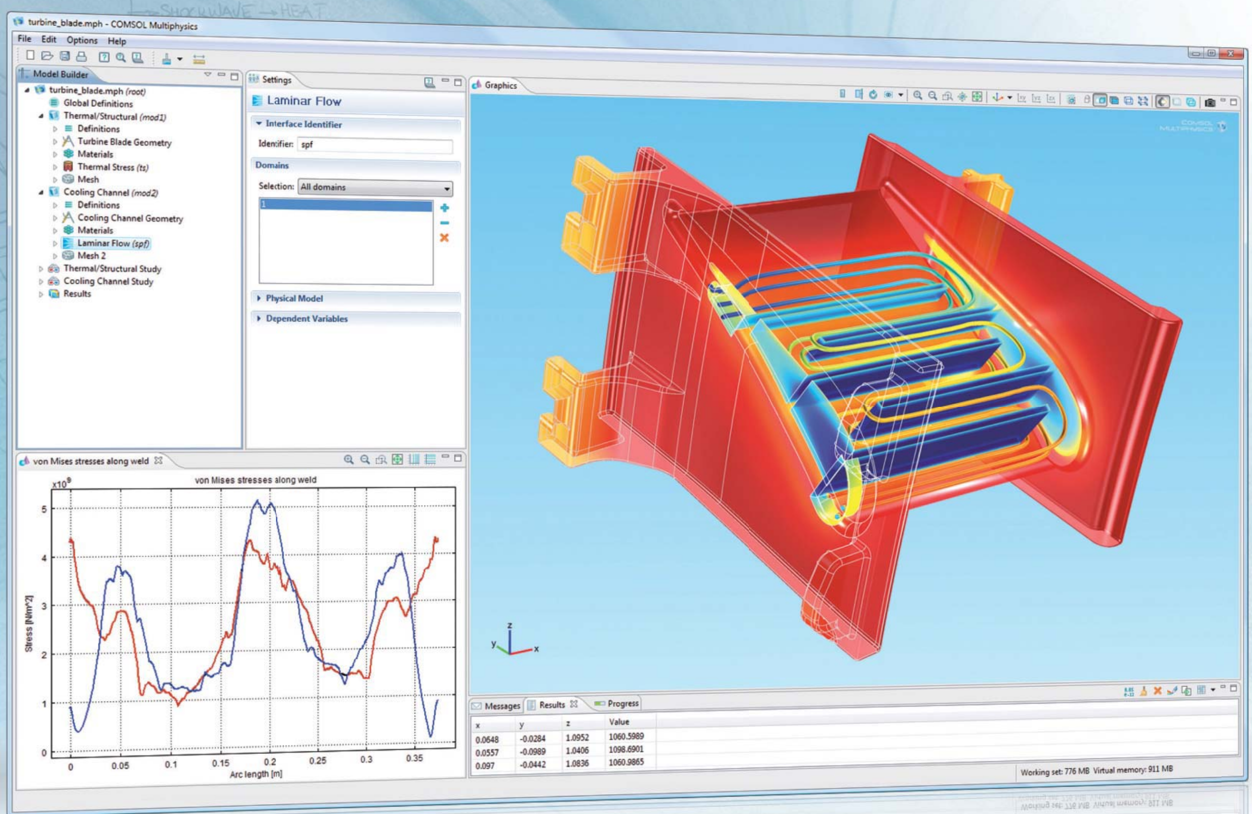
Did the world owe a living to the inventor of the graphical user interface (and I don't mean Steve Wozniak)? To the company that first commercialized computers (and I don't mean IBM)? How about the inventor of the telephone (and I don't mean Alexander Graham Bell)? To those of you keeping tally, the people and organizations I am referring to are Xerox PARC, the Eckert-Mauchly Computer Corp., and for the possible inventors of the telephone, well, there's Johann Philipp Reis, Antonio Meucci, Elisha Gray—indeed, a very long list of names.

Fifteen years ago, in a previous life as a business reporter, I cowrote a story predicting that search engines would be among the first to make big money on the newborn Web. My coauthor and I reported on every search engine we could find. Although it was clear that most of them would go to the wall, it seemed equally clear that at least one—I favored AltaVista—would rule the Web. Wrong. Two months after the article came out, Larry Page and Sergey Brin began working on Google—and that's the company that ended up ruling the Web. For now, anyway.

The moral is that the winners write the history books. Or, to be precise, we humans are prone to an error in thinking known as survivorship bias—the tendency to take the readily available evidence of the past as a fair mirror of that past.

Survivorship bias lives on, fooling generations of investors. In a landmark study years ago, economists found that more than half of all mutual funds had beaten the market—a seemingly impossible feat, given that such funds make up such a huge share of the market. The reason is that a fund generally can make it into the record books only after it's been around for a while, and the only funds that last long enough are those that do well from the get-go—likely through sheer luck. The losers' results aren't fully counted. Other economists have speculated that stocks are not quite so good an investment over the long haul as they're cracked up to be, given that all the really long-term data come from the New York and London exchanges, which were lucky enough to be based in the two best-performing countries of the past two centuries.

In a world seen through the forgiving lens of survivorship bias, most mutual funds and tech stocks may be above average. But in the real world, past performance is no guarantee of future results. —PHILIP E. ROSS



TURBINE STATOR BLADE. A stator blade in the turbine stage of a jet engine is heated by the combustion gases. To prevent the stator from melting, air is passed through a cooling duct in the blade. The resulting temperature gradients introduce significant stresses.

forum

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SCANNING FOR LIES

MARK HARRIS'S article on fMRI scans and lying ["Liar!," August] was quite interesting; however, the technique seems impractical for use as a legal tool. Some years ago, a government agency approached a local university to study the feasibility of using brain-photon analysis to detect the mood of airline passengers during routine security screenings. The theory was that a person intent on committing a crime would be in an agitated and categorically unique state of mind compared to that of innocent (yet annoyed) passengers. The idea was interesting, but not practical. A more appropriate technology for the detection of lying might be voice stress analysis. According to Wikipedia, although voice stress analysis was discovered in 1957, the technique remains controversial, presumably because it remains relatively unexplored.

ROBERT SCHROEDER
IEEE Member
Ewing, N.J.

TALES FROM THE BOX

I ENJOYED the thoughts about in-flight data recorders ["Beyond the Black Box," August], but the statement that "all you need to do is secure the communications between onboard and ground-based systems and to protect the saved data from prying eyes" strikes me as naive. Encryption, when properly used, can improve security and privacy, but it is notoriously difficult to get right in practice. The article cites the Health Insurance Portability and Accountability Act as an exemplar for protecting privacy, but articles in the *Journal of the American Medical Association* show that HIPAA paradoxically hinders the ability to both gather data and protect privacy. Encryption is not pixie dust. It has system-level complexity as vexing as that of safety engineering.

KEVIN FU
IEEE Member
Amherst, Mass.

THE SPEED OF LIGHT

CONCERNING "Traveling Light" [The Big Picture, September]: To give the Solar Impulse HB-SIA's cruising speed as 70 kilometers per hour without proper context is rather misleading and vague, for the speed of a flying vehicle may be measured relative to a number of other entities, such as the ground or the velocity of the surrounding air. "Kilometers per hour" gives the impression that the plane can reach this speed relative to that of motor vehicles on roads.

REUBEN KOUTAL
IEEE Senior Member
Tel Aviv

Assistant Editor Willie D. Jones responds: In describing the HB-SIA's performance characteristics on the Solar Impulse Web site, the plane's designers indicate that its *takeoff* speed is 35 km/h—obviously in relation to the ground. The number they give for average flying speed, 70 km/h, also describes how fast the plane moves in relation to the ground. They're careful to list this figure as an average, because the strength and direction of the wind will determine how long it takes to fly from point A to point B.

ADVANCING TECHNOLOGY FOR HUMANITY

THANK YOU for your September issue. With "Technical Sweetness Isn't Enough" [Spectral Lines], "This Is Your Brain on Robots" [sidebar from "When My Avatar Went to Work"], and "After Utopia," *IEEE Spectrum* is asking important, hard questions about how our technologies are changing society, as well as reporting on advances in the state of the art. We in IEEE have demonstrated our power to invent world-changing technologies, but we are quicker to ask "can we?" than "should we?" The latter question is far more important if we want our technology to really *benefit* humanity. Thanks for raising the questions that can start this valuable dialogue.

W. BEN TOWNE
Graduate Student Member
Pittsburgh

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update

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EUV's Underdog Light Source Will Have Its Day

A new plasma source may outshine contenders for the next chip lithography technique

EXTREME ULTRAVIOLET lithography, the key process in making the finely featured chips of the coming decade, has had a long list of detractors, but its time seems to be at hand. The proof? ASML Holding, the Dutch company that makes most of the world's chip lithography tools, has sold six of its monstrous EUVL machines to six separate customers, including foundry behemoth Taiwan Semiconductor Manufacturing Co. These chipmakers will use ASML's NXE3100 to print the tiniest features of the most critical layers on their future chips.

The biggest roadblock for EUV over the past 10 years has been the light source, which has been nearly impossible to make sufficiently intense. Two competing technologies have faced off for years to be the preferred option for EUV customers. One will be in the first machines and is the current favorite for commercialization. But if some experts are correct, the other technology could win in the long run.

The two candidates—laser-produced plasma (LPP) and discharge-produced plasma (DPP)—each emit the needed light at a wavelength of 13.5 nanometers. LPP sources, the leading technology at this point, are being developed by San Diego–based Cymer and Japan-based Gigaphoton. DPP is being advanced by Xtreme Technologies, based in Aachen, Germany, a former subsidiary

EUV ENDGAME: ASML's NXE3100 weighs in at 50 metric tons, contains more than a million parts, and will set you back a cool €60 million. It is set to start printing chips soon.
PHOTO: ASML HOLDING

update

of Philips that is now owned by Tokyo-based lighting giant Ushio. ASML says that most of the NXE3100 units will contain Cymer's source.

LPP sources blast falling tin drops with a high-power laser. When the laser-excited tin electrons return to their normal orbit, they emit EUV photons, which are harvested and funneled into a stream that eventually ends up casting the chip pattern onto a wafer. Xtreme's DPP light source is different. Instead of falling tin droplets, it blasts a lightning bolt's worth of current through a tin vapor to form the 13.5-nm photons.

By numbers alone, LPP appears to vastly outperform DPP. The eventual power goal for EUV volume production is 250 watts. (The brighter the light, the less time the wafer needs to be exposed to it.) In April, Gigaphoton reported that its LPP prototype met a major benchmark, producing 104 W. Contrast that with Xtreme's DPP technology, which produces only 34 W.

So it's a bit surprising that ASML has also expressed faith in that seemingly inferior technology. "There is a chance that one of the 3100s will be fitted with a DPP source," an ASML spokesperson told *IEEE Spectrum*. And ASML's Noreen Harned says future EUV machines will be "source agnostic." These NXE3300 machines, due to ship in 2012, will allow customers to plug in either LPP or DPP.

The two LPP firms and Xtreme "all have credible plans," says Harned, who is ASML's vice president of technology marketing. Though she acknowledges that Xtreme's source is not yet ready for ASML's scanner, she still insists that her company expects that it will be. ASML knows what Xtreme is doing to boost its machine's output, Harned says. "We think it's going to catch up."

Chaohai Zhang, a professor of electrical engineering at Harbin Institute of Technology, in China, who studies DPP sources, thinks it will more than catch up. He says DPP may surpass LPP in the long run for four reasons: It uses power more efficiently, is smaller, keeps the lithography optics cleaner, and should last longer. LPP requires wall-plug power an order of magnitude higher than DPP to produce the same number of photons, says Marc Corthout, president of Xtreme. The DPP architecture also takes up less space, which is at a premium inside the EUV tool. Finally, Xtreme mitigates EUV's well-known contamination problems with a trap that prevents tin droplets from spattering the collector mirror and thereby dimming the EUV light. Corthout says less contamination contributes to DPP's greater longevity.

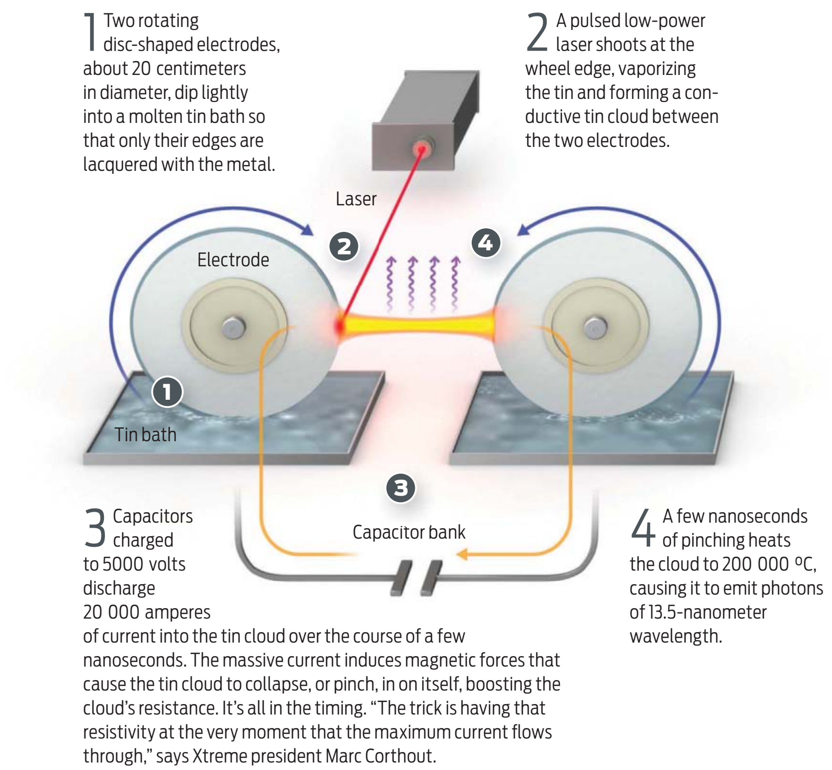
And there's one more thing, according to Corthout: The reported source power numbers that make DPP look so unappealing may be misleading. Industry insiders acknowledge that there is no standard for reporting the power of these systems. Gigaphoton's 104 W, for example, was delivered in very short blasts. While Xtreme's DPP power may appear low, it is continuous.

Corthout maintains that a lithography tool will be more effective with a continuous beam of light. Cymer disputes that claim, but there are no concrete data yet to prove it either way.

Before the end of 2010, one of ASML's six customers will have created wafers with the NXE3100, Harned says. Xtreme won't be the one providing the light source, but if Corthout and Zhang are right, eventually DPP will prevail.

—Sally Adee

DISCHARGE-PRODUCED PLASMA



EMILY COOPER

85 PERCENT Population of South Korea covered by what the country considers the world's first nationwide WiM

The Era of Error-Tolerant Computing

Errors will abound in future processors...and that's okay

THE COMPUTER'S perfectionist streak is coming to an end. Experts say power consumption concerns are driving computing toward a design philosophy in which errors are either allowed to happen and ignored, or corrected only where necessary. Probabilistic outcomes will replace the deterministic form of data processing that has prevailed for the last half century.

Naresh Shanbhag, a professor in the department of electrical and computer engineering at the University of Illinois at Urbana-Champaign, refers to error-resilient computing (also called probabilistic computing) by the more formal name of stochastic processing. Whatever the name, the approach, Shanbhag says, is not to automatically circle back and correct errors once they are identified, because that consumes power. "If the application is such that small errors can be tolerated, we let them happen," he says. "Depending on the application, we keep error rates under a threshold, using algorithmic or circuit techniques." For many applications such as graphics processing or drawing inferences from huge amounts of data, errors in reasonable numbers do not materially impact the quality of the results. After all, your eye wouldn't even notice the presence of a single bad pixel in most images.

The newfound attitude toward errors is, in a way, simply a pragmatic nod to a new reality. As transistor dimensions shrink, the minute variations in circuit patterns and in the composition of the silicon itself have a more noticeable effect. In particular, the number of dopant molecules in a transistor—key to its ability to conduct current—is now so small that a few more or a few less make a measurable difference. And the natural roughness of transistor structures is now big enough, compared to the size of the transistors, to impede their function. According to Kevin Nowka, faculty research program manager of the IBM Austin Center for Advanced Studies, designers of future chips will even have to contend with variations in such seemingly uncontrollable characteristics as the size of metal grains in the transistors' gates.

The result of all this variability is that the threshold voltage—the voltage at which the transistor switches from on to off—varies from device to device. And at the low voltages and high clock frequencies needed in today's low-power processors, that kind of variability means mistakes.

Several demonstration processors are in the works. Shanbhag's team is applying stochastic processing to a wireless receiver. They've created an algorithm and stochastic circuitry to implement a filter that consumes far less power than conventional filters and does so at similar error levels.

A team at Urbana-Champaign led by assistant professor Rakesh Kumar and a group at Stanford headed by assistant professor Subhasish Mitra are developing error-resilient processor architectures. Kumar says his project, called the Variation-Aware Stochastic Computing Organization (VASCO), manages errors through architectural and design techniques. In VASCO, the processor consists of one highly reliable core, in which errors are corrected. And that core supervises a number of lower-power and more error-prone cores, which do the bulk of the computation. Overall, the scheme reduces power consumption by allowing "relaxed correctness," he says.

Jan Rabaey, a researcher at the multiuniversity Gigascale Systems Research Center, based at the University of California, Berkeley, says error-resilient computers are perhaps 6 to 10 years away from being commonplace. But as variability worsens and power consumption continues to dominate the industry's concerns, Rabaey predicts that error-resilient systems will make steady inroads, ranging from exascale supercomputers down to smartphones.

Probabilistic computing is "unavoidable," Rabaey says. "We have to take a holistic look at how to handle errors, particularly as we scale chip dimensions down to levels where variability takes over." It is the only way he knows of to keep Moore's Law going, he says. —DAVID LAMMERS

ERGE BLOCH

update

SLOW DOWN: Ford's answer to dangerous driving is to take control of the brakes.
PHOTO: CLAUDIA DEWALD/ISTOCKPHOTO

Ford Executes Perfect Turns

Automaker's technology keeps cars from crashing on curves

Automotive engineers have saved countless lives by making up for drivers' slow reflexes and wandering minds with such systems as antilock braking, electronic stability control, and adaptive cruise control. This December, when the 2011 Ford Explorer gets pride of place in dealer showrooms, engineers will go even further.

This sport utility vehicle boasts new technology aimed at yet another common driver failing: taking curves too quickly. The revamped Explorer will feature Ford's proprietary Curve Control technology, which senses when a vehicle is going too fast to turn safely and temporarily takes control of the throttle and the brakes.

According to the U.S. National Highway Traffic Safety Administration, there are roughly 50 000 accidents in the United States each year that are the direct result of drivers losing control on curves. In 2009, such crashes killed more than 17 000 people.

The new technology combined with Ford's existing stability controls "provides a significant advantage over existing stability systems," says Saied Taheri, an expert in intelligent transportation at Virginia Tech, in Blacksburg, who did not work on the technology's development. Such systems are changing the nature of driving, says Taheri. "We're headed toward autonomous driving, and each of these systems—Curve Control, adaptive cruise control—is a step toward that."

Curve Control is a new wrinkle applied to Ford's existing AdvanceTrac System with Roll Stability Control, which the automaker developed a decade ago in response to a series of rollovers that occurred with Explorers outfitted with incompatible tires. AdvanceTrac uses accelerometers and gyroscopes to keep careful track of the vehicle's response to changes in momentum that would cause it to roll onto its side. These sensors—plus those that monitor the steering wheel angle, the speed of each wheel, and the engine torque—offer updates 100 times per second on the vehicle's performance to a system that brakes or spins each wheel independently to keep the car from skidding or rolling.

According to Dan Eisele, head of the Ford engineering team that developed Curve Control, the new system uses AdvanceTrac's sensors to determine whether the rate at which the vehicle is moving laterally is in sync with the driver's intent. Eisele explains that the rate of movement around the vertical axis, or yaw rate, for a vehicle entering a highway exit ramp with a 30-meter turning radius should be somewhere between 27 and 30 degrees per second. But a driver, having decelerated from over 110 kilometers per hour and feeling confident that he can guide the vehicle through the curve at, say, 70 km/h, can turn the steering wheel as far as it will go and still fail to get the yaw rate beyond about 20 degrees. The result: The vehicle ends up as many as three lane widths away from the driver's intended course.

Curve Control closes the gap between the driver's intent and the car's motion by cutting power to the engine and, as a last resort, applying the brakes to decelerate the vehicle by as much as 4.4 meters per second (16 km/h) per second.

Ford says it plans to make Curve Control a standard feature on nearly all of its SUVs, light trucks, and vans by 2015. —Willie D. Jones

370 MILLION METRIC TONS Amount of carbon dioxide that will be emitted by data centers in the United States in 2020.
According to researchers at Rice University, in Houston, data-center CO_2 emissions will triple from today's level.

tech in sight

Space Sailing

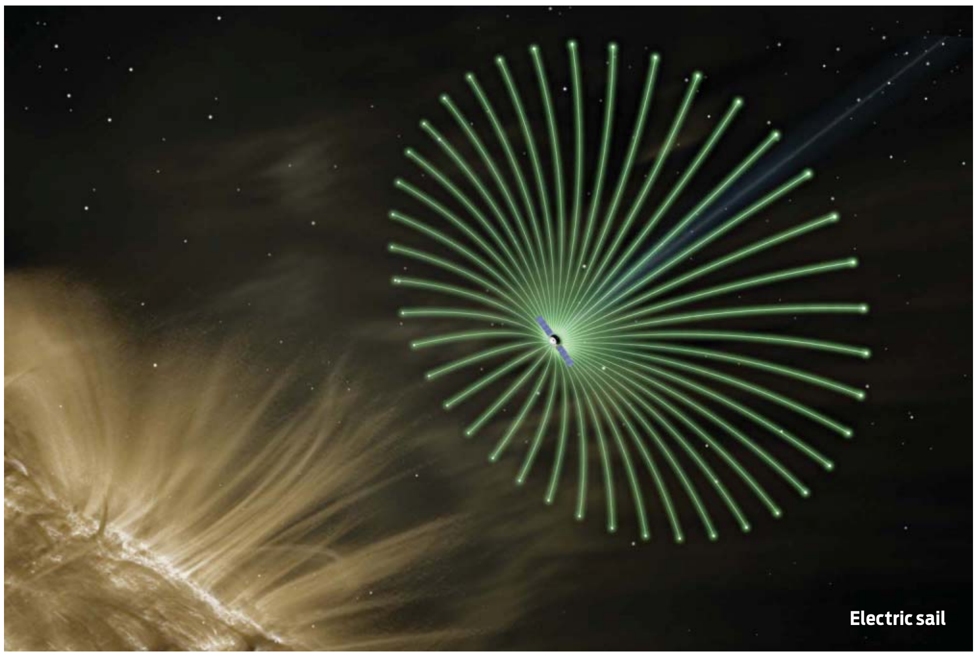
If the seven seas don't satisfy, aim a little higher

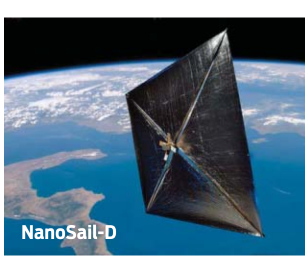
JOHN F. KENNEDY called space "this new ocean." This year, we're finally starting to sail on it. In May, Japan's space agency launched a craft that steals momentum from energetic photons blowing off the sun for a free ride through the solar system. The concept isn't exactly new. Back in 1974, NASA's *Mariner 10* spacecraft used the light hitting its solar arrays to adjust its angle on the way to Mercury.

Given Japan's success, sailing prospects seem better than ever. NASA plans to launch a sail this year, and in 2011, the Planetary Society expects its own craft will be ready to fly. By the 2030s, the European company Thales Alenia Space hopes to launch "data clippers"—essentially sailing hard drives that could shuttle data between probes exploring Saturn's and Jupiter's moons and Earth.

Les Johnson, now NASA's deputy manager for the Advanced Concepts Office, helped develop solar sails for the agency in the early 2000s. Besides their rather practical applications, as probes monitoring Earth's poles or as part of a solar storm warning system, Johnson says a craft could sail to the nearest neighboring star system in less than 1000 years—a feat he estimates would take 75 000 years using chemical propulsion. Of course, for that you'd need a sail the size of Alabama deployed from a probe that's closer to the sun than Mercury.

—JOSEPH CALAMIA





NANOSAIL-D
(United States)

NASA hopes to deploy NanoSail-D this year some 600 kilometers above Earth's surface. While that's not high enough for the photons' boost to overcome the drag of Earth's atmosphere, the flight will allow the agency to test the unfolding—in just 5 seconds—of almost 10 square meters of polymer no thicker than single-ply tissue paper. As it falls out of orbit, the sail will also provide a useful demonstration of how such materials could drag space junk to a fiery demise.

IKAROS
(Japan)

Already cruising, IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) is technically a solar-*powered* sail. The craft's almost 200-square-meter polyimide reflector, only 0.0075 millimeter thick, has solar panel patches to exploit light for both propulsion and power and LCD panels that steer the craft by changing the reflectivity of certain segments.

ELECTRIC SAIL
(Europe)

Solar wind, made up of sun-spewed charged particles, might also prove a useful means to sail. Pekka Janhunen, a research fellow at the Finnish Meteorological Institute, has plans for what's called an electric sail. The craft would charge 50 to 100 tethers, each 20 to 30 kilometers long. The resulting electric field would reflect protons in the solar wind to propel the proposed 100-kilogram craft. Five European Union countries are discussing a 3-year project to build laboratory prototypes of craft components.

LIGHTSAIL-1
(The Planetary Society)

The launch malfunction that doomed its first solar sail, Cosmos-1, in 2005 has not discouraged the Planetary Society. The space advocacy group, based in Pasadena, Calif., expects that its LightSail-1 will be ready for launch in 2011. Three cube-shaped satellites, or "cubesats," each 10 centimeters to a side, will hold the 32-square-meter Mylar sail and the craft's electronics and controls.

ILLUSTRATIONS, CLOCKWISE FROM LEFT: ALEXANDRE D. SZAMES/ANTIGRAVITE; JAXA; NASA

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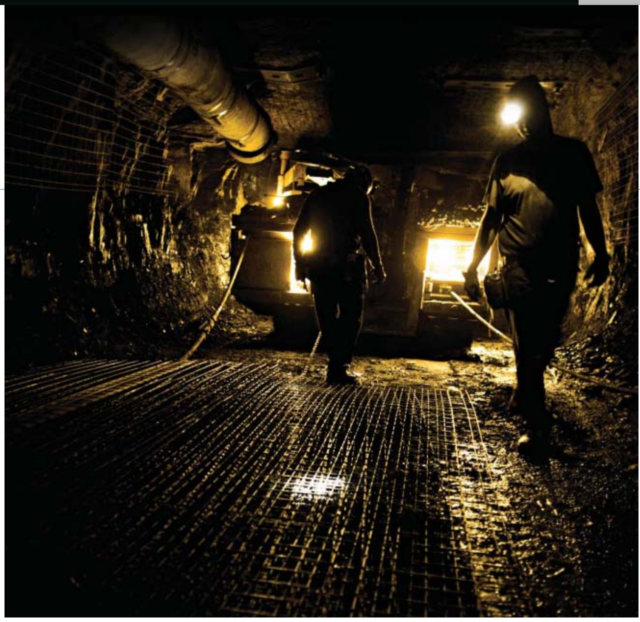


DEEP DOWN: Sometimes coal miners can't call for help.
PHOTO: TYLER STABLEFORD/GETTY IMAGES

update

Talking to Trapped Miners

Rescue workers are only now getting the tools to communicate with coal miners

On 5 August, the collapse at a Chilean gold and copper mine left 33 miners trapped in a chamber nearly 700 meters below the surface. When this issue went to press in mid-October, they were finally nearing freedom. As bad as that situation was, it could have been much worse: They could have been mining coal.

The Chilean miners were able to talk to their families by phone, and video images of the men have been broadcast around the world. But if they'd been in a coal mine, their television debut would likely have been impossible. The slightest spark from electronic equipment can ignite methane gas and coal dust, touching off a deadly explosion.

In the aftermath of a lightning-induced explosion at a West Virginia coal mine in January 2006, everything went wrong for the 13 miners trapped inside. With no way to communicate, it took rescuers nearly two days to find them. By then, all but one had died.

By June 2006, the Mine Improvement and New Emergency Response (MINER) Act became law in the United States. Under the act, the National Institute for Occupational Safety and Health (NIOSH) was given just three years to commercialize wireless two-way communication and electronic tracking systems for coal miners.

According to David P. Snyder, senior mine electrical engineer at NIOSH, the agency focused its efforts on getting the systems to be, in mining industry parlance, "permissible." A component is permissible when the Labor Department certifies that its circuits are incapable of releasing enough energy—during normal operation or if they're damaged in an accident—to trigger an explosion by igniting methane gas or coal dust. It doesn't take much to spark an explosion. "A methane-air mixture requires less than a half millijoule of energy to ignite," says Snyder.

Nevertheless, systems will be available soon that meet the need. Pillar Innovations of Grantsville, Md., for one, has developed a rugged leaky-feeder system. It consists of a coaxial cable with openings in the shielding along its length, which allow it to give off and pick up signals. The cable loops down into the mine and back to the surface. And unlike standard leaky feeders, it is powered from both ends, and the signals it transmits run in both directions. So even if the cable is severed in a collapse, signals from miners' radios can still reach the surface.

L-3 Communications, in Chantilly, Va., and Innovative Wireless Technologies, in Forest, Va., have together commercialized a wireless mesh communication network they call Accolade. The system operates at 900 megahertz, which is within a range of frequencies that offer the best propagation down the twists and turns of a coal mine tunnel.

But at best, conventional radio signals only propagate perhaps 300 to 600 meters down a coal mine tunnel, says Snyder. If all the infrastructure within a thousand meters or so is destroyed by a catastrophic event, "you would be out of business." So NIOSH also contracted for some unconventional alternatives: transmitting through the earth and a technology called parasitic coupling.

Research has shown that it is possible to transmit signals through solid rock at frequencies below 10 kilohertz, but those studies were conducted with high-powered military transmitters. "We're now talking about doing the same thing on a watt or two of power," Snyder says.

NIOSH has contracts for earth transmission technology with five firms, among them Lockheed Martin. The company has a product called MagneLink that is up for approval.

The other alternative, parasitic coupling, takes advantage of the fact that radio signals in the frequency band between 300 kHz and 3 MHz propagate through any metallic objects in a mine, such as rails or pipes, creating non-line-of-sight communications links that can stretch for kilometers. One such system, developed by Kutta Technologies, in Phoenix, recently received permissibility approval.

Considering the MINER Act's tight time frame, Snyder is pleased with the results. "We had to look at technology that was available or on the cusp of availability to have any shot of meeting the deadline," he says. "Maybe if we had 10 years, we would have approached things differently." —Willie D. Jones

A more detailed version of this story appeared online as "Technology to Talk to Trapped Miners" in September.

 BY ROBERT W. LUCKY

Black Swans

What if Gaussian engineering is clear, simple, and wrong?

MY HOUSE is on a river, and I often see swans drifting by my backyard in their swanlike serenity. Over the years every swan to come by has been white. I have thus reached an inescapable statistical conclusion: All swans are white.

I have watched that river through many storms, and though it has washed high up my back lawn, it has never reached my house. Given all my observed data on water levels, I have reached another conclusion: My house will never be flooded.

A popular book by Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable* (Random House, 2007), has me reassessing these conclusions, as well as rethinking much of my experience and education. Taleb assures me that black swans do indeed exist; it's just that I haven't seen them. How much data do I actually have, and what is the probability of an event that I have not yet seen?

Taleb calls an event a "black swan" when it is rare, unexpected, and impactful. He claims that life is dominated by such events—the chance meeting one day of your future spouse, the random acquaintance that forges your career, the serendipitous observation that leads to the next penicillin.

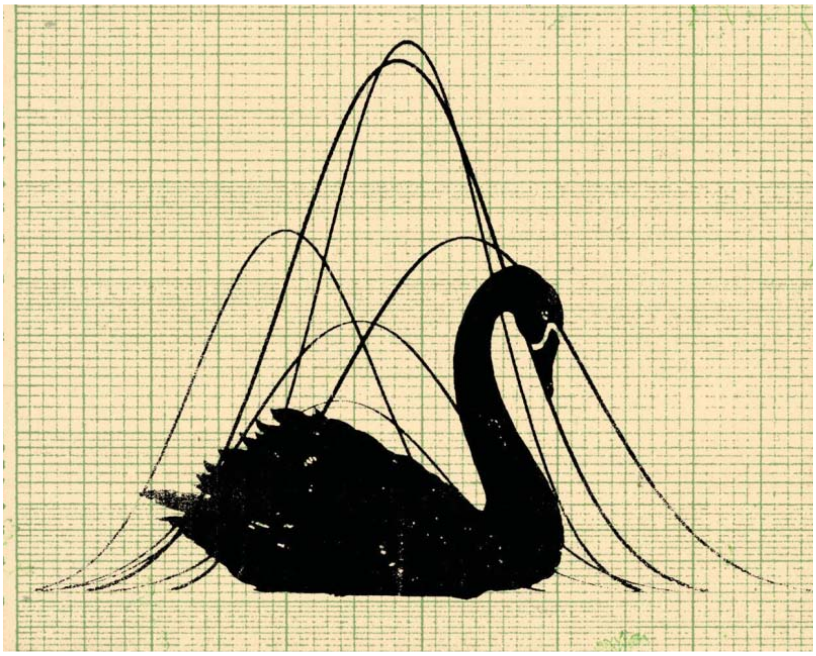
Throughout his book Taleb rails against the traditional way of teaching statistics and probability theory. You would be better off, he says, taking a course on postcolonial African dance. The problem, he says, is that statistics as taught and practiced leads to an unwarranted belief in mathematical certainty, in predictable behavior, and in a world dominated by bell-shaped "normal" Gaussian curves.

It isn't so, he says. Most of the world isn't Gaussian. Instead it's mostly ruled by the dreaded power law, with its heavy tail that presages regular occurrences of far-outlying events that are almost impossible in a Gaussian regime. Much of the Internet has this character: the popularity of Web sites, the frequency with which a book is sold online, the traffic rates of individual users. Such a distribution curve looks like a downhill ski run: It starts with a precipice of heavy users, swooping sharply downward into a long tail of rare instances that can't be ignored.

It seems to me there is a great deal of truth and wisdom in what Taleb says. We engineers do indeed relish the certainty of mathematics. We dote on our models; over time we forget the assumptions that went into them. We cling to the central limit theorem and its promise of normality. Flip a random coin a few more times and the percentage of tails gets even closer to 50. Many of our designs depend on this kind of near certainty.

Most of communication theory, for example, is based on the "fiction" of additive white Gaussian noise. Look at received signals over a long enough interval and the multidimensional vector lies ever closer to the surface of a multidimensional sphere. If the spheres around other possible signal vectors don't intersect, then the probability of error can be made arbitrarily small. The math is beautiful and seductive.

Taleb, however, says that elegant mathematics appeals to mechanistic minds that don't want to deal with ambiguity,



RICHARD MIA

and that to make it fit the real world you have to cheat somewhere in your assumptions. Like maybe the world isn't filled with additive white Gaussian noise after all.

I suppose we're guilty as charged, but I'd like to offer a mild defense. We do sort of know that the noise probably won't fit our nice model, but nonetheless all that elegant math does produce designs that are relatively robust against disturbances. Outliers resulting in errors still do occur, of course, but usually their effect is not catastrophic, as it can be in the financial realm, which is Taleb's bête noire. So I'm thinking that all of those old courses with bell curves and other Gaussian statistics weren't so bad after all.

I'm watching the river now, and here come the swans. I'm still convinced I will never see a black swan, but I am kind of worried about that flood thing. ❑

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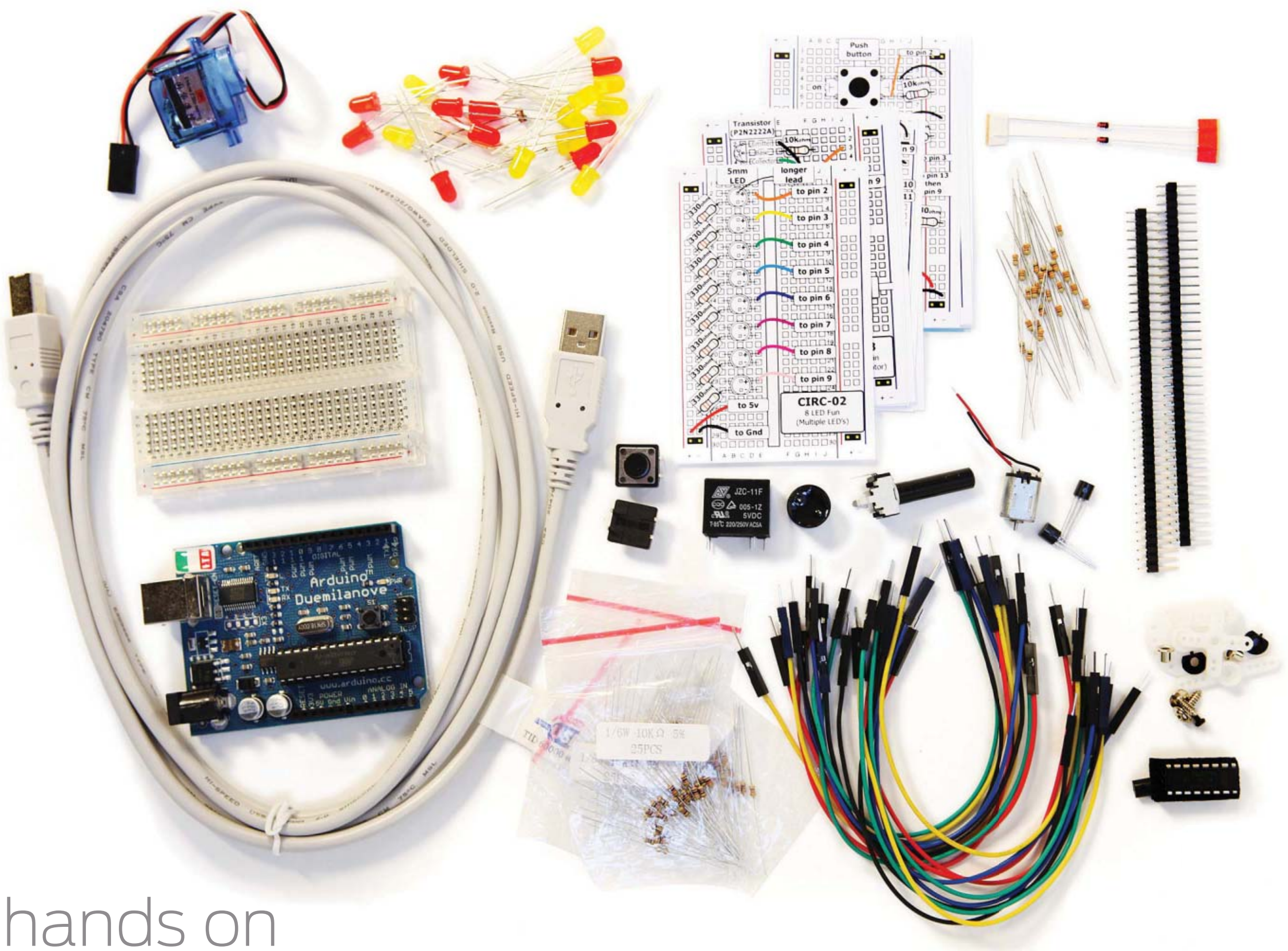
the big picture

BIRD'S-EYE VIEW

A researcher from India's National Aerospace Laboratories, in Bangalore, launches a micro air vehicle prototype. The remotely operated drone, which will soon go into commercial production, is one of several models, each less than a meter across, that will be used for military reconnaissance, as well as search-and-rescue support at natural disaster scenes. The plane, which is designed to avoid detection by radar, can soar for up to 40 minutes at a time.

PHOTO: DIBYANGSHU SARKAR/AFP/GETTY IMAGES

gifts



Arduino Inventor's Kit
US $85; http://sparkfun.com
PHOTO: RANDI SILBERMAN KLETT

hands on

THE GIFT OF GADGETRY

These four DIY gifts are so much fun, kids won't know they're learning

THERE'S NO better way to encourage a kid's inclination toward electronics than with a holiday gift. The trick, of course, is finding something that's fun as well as educational.

Catering to the younger crowd—those who shouldn't yet wield a soldering iron, for example—is perhaps the most difficult. But they can safely and enjoyably learn about the many things electrons can do with a set from Elenco Electronics. The Snap Circuits Jr. 100-in-1 kit, just US $21 from Amazon, cleverly avoids soldering; its nicely mounted and labeled components can be placed on a plastic grid. Your budding EE then hooks them together by merely snapping in place wire jumpers or rigid connector bars.

The Snap Circuits Jr. kit is appropriate for children in elementary school, but a bright youngster will soon exhaust its educational potential. Fortunately, the more advanced kits allow for much more experimentation. The Snap Circuits SC-500 Student Training Program, for example, provides three times the fun and includes teacher and student guides, along with a sturdy carrying

Snap Circuits SC-500
List price: US $155; http://elenco.com/snapcircuits.html
PHOTO: RANDI SILBERMAN KLETT

DSO Nano
US $89; http://seeedstudio.com
PHOTO: RANDI SILBERMAN KLETT

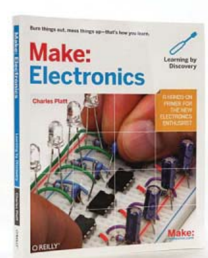
case. All this can be had for about $140 from Amazon.

For a capable middle or high school student, an excellent gift would be *Make: Electronics* (Make, 2009), a remarkably comprehensive handbook for the novice electronic hobbyist, available for about $25. The author, Charles Platt, shows a good sense of humor and stresses hands-on tinkering over plodding book learning as he painlessly guides the reader.

The tutorial begins at a low level—with alligator clips to attach wires together—but rapidly works its way up to prototyping circuits using breadboards and finally soldering components to perforated boards. I commend Platt for the wealth of detail he provides. Having more description than necessary in a reference like this is far better than having too little. He still manages to cover quite a bit of territory, including the basics of most common electronic components, both analog and digital, along with DC, stepper, and servo motors.

Although I have some minor quibbles with the book—it relegates wire wrap to a sidebar, misses a key trick when it describes how to solder, and lacks any discussion at all of operational amplifiers, to name a few—it's still a great guide for teens wanting to get their hands dirty building real electronic projects.

But I also have one larger quibble. This guide includes a very brief introduction to a simple microcontroller, the Picaxe. The author acknowledges that others, in particular the ever-popular Arduino, are far more capable. Yet, he chooses not to cover the Arduino because it requires "programming in the C language." In truth, the Arduino uses a variant of C and is really quite user friendly.



Make: Electronics
By Charles Platt;
Make, 2009; 352 pp.;
list price: US $35;
ISBN: 978-0-5961-5374-8
PHOTO: RANDI SILBERMAN KLETT

To be sure, most of the information needed to program an Arduino is available online. But if you want to make the process really painless for a budding engineer, buy him or her an Arduino Inventor's Kit, available for $85 from Sparkfun Electronics. It includes an Arduino Duemilanove board, along with a prototyping breadboard and the components needed to work through the dozen or so simple exercises described in the accompanying guide. The guide is online at the kit's manufacturer's site, Oomlout, which also provides video tutorials. With all that support, it's hard to imagine a youngster running into roadblocks.

For the next step in your young engineer's education, you might consider the DSO Nano, a pocket oscilloscope from Seeed Technology. This featherweight digital 'scope is cleverly built into a case that was surely designed for an MP3 player. At $89 and with just one input channel, don't expect it to replace your trusty Tektronix. But the Nano is capable enough for simple tasks—examining a serial communication line or the pulse-width modulated signal sent to a servo motor, for example. Years from now, your engineer scion will probably remember the Nano as the most unusual stocking stuffer of his or her childhood.

—David Schneider

Prices are those paid at press time. Current prices may vary.

AVANT GARDE GIFTS

Motormouse US $50; http://motormouse.us.com

As a die-hard track-pad user, I don't own a mouse. But if I did, it would be the Motormouse, from Avant Garde Gifts, in Marco Island, Fla. It's easily the best-looking accessory ever to grace my desk—a lipstick-red Porsche replica. And it's the easiest to set up—pop two AAA batteries into the trunk, plug a tiny receiver into your computer's USB slot, and you're good to go. As befits a Porsche, the cursor initially flew across my 20-inch screen at Le Mans speeds, but a quick pit stop at system preferences fixed that. —*Steven Cherry*

gifts

ULTIMATE POCKETKNIFE

Quirky's shape-shifting Switch is the world's first modular pocketknife

Switch
US $79 (includes carrying case)
http://quirky.com
PHOTOS: QUIRKY

THE 2008 MOVIE *Get Smart* featured a Swiss Army knife with a crossbow, a flamethrower, and a dental floss detonator, but the true test of a pocketknife is its versatility—the best knife is one you can change from day to day and from task to task.

That's the idea behind the Switch, from the crowd-sourcing design house Quirky. In February, a user suggested that Quirky design a "modular pocketknife." The self-

selling idea quickly jumped to the top of the queue. Within three weeks, Quirky's New York City–based design team had a preliminary CAD mock-up as well as a name and logo.

Unscrew the Switch with a coin and install whichever blades, tools, or doodads you like. It comes with three interior axles: small (2 to 6 tools), medium (4 to 10), and large (up to 13). The pen, scissors, Phillips-head screwdriver, LED flashlight, and 1-gigabyte USB memory stick make a good combo for the office. But a camping weekend might call for the more traditional knife, saw, pliers, and…come on, that LED flashlight's going to get used sometime.

—MARK ANDERSON

software

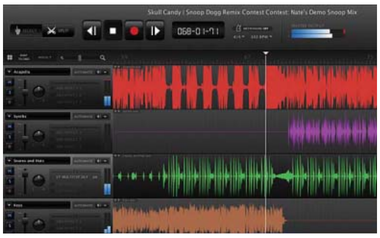
A Music Studio in the Cloud

When your studio is the Internet, you're your own recording engineer, but Mantis offers a lot of help

For the music maker on your holiday gift list—whether it's your mezzo-soprano sister-in-law or that nephew in a pop band—is there a better gift than a few hours at a recording studio? Yes, there is—unlimited time at a recording studio. For US $50.

Indaba Music, a musical social network company based in New York City, has launched a Web-based recording and mixing app called Mantis; $50 buys a year's access to a growing library of loops, samples, and effects—created by professional studio musicians—and 5 gigabytes of storage space (Platinum subscribers get 50 GB).

Every other week, on average, a professional recording artist or musical project presents a new challenge to the community, says Indaba Music CEO Dan Zaccagnino.



Mantis
US $50 Pro ($250 Platinum) per year; http://indabamusic.com/mantis; Ages: 13+
IMAGE: INDABA MUSIC

Last year, world-renowned cellist Yo-Yo Ma posted his track of the traditional melody "Dona Nobis Pacem" to Indaba's boards, and 350 Indaba subscribers recorded their own virtual duets. Ma selected his two favorite collaborations, earning the artists—a Colorado Springs handbell choir and a Canadian heavy-metal guitarist—studio time with Ma himself to record a live duet. This year rapper Snoop Dogg posted vocal tracks for his single "That Tree," which occasioned remixes in wildly different styles, including electronica, country and western, and sea chantey.

The social networking of music doesn't stop there. Record a guitar track on Mantis, add a dab of reverb or distortion from its library of effects, and a few clicks later you can post the track to Indaba's member boards for its 500 000 subscribers around the world who might want to mix in their own instrumental or vocal tracks.

The nascent session then becomes a kind of help-wanted ad for like-minded session players. Maybe it's the nugget of a power-pop gem that draws another member's Fountains of Wayne–influenced rhythm section, or a toe-tapping bluegrass number that's calling out for an Alison Krauss–style fiddler to bring it on home. *—Mark Anderson*

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AHEAD OF ITS TIME: LENOVO IDEAPAD Y560D

This laptop delivers a 3-D portable game experience, though not much else

IT'S ONLY been about five years since HDTV was the up-and-coming thing. Now we're being told that HD isn't quite enough; 3-D HD is actually what we want. And not just for television—for computers as well.

Acer, Asus, Lenovo, and Toshiba have all released 3-D laptops recently, and I took the opportunity to try out the Lenovo Y560d. My demo unit was equipped with a quad-core Intel i7-720QM CPU, 4 gigabytes of RAM, a 500-GB hard drive, a 1-GB ATI Radeon 5730 graphics card (which drives the 15.6-inch 1366-by-768 display), and a pair of 3-D glasses. A utility application preinstalled on the Lenovo will search for games that can take advantage of the 3-D, or you can register a game by hand.

The computer achieves the 3-D effect by linear polarization of every other scan line of the screen, dividing the image into halves, each of which passes through only one of the two lenses. The brain combines the two halves into a single stereoscopic image. The effect is convincing, provided you're properly centered in front of the screen.

I put the Y560d through its paces with the classic game *World of Warcraft*, and it worked very well—for the game's 3-D elements. Particles in the air appeared to float out from the screen, and it seemed as if I could reach into the game and pick up my avatar.

However, the 3-D capability made the game's 2-D elements look significantly worse. For one thing, the alternating of scan lines made small text nearly illegible. I found myself raising and lowering the glasses so that I could read the chat window or the text to a quest I was being offered. The problem is exacerbated by the 1366-by-768 resolution, unforgivably low for a 15-inch screen. On an 11-inch netbook with the same resolution, the pixels are small and tight. But on a larger notebook it's as if you're looking through a screen door. A modern 15-inch laptop can come with a resolution as high as 1680 by 1050, a much more pleasant experience. If this is the price that must be paid to enable 3-D, it's a heavy one, because it affects everything you do with the computer.

With its full-time screen resolution so low and the imperfect 3-D experience, I have a mixed recommendation of the Y560d. The average user will likely be disappointed, but gamers who want both 3-D and the portability of a laptop may not mind. —HARRY TEASLEY

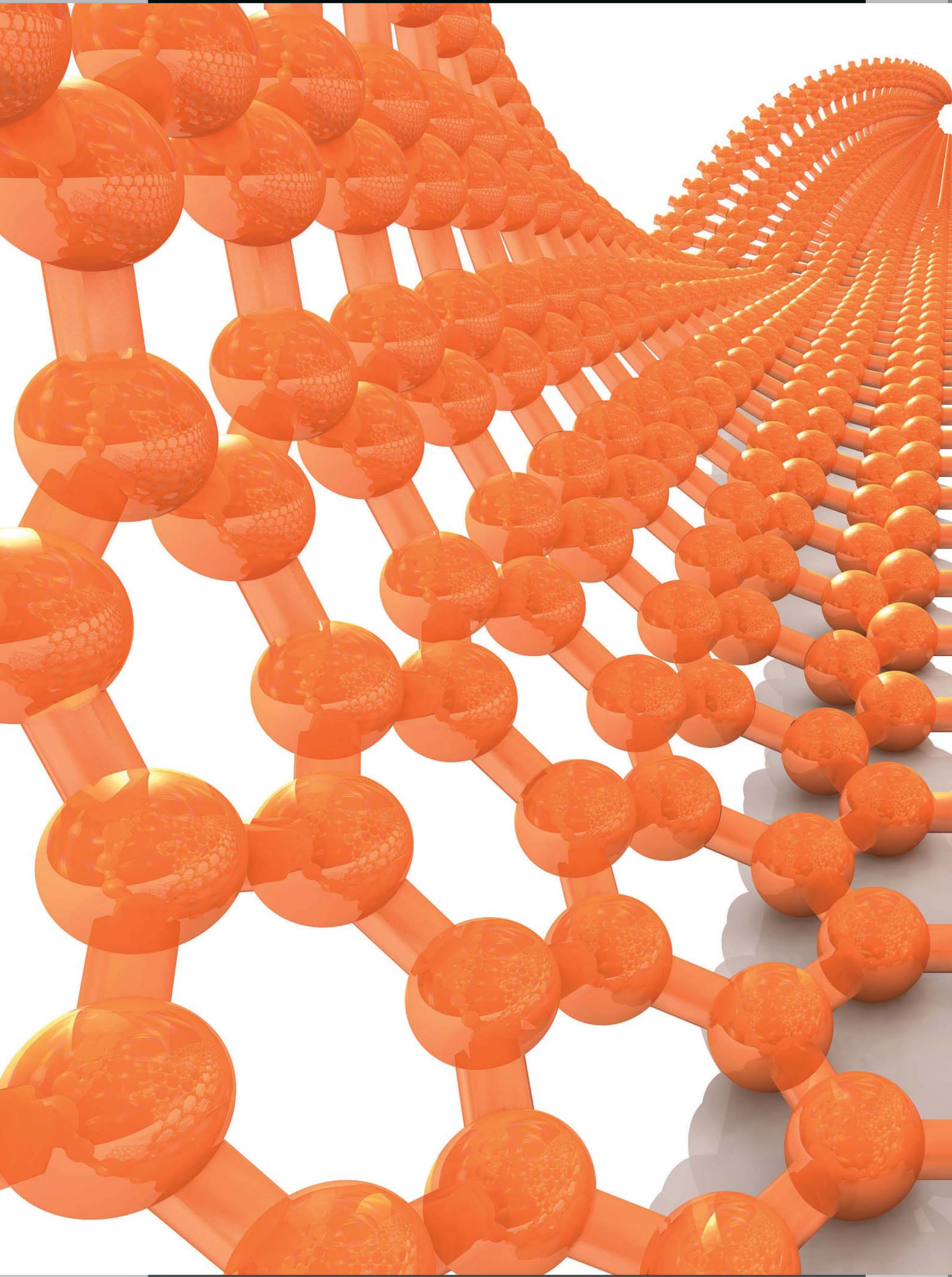
Lenovo IdeaPad Y560d
US $1599; http://www.lenovo.com
PHOTO: LENOVO

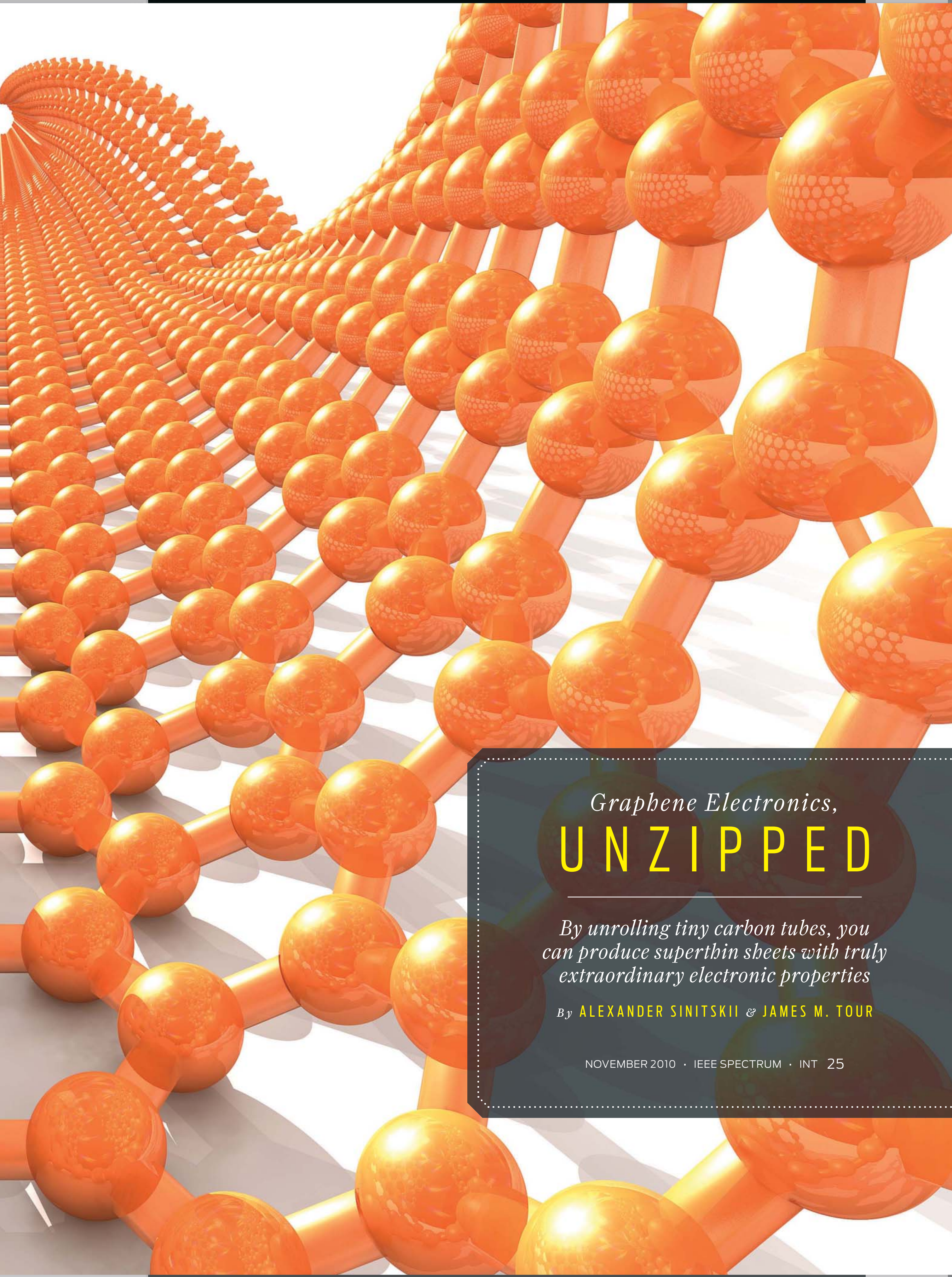
Banzai Jelly V7 CMOY Amp
US $71
http://electricsumo.com
PHOTO: MICHAEL N. DAUGHERTY

Color My Audio World

If T-shirts can come in 11 colors, why can't headphone amplifiers?

A great design is, ultimately, a perfect marriage of function and form. Sadly, engineers sometimes focus on the one at the expense of the other. And when it comes to, say, an amplifier, who can blame them? If it sounds great, the dials work, and there are no rough edges, it's done, right? Not quite. The Banzai Jelly V7 CMOY amp comes in eight vibrant colors, plus silver, white, and black. It remains only for someone to build an amp and encase it in paisley. (Should you, dear reader, be so inspired, please send a photo.) *—Steven Cherry*





Graphene Electronics,

UNZIPPED

By unrolling tiny carbon tubes, you can produce superthin sheets with truly extraordinary electronic properties

By ALEXANDER SINITSKII *&* JAMES M. TOUR

CAN ANY ELECTRONICS MATERIAL rival silicon—tunable, current-carrying, self-insulating, easy to fabricate, as common as sand on the beach? Even if another rival came forward, could it ever overcome silicon's 50-year, trillion-dollar head start in development?

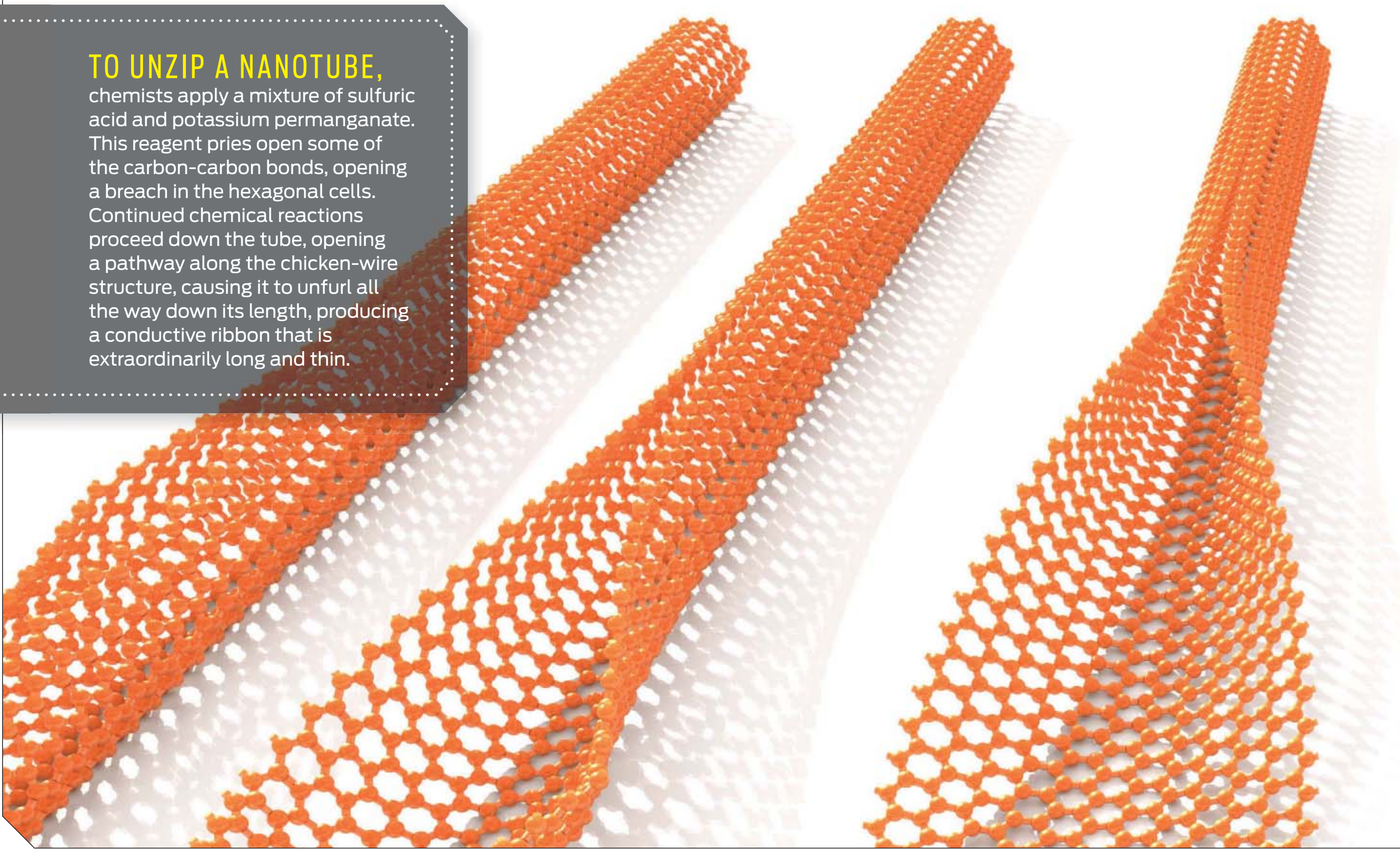
Yet we do need an adjunct to silicon, because so much of the potential market for electronics has yet to be opened. Electronics in paper, on walls, and in clothing are today mere novelties, simply because silicon can't easily be painted on a surface, draped on a flexible platform, or used to cover large areas. What's needed is something that can do all that and still be churned out cheaply and in bulk, processed easily, and slipped deftly into the guts of the next generations of electronics.

Allow us to suggest a candidate: graphene, an atom-thick sheet of carbon linked in a hexagonal network, like chicken wire. The material isn't so much a replacement for silicon as a complement to it, serving many purposes where silicon is inadequate and mixing with silicon in the fabrication of certain devices. Graphene was discovered in the 1970s but first properly appreciated only in 2004, when Andre Geim and Konstantin Novoselov, Russian-born researchers at the University of Manchester, in England, managed to transfer it to a substrate and study its unique attributes. That work has won them the 2010 Nobel Prize in Physics.

OF COURSE, ANY NEW FORM OF PURE carbon would be big news, but graphene's properties are remarkable. As thin in one of its dimensions as a material can get, it is nevertheless impermeable to gas and is the strongest two-dimensional material ever tested, with a tensile strength 200 times as great as that of steel. What's more, it conducts heat better than any metal. Best of all—to readers of this magazine—are graphene's unusual electrical characteristics, especially its ability to carry charge carriers at speeds dwarfing those possible in silicon. That ability could allow for superfast switching in data processing.

Silicon has seen many a contender in the past—for instance, germanium, the material used for the very first transistor, and gallium arsenide, which for all its usefulness remains a mere niche material. So why do we nurse such high hopes for this rarefied form of carbon?

First, recall that carbon stands just above silicon in the periodic table, and hence shares many of silicon's inherent properties. Second, consider that researchers around the world are rapidly accumulating new knowledge of graphene's fantastic properties and getting better by the month at manufacturing it

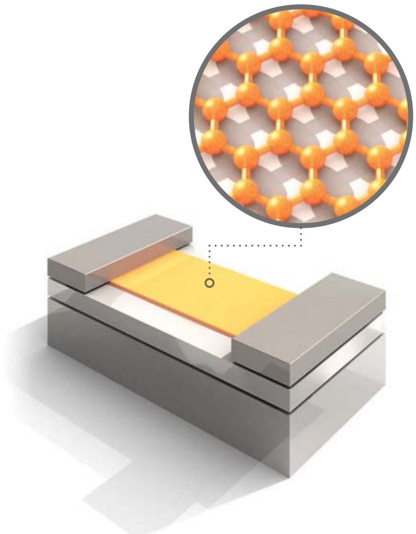


TO UNZIP A NANOTUBE, chemists apply a mixture of sulfuric acid and potassium permanganate. This reagent pries open some of the carbon-carbon bonds, opening a breach in the hexagonal cells. Continued chemical reactions proceed down the tube, opening a pathway along the chicken-wire structure, causing it to unfurl all the way down its length, producing a conductive ribbon that is extraordinarily long and thin.

THIS SPREAD AND PREVIOUS: BRYAN CHRISTIE DESIGN in bulk. Finally, keep in mind that the semiconductor manufacturing industry is under increasing stress to keep pace with Moore's Law, and therefore more likely to consider new materials.

So the question really isn't "Why graphene now?" but rather: "Why didn't the electronics industry start with graphene in the first place?"

TO APPRECIATE THIS WONDERFUL stuff, you have to put it in its context as one of the handful of forms that pure carbon can assume. There's diamond, a three-dimensional crystal. There are the hollow cage molecules of fullerene, which are nearly dimensionless dots, and the related carbon nanotubes, whose length is so much greater than their width that they're essentially one dimensional. And then there's boring old graphite, made up of stacks of two-dimensional graphene sheets, mined or produced synthetically in the hundreds of thousands of tons and used in electrodes, lubricants, carbon-fiber-reinforced plastics, and pencil lead. The distinction between graphite and graphene is somewhat arbitrary; current thinking holds that more than 10 stacked sheets of graphene qualifies as graphite, and anything less is graphene.



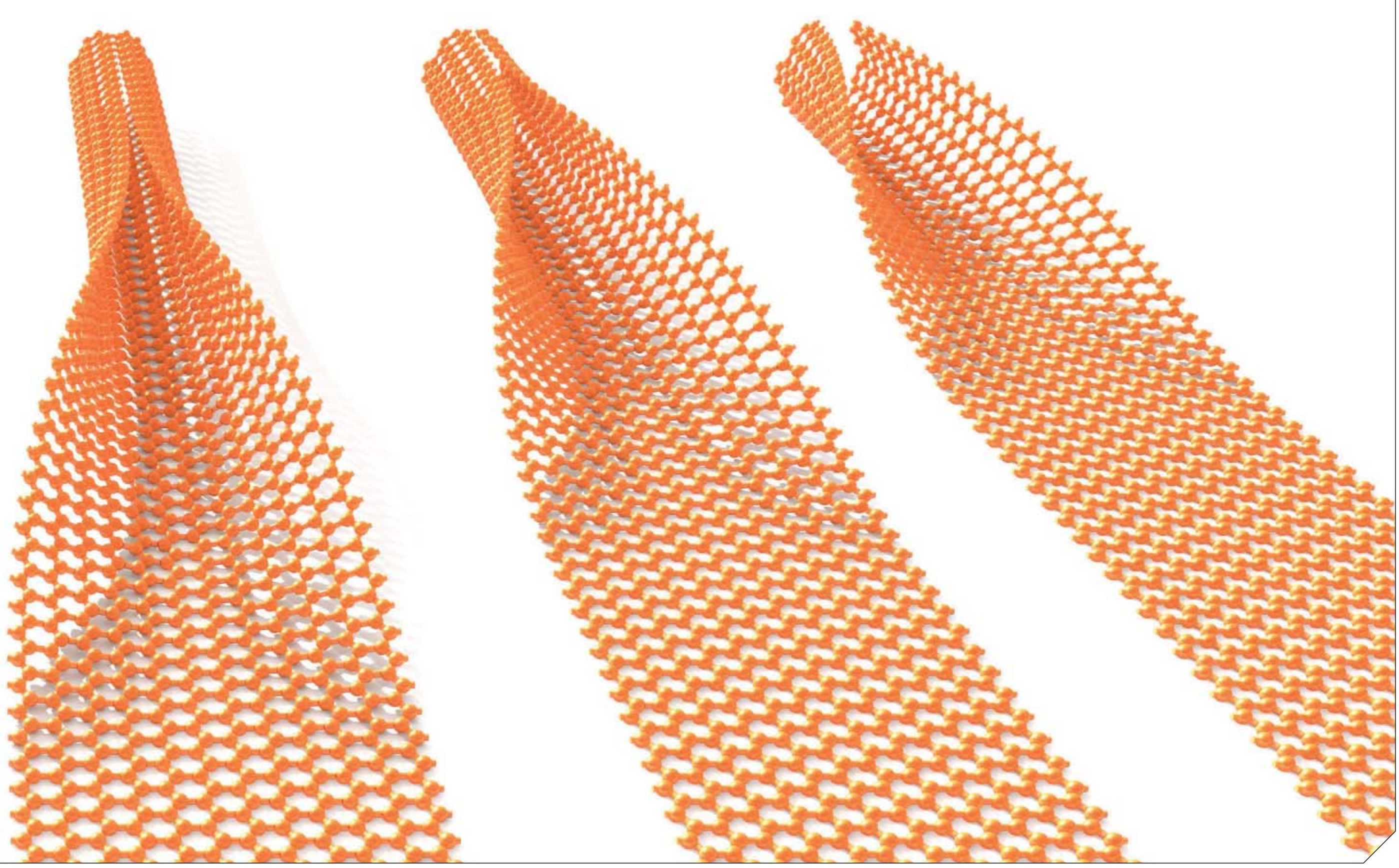
A GRAPHENE FET, or field-effect transistor, consists of a single ribbon of graphene with one side laid down on a positive electrode, the other laid down on a negative one. A third electrode, or gate, can then modulate the flow of electrons through the ribbon, turning the device into a switch.

Interestingly, graphite behaves differently in one direction than it does in another. The atoms in a given layer grip one another with strong carbon-carbon bonds, the same kind that give diamond its hardness. These links are only about 0.14 nanometer long. However, the layers are about 2.5 times farther apart, so the attractive forces in those directions are weaker. The layers can therefore easily slide across one another; the friction of a pencil passing across a sheet of paper is enough to shear off graphene sheets. We've been writing with graphene for centuries without appreciating it.

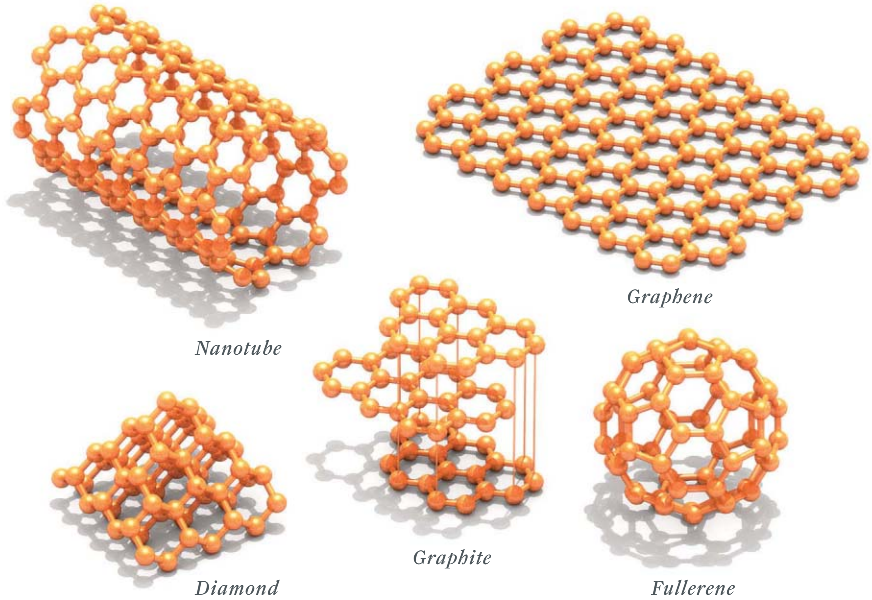
For decades, researchers thought (with some theoretical basis) that graphene could not exist in a freestanding form but only as a component—stacked into graphite, rolled into nanotubes, or balled into fullerenes. As often happens, the theorists were proven wrong by experimentalists.

Before that great discovery in 2004, some researchers had actually created graphene by laying hydrocarbons down on metal surfaces through chemical vapor deposition (CVD). But nobody paid much attention to these results, because the researchers had never bothered to transfer the graphene films onto insulating substrates, where the films might have been probed electronically.

Astonishingly, in the 21st century, when groundbreaking scientific discov-



THE CARBON FAMILY has a new member: graphene. It comes on top of plain old graphite, now understood as a layer cake of graphene sheets; diamond, a cubic crystal; nanotubes, which consist of hexagonal cells shaped like a straw; and fullerenes, in which five cells are pentagons and the rest are hexagons, an arrangement that causes the structure to close up into a soccer-ball shape.



BRYAN CHRISTIE DESIGN

eries are supposed to require sophisticated research tools, these first graphene flakes were "fabricated" simply by peeling them from a graphite crystal using adhesive tape. These first graphene samples were then subjected to tests of their strength, thermal conductivity, and electrical behaviors. Even after six years of intense research, graphene continues to reveal new and stellar properties.

THE MOST STRIKING PROPERTY OF graphene is the speed with which it can convey charged particles, the medium for information in all electronic systems. Even at room temperature, electrons and holes—positively charged entities that each represent the absence of an electron—can zip through graphene ballistically, traveling for micrometers at a stretch without bouncing off a carbon atom or a structure defect. They thus can move up to 2000 times as fast as in silicon, enabling the device or transistor to switch faster. That capacity would make graphene a wonderful complement to silicon in the building of high-performance field-effect transistors (FETs), provided this great switching speed was coupled with a field effect.

Just how fast might charges propagate through such a hybrid FET, made of graphene and silicon? They could move at about 20 000 square centimeters per volt-second if placed on a substrate, about 14 times as fast as silicon alone allows. Better still, the speeds remain high even when the charge carriers reach densities of up to 10 trillion per cubic centimeter. In a conventional semiconductor, such mobilities drop as you boost the concentration of dopants, the impurities that add surplus charge to the mix.

Another great advantage to graphene is that it works even in tight spaces. In today's FETs, the speed with which charged particles can move falls dramatically as you pare down the transistor's channel, its thinnest part. No such problem plagues graphene. And not only does it conduct current, it conducts heat as well, which moves horizontally through the sheet. That quality makes it perfect for dissipating the waste heat thrown off by today's ever more densely packed electronic components. Further, and in contrast to other materials proposed for future electronics, such as semiconductor nanowires and carbon nanotubes, graphene is intrinsically flat. It doesn't have to be grown on a surface; it can be sprayed on. That makes it compatible with today's lithography, etching, and patterning techniques.

Just as important is graphene's mechanical and chemical stability, even at feature sizes under 10 nm wide. Such stability means that graphene retains the character designers intended as it passes through the often brutal steps involved in manufacturing a device. Yet for all its stability, graphene can be fine-tuned with relative ease. For instance, to make it into a chemical sensor material—the sort that might detect a particular protein in a biological sample or a simple compound such as carbon monoxide—you merely expose the graphene to the molecule to be detected. Through a process called adsorption, the protein or the carbon monoxide gently binds to the surface by electrostatic interactions, thereby changing the electronic properties of the graphene, a change that can then be sensed by the associated electronics.

Too bad we can't fashion graphene into a full replacement for silicon, but only a complement. Unlike silicon, graphene is ambipolar, which means it lets current go through regardless of whether a positive or negative gate voltage is applied. Doped silicon, by contrast, is unidirectional—that is, it allows current flow only when the gate voltage is at a certain polarity (say, positive or negative). Ambipolarity may seem like a bug rather than a feature, but with a little thought, electrical engineers can design around this problem and even create devices that take advantage of it. Researchers at MIT have demonstrated an elegant example of this by using ambipolar graphene FETs as frequency multipliers, which double the frequency of an electromagnetic signal in radio communications and other applications. (This device employs pure graphene FETs, enabling it to perform a function that carbon can handle but silicon cannot.)

Sadly, though, graphene appears at the moment to be unsuited for use in logic chips. Logic applications require a transistor to have distinct "on" and "off" states, in which the gate is conductive and nonconductive, respectively. But a graphene gate remains slightly conductive even when no voltage is being applied. That's because in its pure state, graphene is a zero-band-gap semiconductor, having small conductivity at zero gate voltage.

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There may nonetheless be a way to engineer significant semiconductor band gaps in graphene. One of the most promising approaches is to carve the graphene into ribbons less than 10 nm across; this confines the active zone to one dimension. Theory predicts and experiment confirms that the band gap in graphene ribbons is inversely proportional to their width. As a result, such ribbons have on/off ratios as high as 10 million to 1.

Although creating graphene sheets using adhesive tape may be a fine laboratory technique, it's hardly practical for mass production.

Here's a better way: Start not with graphite but with a carbon nanotube—essentially a rolled-up sheet of graphene—and unzip it along its length. We do this with a chemical reagent combination known since the 1800s, sulfuric acid and potassium permanganate. Dmitry Kosynkin, a postdoctoral researcher and one of our associates at Rice University, in Houston, discovered the process while trying to oxidize the nanotubes. We found it so remarkable that we spent months accumulating enough evidence to convince ourselves that it worked. The beauty of it is that the chemical reaction can easily be turned into a large-scale process, with a yield approaching 100 percent.

Because carbon nanotubes come in single-walled and many-walled varieties, with diameters from 1 to 100 nm, this process can produce graphene nanoribbons from 3 to 300 nm in width. By selecting the ribbons of the proper size, we can get the building blocks of the particular devices we wish to construct.

We have taken some of these tube-born ribbons, deposited them on a silicon substrate topped with silicon dioxide, and fabricated them into FETs, which turned out to have electrical properties similar to those of devices that use graphene produced by other techniques. We also demonstrated gating—the inherent property of a FET wherein the transport of carriers is modulated by the third, or gate, electrode—as well as adsorption properties that would make the devices promising for use as sensors and nonvolatile memory.

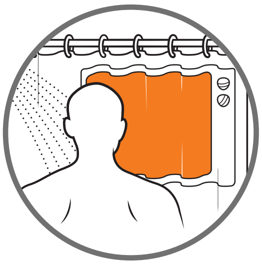
ALTHOUGH THE UNZIPPING PROCESS appears promising, there are several problems to solve. First, the graphene nanoribbons are partially damaged by the harsh oxidative environment in the chemical bath, so we are now developing gentler ways to unzip the nanotubes. Second, we need to be able to put the ribbons exactly where we want them, in a way that can be reliably reproduced thousands of times a day in a factory. We'll also need techniques that can stand the ribbons vertically—like blades of grass—so as to pack more of them into a given area on a chip. Meanwhile, for applications where discrete placement is not required, as in photovoltaic arrays, the graphene ribbons might simply be painted on.

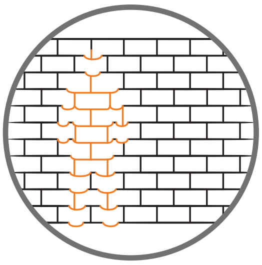
Other techniques to unzip carbon nanotubes are also possible. A group at Stanford has used plasma jets to blow the tops off multiwalled carbon nanotubes while protecting the sides of the tubes under a polymer film. The resulting nanoribbons seem to resist oxidative damage better than the chemically unzipped ribbons do, but it seems there is no way to scale up the fabrication technique. Other researchers have produced graphene using CVD techniques, wafting methane or some other volatile carbon compound onto nickel or copper surfaces, which then catalyze the conversion of those compounds into graphene. It's also possible to grow graphene epitaxially, by annealing silicon carbide at high temperatures to assemble graphene directly on the SiC wafer, using the carbon atoms that are already there.

This past summer, for instance, researchers at Samsung, together with colleagues from Korea's Sungkyunkwan University, the National University of Singapore, and Japan's National Institute of Advanced Industrial Science and Technology, reported using CVD to produce stupendous growth areas, approaching a square meter, on a copper substrate. When the researchers dissolved away the copper, they were able to keep that vast, one-atom-thick sheet of carbon from wrinkling! They also chopped it into transistors, showing the way to mass production. This year IBM achieved another milestone by demonstrating 100-gigahertz graphene-based transistors, and recently a group at the University of California, Los Angeles, set a new record at 300 GHz.

Of course, these transistors are much larger than the silicon variety, but smaller isn't always better—sometimes faster or more flexible is what you're looking for. Engineers have already shown that it's no problem to transfer graphene sheets from a copper growth substrate to a flexible one made of polyethylene terephthalate, the same kind of plastic used in soda bottles. Such devices would be good for transparent, touchscreen displays that roll up when you're finished using them.

TO BE SURE, SILICON WILL REIGN supreme in many of the applications in which it is now found. But carbon, silicon's little brother, has new realms to conquer. And if graphene keeps progressing as fast as it has in the past two years, it will surely attract the immense weight of investment in research and development that has so far gone almost exclusively to silicon. If that happens, then little brother will at first supplement silicon and at last supplant it, as little brothers often do. ❑





GRAPHENE GOODNESS might include a flexible video display incorporated into a shower curtain, camouflage clothing, and a virtual-reality theater in the round.

JAMES PROVOST

GREEN GOLD

Algae could make the perfect renewable fuel

By PHILIP T. PIENKOS, ERIC JARVIS & AL DARZINS

E.J. CARR (2)

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Most people consider algae a nuisance.

But it turns out that one man's pond scum is another man's gold, to draw on an old expression. An algal species with the right properties could be immensely valuable. That's why we and others at the National Renewable Energy Laboratory, in Golden, Colo., have been busy "bioprospecting" for promising scoops of slime.

Recently, we dispatched a graduate student to pan for algae in a nearby creek, in Utah's Great Salt Lake, and in other spots where we hoped to find organisms thriving in extremes of temperature, pH, and sun exposure. We're hunting for novel strains that can grow quickly and efficiently enough to provide a renewable source for diesel, gasoline, and jet fuel, which would help reduce the world's dependence on fossil fuels while slowing the buildup of carbon dioxide in the atmosphere.

What kind of algae could do all that? Right now, that's an unanswered question. Algae are microscopic organisms, which, like plants, use photosynthesis to convert light into chemical energy while at the same time absorbing carbon dioxide from the atmosphere. Algae turn the carbon they take in first into sugars and then into oil, which can be made into fuel. But some strains produce much more oil than others.

Our recent bioprospecting ventures have unearthed hundreds of different algae types. There are also about 30 000 known species to consider. We want to figure out which of them could thrive on polluted or salty water, reproduce rapidly, and of course, make copious amounts of oil. Luckily, we can go through them pretty quickly, using a microscope, a few other specialized instruments, and a dye that fluoresces when it contacts oil. Several strains we examined recently exploded in glowing green halos when we tested them in this way.

The simple elegance of these microscopic oil factories has motivated a hundred or so start-ups to try to tackle algal biofuel production. Major oil companies, including Chevron, ConocoPhillips, ExxonMobil, and Royal Dutch Shell, are studying this idea. Several airlines have even performed test flights using fuel blends consisting of a petroleum-based fuel, algal oil, and oils from more traditional biofuel crops, such as *Jatropha*, a genus of succulent plant that produces oil-rich seeds.

If you can make biofuel with jatropha or other vegetable crops, why consider algae? In short, because they grow much faster and produce more oil than terrestrial plants. A glance at the mossy film on the surface of virtually any pond will confirm that the needs of these organisms are truly humble. Like houseplants, algae require water, sunlight, a few nutrients, and carbon dioxide from the air. They grow prolifically and accumulate large amounts of oil when they experience environmental stress.

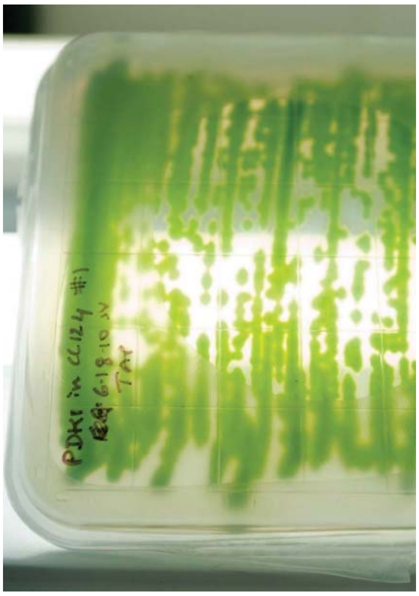
That algae produce oil isn't a great surprise. The fossil fuels that run our cars likely came from ancient algal cells that dropped to the bottom of former oceans and were covered by sediment. Algae use their oil the same way animals use body fat, as a source of energy when times are lean. For animals, lean times come between feedings; for algae, this happens every night, when there isn't any light to power photosynthesis.

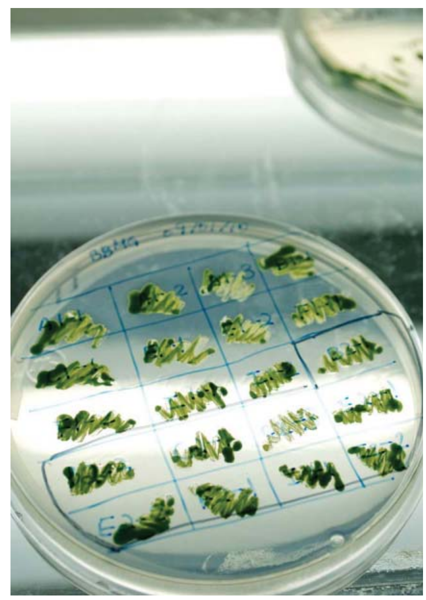
Oil production also helps algae overcome the stress of growing in full sunlight, which can be hard on these cells, particularly when they are starved of one or more nutrients. Such deprived algae tend to generate highly reactive chemicals called free radicals, which can cause molecular havoc within. The conversion of CO_2 to oil prevents the buildup of free radicals, helping the cells avoid internal damage. This oil is very similar to the vegetable oil you might buy at the grocery store.

But unlike corn or olives or soybeans, which can be harvested only once a season, algae grow rapidly enough to be reaped continuously. They also have a higher oil content—some as high as 50 percent. A hectare of soybeans, for example, typically produces only about 500 liters of oil each year, whereas a hectare of algae growing in a shallow pond can easily generate 9000 L of oil—and perhaps as much as 47 000 L—annually. That makes algae many times as productive as oil palms, the most oil-rich source of biodiesel

POND POWER: Some of the algal cultures grown at the National Renewable Energy Laboratory, in Colorado, [top] were collected from nearby Golden Creek by graduate student Lee Elliot [middle]; authors (from left) Al Darzins and Philip Pienkos [bottom] consider a sample.

PHOTOS: E.J. CARR





BUSINESS WIRE

now in use. (The expanding cultivation of oil palms is problematic, however, as they are responsible for much of the deforestation across Southeast Asia.)

For making the most oil in the least amount of space, algae win hands down. But there are other reasons to believe they provide the most promising source for biofuel. To understand why, you need to take a closer look at the competition.

THE LEADING alternative fuel today—no surprise here—is ethanol, which can be used either as an octane-enhancing additive, cutting down on carbon monoxide and other smog-causing emissions, or (in suitably equipped vehicles) in much higher concentrations. "Flex-fuel" vehicles in the United States, for example, can burn E85, a blend of 85 percent ethanol and 15 percent gasoline. Ethanol now accounts for about 6 percent of the global consumption of what's normally just labeled "gasoline."

Today the fuel is made almost entirely from corn kernels or sugarcane, but scientists are also pursuing ethanol made from lignocellulose, the fibrous material that makes up the bulk of most plant matter. Plentiful sources of such biomass include the by-products from agriculture, forestry, and the food-processing industry. Switchgrass and *Miscanthus* grasses grown specifically for ethanol production on nonagricultural lands are also expected to add significant amounts of biomass for ethanol production in coming years.

Although these emerging sources are not yet producing much, the U.S. Energy Independence and Security Act of 2007 calls for the production of 136 billion L of renewable biofuels by 2022. Another regulation caps the amount of corn-based ethanol at 57 billion L and requires that at least 61 billion L of the remaining biofuel allotment come from lignocellulose.

Whether this can be done in an economic and environmentally responsible manner is open to debate. We'll almost certainly continue to use ethanol as a transportation fuel, but it has its disadvantages. For one thing, it makes for hard starting in cold weather. Also, its energy density is considerably lower than that of gasoline or diesel. The energy content of biodiesel, on the other hand, is nearly equivalent to that of petroleum diesel.

Biodiesel is usually made by combining methanol and lye with vegetable oil, animal fat, or recycled cooking grease. It can be blended with ordinary diesel to reduce vehicle emissions or used in its pure form. And it can even be transformed into a kerosene-like jet fuel. Unfortunately, the world doesn't currently have enough vegetable oil or old grease to make sizable quantities of biodiesel. Even if the United States were to devote its entire annual crop of soybeans to producing biodiesel, it would barely make a dent. But no nation would ever do that, because food production is still the No. 1 use for soybean oil. Algae, on the other hand, need not present such a conflict. Here's how we'd like to see them put to work.

YOU CAN cultivate algae in three ways, the easiest of which employs shallow ponds with paddle wheels that constantly mix the water. Large tracts of desert might be the ideal place to grow algae as long as enough water and the proper nutrients can be secured. Such cultivation is practiced in several areas of the world, including the United States, Australia, New Zealand, Israel, China, and parts of Europe, mostly using otherwise undesirable land and saline water or brackish groundwater.

GROWING OIL

Algae need not be grown in open ponds. Photobioreactors are another option for large-scale cultivation. These containers come in many shapes and sizes, including arrays of clear tubes, flat panels sandwiching a thin layer of growth medium, or plastic bags, which can be arrayed vertically [above], laid out horizontally along the ground, or suspended in cooling water. Photobioreactors can solve some of the problems of open ponds, including reducing the loss of water to evaporation and the growth of competitors (algal "weeds"), predators, or pathogens that can kill the crop. But using closed bioreactors adds greatly to the cost of producing algae.

Algae can also grow in large tanks called fermentors, similar to the stainless steel tanks used to produce ethanol. But for algae you need to add sugars, because the steel walls of the tanks block light, preventing photosynthesis. As a result, algae grown in fermentors do not produce their own sugars and do not capture CO_2, giving such biofuels the same disadvantages as corn ethanol.

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But algae have another neat attribute. As we mentioned, these organisms take up carbon dioxide, and they can do that much more readily when it's highly concentrated, such as in the flue gases from a power plant. Using emissions to grow algae can thus cut down on the release of this worrisome greenhouse gas while producing the oils that are so sorely needed for biodiesel. After the oils have been extracted, the remaining residue can be burned to generate heat and power, or it can be turned into animal feed or nutritional supplements, such as omega-3 fatty acids and antioxidants. Not bad for simple pond scum.

Given this rosy picture, you'd be right to wonder why algal biofuels haven't already taken off. It's not as though people haven't been working on the idea for a long time. One early research project, begun in 1978, was the U.S. Department of Energy's Aquatic Species Program at the Solar Energy Research Institute, which later became the National Renewable Energy Laboratory. During this 18-year effort, the Department of Energy spent about US $25 million exploring virtually all aspects of algal biofuels. Researchers screened more than 3000 strains of algae for robustness and the ability to produce oil. These investigators eventually culled their collection to the 300 most promising species. Unfortunately, only a fraction of those cultures survived, necessitating our recent trips back into the field.

During the later years of the Aquatic Species Program, molecular biologists isolated key enzymes in algae and attempted to genetically modify some of them to produce more oil. Other researchers worked on cultivation techniques, constructing what they dubbed the Outdoor Test Facility, in Roswell, N.M., which had two shallow ponds, each 1000 square meters in size. There, the growth rate of the algae was sufficient to produce more than 9000 L of oil per hectare—very heartening news. Less heartening, though, was the observation that faster-growing wild strains with lower oil concentrations often ended up outcompeting the species being cultivated.

It also quickly became clear that the process the researchers were using to turn the algae into fuel wouldn't be cost effective. As expensive as gasoline and diesel seem at the pump, they cost less than almost any liquid you can buy at the store. So to compete with petroleum, every step in the conversion of algae to fuel has to be done very cheaply.

Take the process of dewatering—that is, harvesting the algal cells from the suspension they're growing in. It may look like pea soup, but that suspension consists mostly of water, with perhaps only 1 gram of algae in each liter. The technology of dewatering has improved, and the cost has come down since the Aquatic Species Program ended, but not nearly enough. Other steps in the conversion remain pricey, too. Recent estimates of wholesale costs of algae-derived biofuel fall between $10 and $35 per gallon ($3 to $9 per liter)—much too expensive to compete with petroleum-based fuels or even today's vegetable-based biofuels.

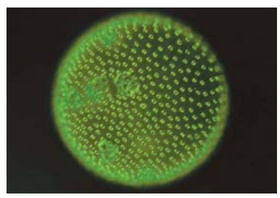
RECENT ADVANCES in technology, however, might soon change this rather gloomy economic picture. For example, we can now grow thousands of cultures simultaneously at the microliter scale using advanced liquid-handling devices and robotics. Instruments can isolate single oil-filled cells from their cultures based on how the cells fluoresce. With our improved understanding of flow dynamics, we can engineer ponds and bioreactors that require the least amount of energy to mix. And new polymers that are both stronger and cheaper can withstand months of punishing sunlight, enabling more affordable photobioreactors. The technical challenges should not be underestimated, but our projections suggest that in the next 10 years or so algal biofuels will be able to compete economically with crude oil costing between $75 and $100 per barrel.

What makes us most optimistic is the renewed financial support for developing this technology. The U.S. Defense Advanced Research Projects Agency was among the first to begin funding research groups to work on the cost-effective conversion of algal oils to jet fuel. The Air Force Office of Scientific Research also issued a number of grants to academic and national labs to carry out such research. And the American Recovery and Reinvestment Act is providing $50 million over three years to a consortium of national, academic, and industrial laboratories, called the National Alliance for Advanced Biofuels and Bioproducts, to develop algae-based biofuels.

Private investment is substantial, too. A few start-ups stand out in this regard. In the past year, Algenol alone has raised more than $900 million from private investors. And in the same period, Aurora Algae, Sapphire Energy, Solazyme, and Solix Biofuels have each raised in excess of $10 million. Although their products are unlikely to be able to compete with conventional fuels anytime soon, the Defense Energy Support Center recently announced that it is prepared to buy more than 2.65 million L of algal biofuels at the cost of production for use in ships and jets. This guaranteed market should provide near-term revenue for such companies, allowing them to improve their processes and reduce costs.

We are confident that we've reached a sort of tipping point and that we'll see algal fuel produced in larger quantities in the next few years. But before that happens, regulators will need to explore the environmental impact of scaling up algae production. We and others will have to evaluate the carbon footprint of these operations, as well as their water and nutrient demands. Another crucial question concerns what ecosystem changes might result from modifications to the land, the evaporation of huge amounts of water, and the disposal of leftover salty brines. Lastly, the cultivation of nonnative algal species presents an unknown risk to our aquatic environments. Government agencies will need to weigh the potential benefits of factors such as adding jobs in rural areas and energy security against any environmental consequences.

Clearly, many obstacles still stand in the way of widespread commercialization, but so far none of these issues strikes us as insurmountable. To our eyes, anyway, the future of these little green cells looks positively golden. ❑



MICHAEL ABBEY/PHOTO RESEARCHERS

ALGAE'S ENTREPRENEURS

A quick survey of algae start-ups serves as a handy guide to the biggest hurdles facing the industry.

To avoid issues such as light limitation and culture stability, Solazyme works on growing algal strains in the dark in large vats, converting sugars fed to them into oil or hydrocarbons.

Algenol uses an engineered strain of blue-green algae, better known as cyanobacteria, which uses photosynthesis to convert CO_2 into sugars and then ferment those sugars into ethanol, which the cells then secrete. This procedure eliminates the need to harvest and dry the algae and then extract the oils.

Both Aurora and Sapphire are developing improved species of algae for open-pond cultivation, while Solix focuses on the engineering of closed photobioreactors.

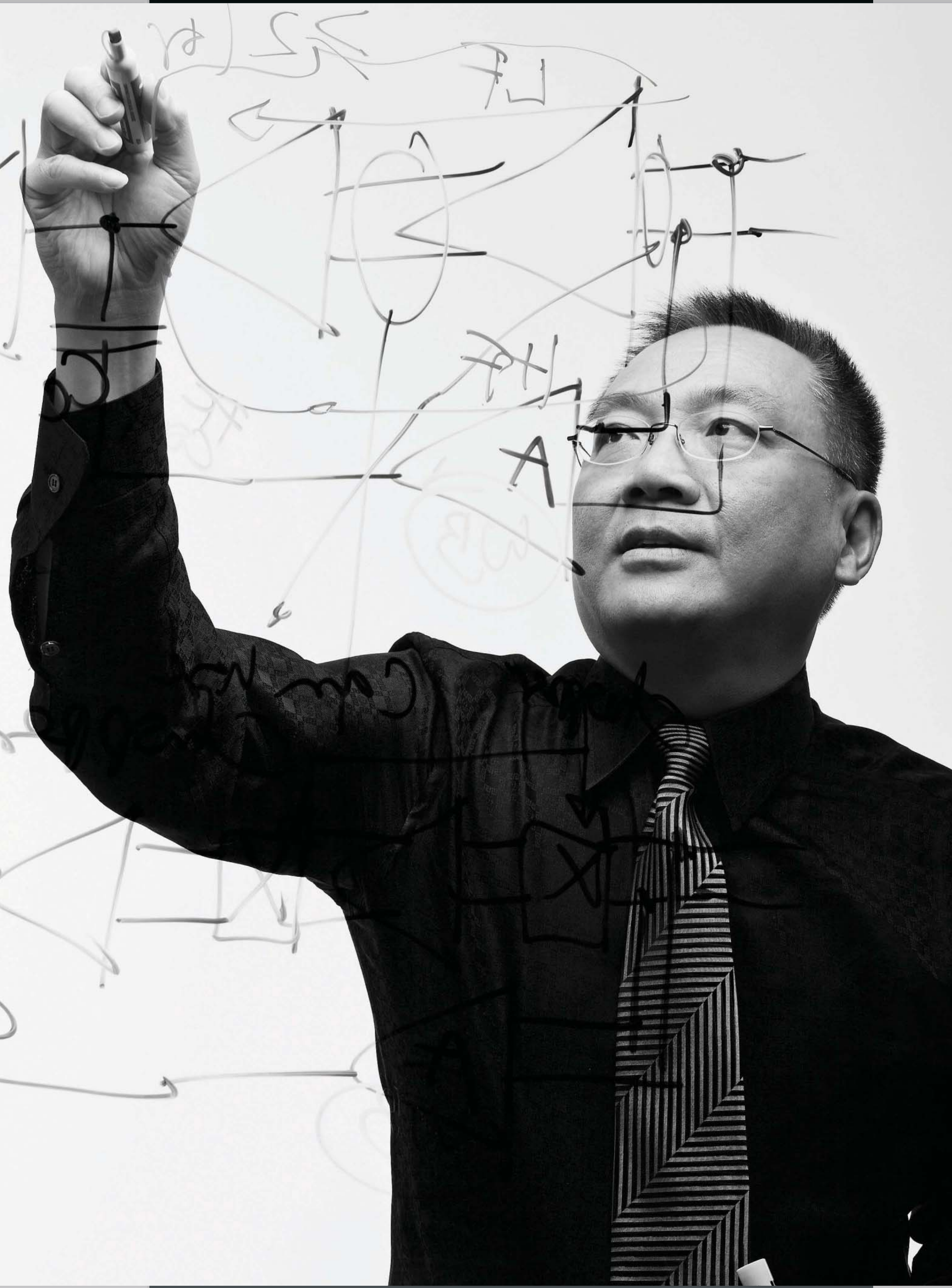
MARVELL INSIDE

Open up today's mobile electronic devices and you'll likely see the imprint of Sehat Sutardja, the beating heart of Marvell

By TEKLA S. PERRY

LOOK INSIDE an e-reader, game console, Blu-ray player, TV, or smartphone and odds are you'll find a cluster of chips designed by Marvell, a 15-year-old Silicon Valley firm. Marvell crafts the CPU as well as the wireless transmitters and receivers, the digital signal processors, the video processors, and even the power management system. Its chips will likely appear in the wave of Android tablets expected to hit the market soon. And the One Laptop per Child organization just announced that its next generation of low-cost computers—the first to finally get below US $100—will rely on Marvell electronics as well.

GABRIELA HASBUN



The reason for Marvell's ubiquity?

Today's consumer electronics, regardless of their functions or users, are designed with one thing in common: high performance at low power. In that arena, Marvell is unrivaled. And that's translating to financial success. The Motley Fool gave a raving buy recommendation for Marvell stock in late August, pointing out that Marvell is at the "forefront of several powerful trends sweeping through the information technology industry like wildfire" and is not only riding those trends but also "taking market share from competitors."

But Marvell and its quietly intense founder and CEO, Sehat Sutardja, aren't exactly household names. That doesn't particularly bother Sutardja. If he's looking for affirmation of his enormous success, he need only consider the company's explosive growth, its lineup of innovative, in-demand products, its more than 5000 employees, its R&D and design centers in Canada, China, France, Germany, India, Israel, Italy, Japan, the Netherlands, Silicon Valley, South Korea, Singapore, Spain, Switzerland, and Taiwan, and its $3 billion in annual revenues. If Sutardja doesn't capture media attention like, say, Apple's Steve Jobs, well, he's okay with that.

But just as Jobs sets the vision for Apple, Sutardja pours his personality and passions into Marvell. And unlike Jobs, who was not the technological powerhouse of the two Steves that founded Apple, Sehat is an engineer to the core, a genius at circuit design for whom electronics is not only a vocation but also his only recreation.

So far, Sutardja, an IEEE Fellow, and his Marvell cofounders—his wife, Weili Dai, and his brother, Pantas Sutardja—have successfully managed the business as well as the technology. But in a sense it's been an off-Broadway production—it may be packing the house night after night, but it hasn't gotten a lot of media attention. Today, however, the company is trying to make the transition to a bigger stage, and Sutardja increasingly finds himself in the spotlight.

BORN IN INDONESIA to Chinese parents in 1961, Sutardja had a fairly ordinary childhood for his time and place. "If it rains," he recalls, "you go out and dance in the rain. You see butterflies, you chase the butterflies. You see dragonflies, you chase the dragonflies. It was a simple life."

And then he discovered engineering, and his butterfly-chasing days were over.

It happened on a visit to Singapore, where his younger brother Pantas was living with their grandparents. Sehat was in sixth grade, Pantas in fifth. As boys will do, Sehat started poking through his brother's possessions, including some DIY books and magazines geared toward electronics hobbyists. He spotted a great project: building a Van de Graaff generator. He and Pantas bought some copper wire at a surplus store and managed to rig together a crude but functional machine.

Back in Indonesia after vacation, Sehat couldn't stop thinking about the generator. He began constructing a miniature version that he could use to shock people as a prank, scavenging gear from his parents' auto parts store. The device worked, but its copper contact points oxidized so fast he had to sand them down every few minutes.

After a little research at the local bookstore, he discovered that transistors could replace mechanical switches. "Okay," he remembers thinking, "I'll have to learn how to use transistors." Sehat found a radio repair shop where he could do just that. Within a year he received his radio repair license, a document he seems more proud of than his college diploma. (His wife carries it for him in her purse in case he wants to show it to people. Which he often does.)

Sehat continued to tinker with circuits, and he also kept abreast of new developments in the field. The most interesting news always seemed to be coming from the likes of Fairchild, National, Motorola, and Texas Instruments. His next step was obvious: He had to go to the United States.

One of the few people he knew in the States was the brother of a friend, who happened to be studying at the University of San Francisco, a private school. So Sehat applied there. He arrived in the summer of 1980, only to discover that the math and physics classes were repeats of what he'd already taken in high school. The college didn't even have an electrical engineering program, he was crushed to learn.

Another Indonesian friend was enrolled at Iowa State University, which did have an engineering school. Sehat transferred and then spent the next two and a half years racing through the curriculum, typically taking two extra classes each semester. During the summers of 1982 and 1983 he worked for IBM in Kingston, N.Y.

By the time he graduated in 1983, he knew a little more about U.S. universities and applied to the University of

FAMILY MATTERS: Marvell's founders are actually one happy family. Sehat Sutardja [center] is the CEO; his wife, Weili Dai [left], and his brother, Pantas Sutardja, are also Marvell executives. The company reflects their passions; for example, the basketball court, pictured above, has special meaning for Dai, who played on an elite team as a child in Shanghai. PHOTO: GABRIELA HASBUN

California, Berkeley, for a graduate program renowned in the analog circuit design community. His brother Pantas was also there, working on his undergraduate EE degree.

Sehat studied low-power, low-impedance amplifiers as part of a research program targeting the Integrated Services Digital Network (ISDN), which at the time was considered the next big thing in communications. He moved on to designing analog-to-digital converters for ISDN phones, again focusing on low-power devices because these phones would be powered through the phone network, not the electrical grid.

Even as a grad student Sehat made an impression, says Stephen Lewis, his office mate at Berkeley and now a professor at the University of California, Davis. "He's a perfectionist. For example, when we were students, we were building pipeline A-to-D converters. The traditional way of setting the gain of a switched-capacitor amplifier to two used two capacitors, one twice as big as the other. He figured out a way to do it with two identical capacitors, increasing the amplifier speed by increasing its feedback factor. We had a solution that worked, but he kept digging until he found a way to do it better."

Lewis recalls that Sehat revised his layouts over and over, trying to eliminate any errors that would prevent the capacitors from matching exactly. These errors wouldn't have caused the device to fail; they would have only reduced the performance slightly. Still, Sehat wouldn't let them go. It's that same doggedness and attention to detail, Lewis believes, that makes Sehat and his company so successful today.

OUTSIDE THE LAB and the classroom, Sehat didn't do much; if it wasn't related to engineering, he wasn't interested. He managed to meet the woman who became his wife anyway.

One day, Sehat and a friend visiting from out of town were getting on the elevator in the electrical engineering and computer science building. Already in the elevator was an undergrad named Weili Dai. Sehat's friend began chatting her up. Sehat said nothing, embarrassed by his friend's corny lines.

Dai wasn't terribly impressed either. "There were two guys," she says, "and one of the guys says, 'Hi, are you a computer science major?' I was like, 'Wow, this guy knows this building is computer science. Wow.' "

But she did remember the quiet guy, and he remembered her, enough to say hello when they ran into each other several weeks later. After a few more encounters, he invited her to study with him in his office. Neither liked bars, so for them this was a perfect date. By the time Sehat got his Ph.D. in 1988, the two were so serious that Sehat was unwilling to consider jobs outside the Bay Area.

He joined Micro Linear Corp., a fabless semiconductor company in San Jose. He worked on D-to-A converters and other chips for disk drives. But instead of using building blocks from the company's design library, as was expected, he designed every circuit from scratch, reducing the latency of the disk controller from 100 nanoseconds to just 10. His superiors doubted the designs would work, though, so Sehat found himself lobbying for his approach all the way up to the vice president of engineering, who eventually agreed to use the new circuits. They worked, and the controller ended up in Hewlett-Packard drives used by a wide variety of manufacturers.

Looking for more challenges, Sehat joined Integrated Information Technology in Santa Clara, Calif., where he designed circuits for digital video compression and decompression. The technology was novel but ended up in a dog of a product: the AT&T VideoPhone. It was time to move on, but Sehat didn't know what to do next. His wife did, though.

"Engineers always talk about technology," she says. "They figure out a way to design something, to make a product better." But Sehat was a little different, she says, for he also thought about how the product would fare in the market. When they were still in school, she had told him, "After your Ph.D., you get some real-world experience. But whenever you're ready, we're going to do a company of our own."

In 1995, he was ready. He asked his brother Pantas, who had recently left IBM's Almaden Research Center, to join the start-up. With some savings and money from Dai's parents, on 10 February 1995 the three incorporated Marvell—so named because they were planning to do marvelous things, and, they had noticed, a lot of successful companies' names ended with "el" or "ell," like Intel, Novell, and Nortel.

BY DESIGN: Sehat Sutardja runs Marvell from a Silicon Valley campus that once housed 3Com. Inside and out, the buildings are gems of clean design, with many of the furnishings selected according to feng shui principles. PHOTO: GABRIELA HASBUN

SEHAT ALREADY HAD plans for the first product: a better read channel for disk drives. It sounds incredibly specialized and it is, but it's also one of the drive's key components. The read channel takes the analog signal coming from the magnetic head as it scans the disk, converts the noisy signal to digital, and puts that information out onto the bus that will take it to the computer. Existing read channels used a bipolar transistor on a complementary-metal-oxide semiconductor substrate (BiCMOS), but Sehat planned to use only CMOS. That way the channels could be manufactured by a chip foundry like the Taiwan Semiconductor Manufacturing Co., so Marvell wouldn't have to build its own fab. Using CMOS also meant that the device would consume less power. This would, however, present an engineering challenge: Existing CMOS read-channel designs were much slower than BiCMOS.

However, Pantas had worked on hard drive technology at IBM, and Sehat had experience in mixed signal chips—those that require combining analog and digital technology. Between them they thought they could design a read channel that could handle 180 megabits per second, putting them well ahead of existing 100 Mb/s BiCMOS products and, they projected, equal to the next generation of BiCMOS chips that would be coming from the established companies.

The traditional method used in read channels involved looking for peaks in the analog waves to define the digital bits. But as the bit density increased, it got harder to distinguish the peaks. The Sutardja brothers instead took multiple samples of the signal and then used digital signal processing circuitry to sort them out. This approach reduced noise and also sped up the bit rate.

"The Marvell founders would come to conferences, say they could do it in CMOS, but wouldn't reveal their secret sauce," says Stephan Ohr, an analyst with Gartner who covered analog devices at the time. "Years later we found out that they simply threw more gates at the problem, creating elaborate filtering circuits." The real breakthrough of this approach, says Ohr, was that it was scalable—they could make faster and faster devices simply by following the CMOS technology curve—and the approach could be transferred to other products.

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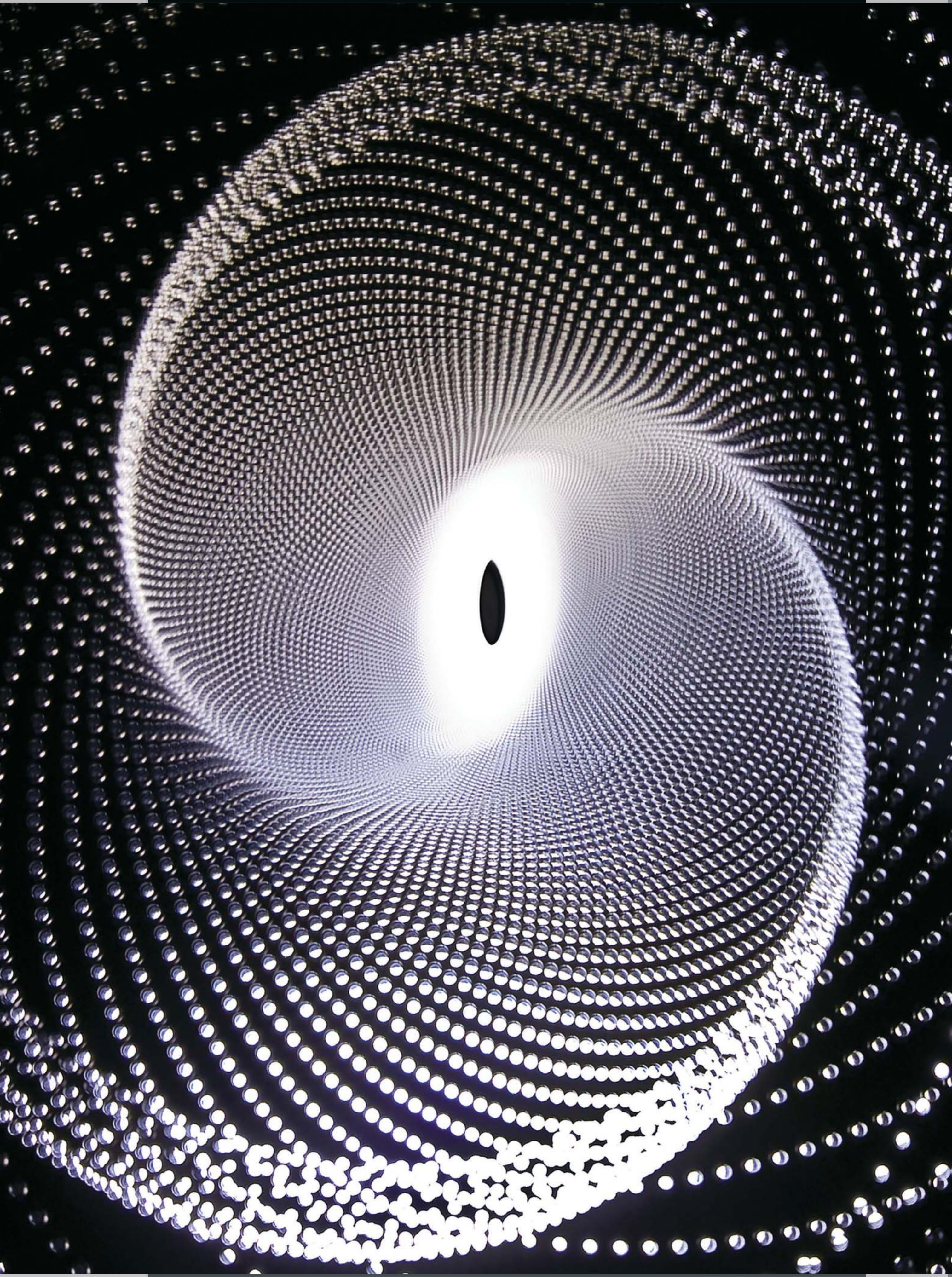


a SPIN *to* REMEMBER

Superdense memories based on the bizarre property of electron spin could replace all other forms of data storage

By SALAH M. BEDAIR, JOHN M. ZAVADA & NADIA EL-MASRY

ELECTRONIC TECHNOLOGY has evolved enormously over the past century, but in the most fundamental way it has not changed at all. From the earliest vacuum tube amplifiers to today's billion-transistor processors, all electronic devices work by moving electrical charges around. The countless discoveries and innovations that made the digital age what it is today were all made possible by our ever-improving mastery over electrons.

But those electrons are now beginning to rebel.

DAVID H. HULL

HOW *a* SPIN MEMORY WORKS

The authors discovered a magnetic semiconductor material that can store spin orientations at room temperature. This property could be used to build a spintronic memory

As we build transistors and other components with nanoscale dimensions, processors and memories are becoming so dense that even their infinitesimal individual currents are combining to produce scorching heat. Furthermore, quantum effects that were negligible before are now so pronounced that they're threatening to render circuits inoperable. The upshot is that we're fast approaching the point when moving charge is not going to be enough to keep Moore's Law chugging along.

In anticipation of that day, researchers all over the world are already working on a promising alternative. We have set our sights on a different property of electrons, which we hope to exploit for storing and processing data. This property is spin.

Spin is a fundamental yet elusive quantum attribute of electrons and other subatomic particles. It is often regarded as a bizarre form of nanoworld angular momentum, and it underlies permanent magnetism. What makes spin interesting for electronics is that it can assume one of two states relative to a magnetic field, typically referred to as *up* and *down*, and you can use these two states to represent the two values of binary logic—to store a bit, in other words.

The development of spin-based electronics, or spintronics, promises to open up remarkable possibilities. In principle, manipulating spin is faster and requires far less energy than pushing charge around, and it can take place at smaller scales. The holy grail in the field is a spin transistor. Chips built out of spin transistors would be faster and more powerful than traditional ones and, farther down the road, may feature such new and remarkable properties as the ability to change their logic functions on the fly.

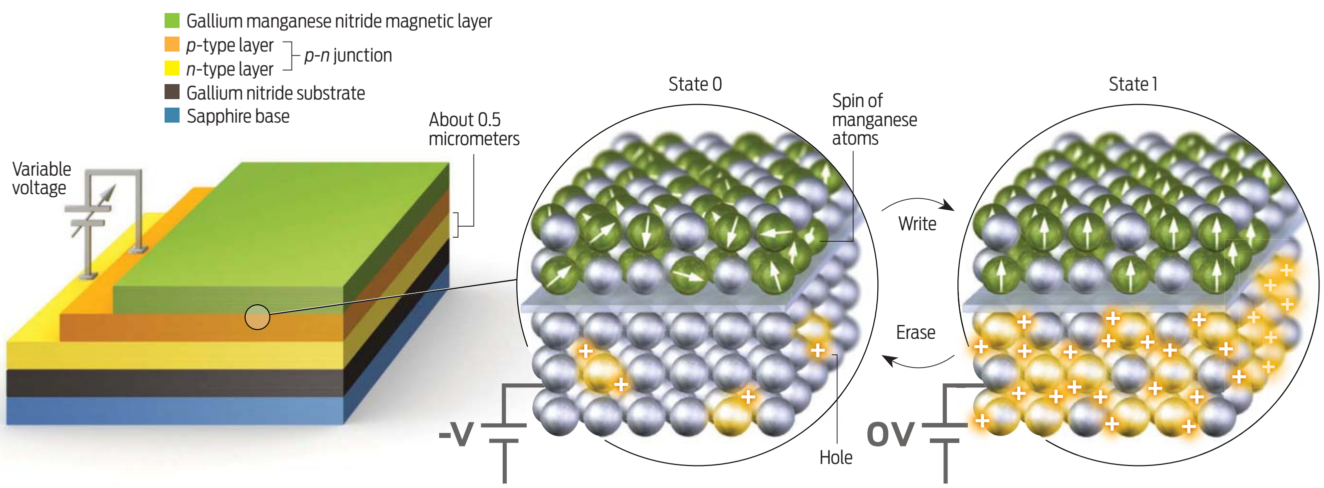
We're still decades away from being able to build such a thing. But chips that exploit spin in a more modest way are already available. At least one company, Everspin Technologies, of Chandler, Ariz., is now selling magnetoresistive random access memory, or MRAM, a kind of spintronic memory. And many others—including Freescale, Honeywell, IBM, Infineon, Micron, and Toshiba, as well as start-ups and university research groups—are busy investigating MRAM technology.

The reason for all this interest is clear. Today's computers often use four kinds of storage. Dynamic random access memory, or DRAM, has high density but needs to be constantly refreshed and consumes lots of power. Static random access memory, or SRAM, used in caches, is fast to read and write but takes up considerable space on a chip. Flash, unlike SRAM and DRAM, is nonvolatile but is quite slow to write to. And then there are hard disk drives; these have high density but rely on moving parts, which impose size and speed limitations. MRAM is attractive because it could, in principle, replace all other kinds of memory.

Rather than representing a bit as charge in a capacitor or as the state of an interconnected set of transistors, MRAM stores data using the spin of electrons in a ferromagnetic substance, which is to say it stores data by creating a magnetic alignment in one direction or the other. In a tiny region of that material, *spin up* means 0, and *spin down* means 1. Proponents say that as MRAM improves, it could combine all the advantages of SRAM, DRAM, flash, and hard disks—with none of their shortcomings. It would be a compact, speedy, low-power, and nonvolatile "universal memory." With MRAM, a computer wouldn't have to juggle data between main memory, cache, and disk; instead, it could load all data into its working memory. This capability would make possible instant-on systems and maybe even change the way we think about computer architecture.

At the moment, however, MRAM suffers from two problems: The density of bits is low, and the cost of chips is high. The early MRAM designs needed lots of current to change a 1 to a 0 or vice versa. This requirement prevented their further miniaturization. Improved designs might overcome that hurdle using novel techniques and materials, but they would operate at only liquid-nitrogen temperatures. This is not going to work for your iPod.

This problem—the need for cryogenic temperatures to reduce the write current of MRAM—has been the focus of our work at North Carolina State University. It's a major challenge, but we've recently made a significant breakthrough: We demonstrated a device that shows potential as an MRAM memory cell. It can be written to using conventional voltage levels and almost no current at all. The key is a material called gallium manganese nitride, a semiconductor whose magnetic properties we can manipulate electrically. And here's the best part: It works at room temperature.



1. ERASE

When a negative voltage is applied to the *p-n* junction, the *p*-type layer is depleted of holes, causing the spin of the manganese atoms in the magnetic layer to become disoriented. You could use this state to store the bit value 0, or erase your memory cell.

2. WRITE

When you remove the voltage, the concentration of holes in the *p*-type layer increases. A quantum mechanical interaction between the holes and the manganese atoms causes the atoms' spins to align. You could use this state to write the bit value 1.

3. READ

The researchers plan to equip each device with a tiny magnetic sensor, similar to a read head of a hard drive but etched as layers in the semiconductor. This supersensitive sensor would detect whether magnetization is present and determine the device's state.

EMILY COOPER

SPINTRONIC TECHNOLOGY is already in your computer, at least in a primordial incarnation. Modern hard disk drives have a read head that relies on an effect known as giant magnetoresistance, or GMR, which was discovered by French and German researchers in the late 1980s. Basically, when the spins of electrons in the read head point in the same direction as those creating the small magnetic domains on the disk, the head's electrical resistance decreases. When the spins are in opposite directions, the resistance increases slightly. More recently, engineers have developed even better read heads that rely on tunnel magnetoresistance, a kind of enhanced GMR. It is this ability to sense very feeble magnetic fields that has allowed hard-disk makers to keep doubling the capacities of hard-disk drives on a schedule that's even outpaced Moore's Law.

Many advances in spintronics resulted from two big research programs that the U.S. Defense Advanced Research Projects Agency, or DARPA, funded in the 1990s. The first one produced the earliest MRAM prototypes. These devices used memory cells consisting of magnetic tunnel junctions: two layers of a ferromagnetic material like iron separated by an extremely thin, nonconductive barrier of magnesium oxide. When the spins of the electrons in the two ferromagnetic layers point in the same direction—in other words, when their magnetizations are aligned—the electrical resistance across the junction decreases; when the spins point in different directions, the junction becomes more resistant to current. The prototypes used this change in resistance to sense whether a 1 or a 0 was stored.

Some MRAM chips built at the time contained millions of memory cells, each with dimensions of about 150 nanometers, an impressive achievement back then. But the researchers soon discovered that going below 100 nm was not going to be easy. The problem had to do with the method they used to change bits, which was to drive currents through electrodes connected to each memory cell, creating a magnetic field that oriented the spin state of the cell. This method required currents that proved quite high, draining lots of power. Worse still, the magnetic fields affected not only the desired bit but also others nearby, resulting in errors.

Researchers are now trying to improve on this scheme. The most promising alternative is called spin-torque-transfer, or STT. The idea is to send electrons through a magnetic layer of cobalt, which tends to orient their spins in the same direction. The resulting spin-polarized current then flows into another layer of cobalt material. There, by virtue of one of the many mysteries of quantum mechanics, the incoming spin-polarized electrons transfer their spin orientation to the electrons on this second layer, thus magnetizing it.

So instead of writing a bit by applying a magnetic field, as early MRAM designs do, STT uses a spin-polarized current of electrons. To be commercially viable, the magnetic region where the bit is stored has to be quite small, of course. Researchers believe STT should work down to at least 65 nm and possibly even smaller dimensions. Last year, engineers at Hitachi and Tohoku University demonstrated a prototype capable of storing 32 megabits this way. But that's not all that much. For comparison, a modern DRAM chip can hold 128 times that amount. And though in theory such memories should require very small currents to change a bit, in practice the currents are still too high for most commercial applications.

For such reasons, our group and several others are betting on a different approach entirely. Forget about current-induced magnetic fields and spin-polarized currents. Instead, find a

MEMORY *vs.* MEMORY

Future MRAM chips could combine all the advantages of existing memories with none of their shortcomings

HARD DRIVE

\+ High density; very low cost per byte stored

– Moderate read and write speeds; bulky moving parts

SRAM

\+ Superfast read and write speeds; low power

– Large memory cells take up considerable space; volatile

storage medium with a permanent magnetism that you can control by applying small voltages. These materials exist: They are called dilute magnetic semiconductors. As their name suggests, they are semiconductors that are also somewhat magnetic. Their magnetism stems from certain metal atoms added in a process similar to doping. What's interesting about these materials is that the presence of charge carriers—electrons and holes (vacancies left when electrons are missing in places where they'd normally be found)—can alter their magnetic properties.

As part of DARPA's second MRAM-research program, initiated in 1999, researchers investigated several dilute magnetic semiconductors, in particular gallium manganese arsenide and indium manganese arsenide. Both proved to be good candidates. There was just one problem: A material is magnetic only up to a given temperature—in this case about 200 kelvin, or –73 °C. That's colder than nighttime in most parts of Mars! Go above that level—known as the Curie temperature—and atomic vibrations cause the spins to lose the orderly arrangement that makes the material a permanent magnet. If this was a memory chip, you'd lose your data.

OUR FIRST breakthrough came in December 2001. At the time we were seeking a dilute magnetic semiconductor with a Curie temperature higher than room temperature. Following what were then just theoretical results, we decided to add some manganese to gallium nitride—about two to five manganese atoms for every 100 gallium atoms—to see what would happen.

The resulting gallium manganese nitride turned out to be very promising. When you apply a magnetic field to this substance, it becomes permanently magnetized. That is to say, when you remove the field, the magnetization doesn't go away, so it can be used to store data.

Our next major step, which we reported last year, was the ability to manipulate the magnetic properties of this semiconductor *electrically*. We started with ordinary gallium nitride. We then applied a thin layer of gallium nitride that contained a little added silicon, a dopant that donates electrons, thereby creating an *n*-type semiconductor. (The *n* stands for "negative," reflecting the addition of negative charges—electrons.) Next we added another gallium nitride layer, this time using magnesium as a dopant to remove electrons from the lattice of atoms, creating a *p*-type layer (*p* stands for positive). Finally, we deposited a very thin veneer of gallium manganese nitride on top of all this.

The junction between *n*- and *p*-type layers was key. That's because you can control the concentration of electrons and holes around a *p-n* junction by applying a voltage across it. And that's exactly what we did next. We connected electrodes to the *n*-type and *p*-type layers and applied a few volts. Then we turned our attention to the upper layer of gallium manganese nitride, using very sensitive instruments to measure extremely weak magnetic fields within it.

When we applied a voltage of –5 volts across the *p-n* junction, the magnetization of that upper layer approached 0. When we removed the voltage, the magnetization shot up. It was a faint magnetization to be sure, but enough for storing bits.

Now, you might ask, why does the voltage on a *p-n* junction change the magnetization nearby? To understand that, you have to first think about what goes on at a *p-n* junction when no voltage is applied across it (or break out the textbook you used in your introductory electrical engineering class in college).

First, recall that the *n*-type material has an abundance of negative charge carriers—electrons—which are free to move around. In the *p*-type material, the charge carriers are holes, spots in the atomic lattice that are lacking in electrons. When you put one of these materials against the other, electrons move from the *n*-type material into the *p*-type material, filling what were vacancies, or holes. So you end up depleting both types of charge carriers in the vicinity of the *p-n* junction, which is called, naturally enough, the depletion zone. This process is self-limiting, though. The loss of electrons from the *n*-type material leaves it with a positive charge, while the gain of electrons in the *p*-type material makes it negatively charged. This sets up an electric field that opposes the migration of any more electrons across the junction.

As with an ordinary diode, if the *p*-type material is made positive with respect to the *n*-type material, the applied voltage can overcome this electric field, sending

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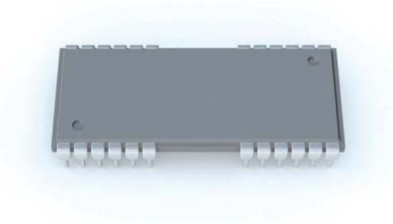
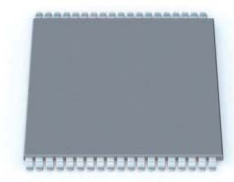


DRAM

+ High density; low cost; fast read and write speeds

– Volatile; constant refreshing of data drains power



FLASH

+ Nonvolatile; high density; fast read speed

– Power consuming; write operation is slow and has limited endurance

MRAM

+ Nonvolatile; high density; fast read and write speeds; low power; unlimited write endurance

holes and electrons racing toward the junction, reducing the thickness of the depletion zone. A voltage of the opposite sense boosts the internal electric field and makes the depletion zone wider.

What makes our device different is that the *p*-type material is very thin and is positioned right next to the magnetic layer of gallium manganese nitride. So by adjusting the voltage across the *p-n* junction, we can control the concentration of holes in the *p*-type layer at the interface with this magnetic material. That's important because the pervasive quantum-mechanical weirdness that arises at these scales allows these holes to interact with the manganese atoms sitting a few hundred angstroms away. Though there is a debate in our community, we believe the quantum phenomenon at work here is what is known as carrier-mediated ferromagnetism. It's as though the holes told some of the electrons around these manganese atoms to align their spins and start acting like a refrigerator magnet.

By the same token, when we apply a negative voltage across the *p-n* junction, we increase the width of the depletion zone enough to diminish the number of holes at the interface with the magnetic material. That then allows the spins of the electrons in these manganese atoms to revert to random directions. The device's magnetization vanishes.

This was the first demonstration that ferromagnetism can be controlled by applying voltages to a *p-n* junction without relying on ultracold temperatures. We hope this discovery will help turn spintronics into a hot topic again, so to speak.

THE INITIAL prototype we built can't be readily used as a memory cell. First, we need a major improvement on our design. The problem is that, although you can control the magnetization of our device using voltages, when you remove the voltages the magnetization returns to a baseline level. For a device to work as a memory, you need to be able to switch back and forth between two stable states.

One idea we're currently considering is making our device's layers even thinner and adding a barrier of nonmagnetic material, also very thin, between the *p*-type and magnetic layers. We're hoping that by applying a voltage across these two layers, we can change the concentration of holes in the *p*-type region and also force some of the holes to cross the newly added barrier and migrate into the magnetic section of the device. The barrier would then play a key role: After the voltage is removed, it would prevent the holes from migrating back to the *p*-type region, thereby maintaining the magnetization of the device even when it's not powered on.

Now, if you take the device in this magnetized state and apply a voltage in the reverse direction, the holes would cross the barrier back into the *p*-type region. The holes would remain trapped there, and the magnetization would disappear. This approach would provide the two stable states we need to use the device as a memory.

If this design is successful, the next step would be miniaturization. In fact, our initial prototype is rather big—each memory cell is about the size of a fingernail. To build smaller memory cells, we're investigating two approaches: One is using conventional photolithography, which we believe could lead to cells about 50 nm in size. Another idea is to grow the cell structures as nanowires, which we speculate might shrink them as small as 20 nm.

Such reduced dimensions would lead to another challenge: reading the bits in these tiny cells. As we proceed to nanoscale dimensions, the strengths of the magnetic fields will become even smaller. How to detect them remains an open question. We might have to equip each memory cell with a tiny magnetic sensor, similar to a read head of a hard drive but etched as a series of layers in the semiconductor. It's a possibility, but we don't know how it will perform and whether the resulting device would be economically viable.

Finally, another issue crucial to the commercial success of our MRAM proposal is its compatibility with conventional semiconductor technology. In theory, because MRAM would be programmed and interrogated electrically, it could be integrated with ordinary chipmaking processes. Then the MRAM devices could be made part of multifunctional integrated circuits, which would be able to perform all the processing, storage, and communication tasks that today require separate chips.

Clearly, overcoming these hurdles will take a lot of work. But if all goes well, our electrically controlled magnetic material may help engineers to ensure their continued mastery over electrons—and their spins. ❑


10 Light Set

BRIGHT LIGHTS, BIG CITY

A little shop in New York City celebrates the glory of the lightbulb in the waning days of incandescence

BY ARIEL BLEICHER

PHOTOGRAPHY BY RANDI SILBERMAN KLETT

ILLUMINATED: In the window display of David Brooks's third-generation lighting store, strips of ice-blue LEDs flash beside lantern lights and amber-toned carbon bulbs. The LEDs are the same kind of lights that hang from the maple trees across the street from Macy's famous Manhattan department store around Christmastime. "The light drips from one bulb to the next in a random pattern," simulating rain or falling snow, Brooks explains. "It just looks neat."

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BELOVED BULBS: Star bulbs [bottom left] are a big hit at Just Bulbs. "They're very popular with old-fashioned Sputnik fixtures—you know, the ones that look like the old satellites the Soviets flew into space in the 1960s, with lots of little arms coming out of a silver globe? They look really special with our little stars on the ends," Brooks says. Also popular are flickering electric chandelier lights [bottom center], which Brooks installed in Gracie Mansion, the Metropolitan Museum of Art, and the now-shuttered Tavern on the Green. His favorites are the antique carbon bulbs [bottom right and top]. They're reproductions of 1890 and 1910 bulbs, with elaborately coiled amber filaments and names like "Squirrel Cage" and "Pig's Tail."

"You have Sylvanias!" David Brooks hoots when a customer plucks from a briefcase two slender glass tubes, long and clouded like fluorescent lamps. They're incandescent Lumiline bulbs, Brooks says, "very popular in the 1930s." He appraises them fondly, like a wine connoisseur regarding a bottle of 1961 Lafite-Rothschild. "Sylvania hasn't made them in maybe 20 years."

A trim, angular man with a thick salt-and-pepper goatee and a brisk stride, Brooks is the proprietor of Just Bulbs, the brightest bulb shop in New York City. Here inside his shop, the simple 19th-century technology—just a resistive filament encased in an evacuated glass globe—is displayed in all its sundry dazzling forms. There are rainbow-striped disco bulbs, frosted flame-tipped holiday bulbs, flickering chandelier bulbs, and full-spectrum-daylight bulbs. White vanity bulbs crowd the shelves, and funnel-shaped halogens spill out into the aisles. Across the ceiling, Brooks has strung strands of party lights in every theme imaginable—flowers, bumblebees, cowboy hats, New York Yankee-logoed baseballs, and Budweiser beer cans. He's got bulbs for microscopes and vacuum cleaners and slide projectors and refrigerators, bulbs that glow like old gas lamps and ones that purport to make you more virile. In total, Brooks has crammed about 45 000 different types of bulbs into his 93-square-meter shop.

Brooks, formerly a lawyer, has sold lightbulbs for 27 years and has seen a lot of lighting fads come and go. But he hasn't seen anything quite like what's happening now: In 2007, the United States passed a law banning the manufacture of common incandescent lamps—notorious energy wasters—starting with 100-watt bulbs in 2012. "These plain old bulbs, they won't

IN STOCK: David Brooks estimates that his New York City lighting shop carries about 45 000 different types of bulbs—not to mention lighting fixtures, sockets, and other parts.

THE PRICE YOU PAY: Among the most expensive bulbs Brooks sells are obsolete projector bulbs [left and far left], which run US $200 to $300. "Typically they go in old movie cameras, old 8-mm theater projectors, old strobe lights, that sort of thing," Brooks says. "These were all handmade. The glass is handblown, and you can see they've got incredibly elaborate guts."

exist much longer," he remarks as he bags up a two-pack box of frosted Bulbrite Long Life lamps.

Elsewhere, the incandescent phaseout has already begun. In the European Union, for instance, it is illegal (as of September 2009) for shops to buy incandescent lamps of the frosted or 100-W variety. In Australia, shops are prohibited from importing tungsten bulbs, low-voltage halogen bulbs, and most other bulbs that radiate less than about 15 lumens per watt. Cuba is the only country that has altogether purged itself of lighting inefficiency, stopping the import and sale of incandescent bulbs in 2005 and sending social workers to Cubans' homes to replace their old-style lamps with watt-saving compact fluorescent ones.

"What's pretty funny is people hate the fact that lightbulbs are going," Brooks says, though he doesn't personally get nostalgic about them. Already he has begun to stock his store with energy-efficient stand-ins: curly compact fluorescents and light-emitting diodes of all shapes and sizes. But many of his customers aren't as compliant about the switchover. "What they're doing is they're stocking up a lifetime supply," he says. "We just had a lady in Tennessee who used to buy, all the time in her supermarket, soft pink lightbulbs, because they make you look good. Old ladies love pink lightbulbs. But you can barely get them anywhere anymore."

Brooks sold the woman 1000 pink bulbs. "Apparently, she's selling them now to all her neighbors and old lady friends," Brooks speculates. "And when her daughter gets married, she's going to give them to her for a present." Lightbulbs for a wedding present? "It's the perfect present!" he insists.

You might say that bulbs are in Brooks's blood. His grandfather, Augustine Brooks, was a light peddler, selling bulbs door to door throughout Manhattan. Brooks claims that Augustine used to replace the lights in the Empire State Building, one by one, "working his way down from the top." Augustine opened Just Bulbs in 1942, in the middle of World War II, when incandescent lamps, like sugar and silk stockings, were scarce.

And they will soon be again. But you can bet that whatever bulb can be had, Brooks will have it. He keeps a list of antique shops, warehouses, and hardware stores that never bother to clear out old stock. So when he's hunting for a rare bulb, he makes his way down the list, top to bottom, calling numbers in the same manner his grandfather once knocked on doors in the Empire State Building. Recently, he even convinced a Chinese bulb manufacturer to make the tubular Lumilines that every other manufacturer has stopped producing.

"How much to replace these, then?" inquired the owner of the obsolete Sylvania brand bulbs.

"A fortune," Brooks sighed. ❑

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IN THE MOOD: Even the lightbulb business goes through fads. "Last year for Halloween and Christmas, everyone bought blue," Brooks observes. "Right now, we're finding that a lot of people are buying the mood lightbulbs. They're supposed to make you feel a certain way." For instance, he's got a bluish-turquoise one called "Serenity," which is supposed to induce calmness. There's also a variation on yellow that's called "Happy."

FULL SPECTRUM: "Did you know there are 35 different shades of white?" Brooks will ask if he catches you gawking at his spectral display [above]. "And every one of them has a different purpose. We just redid a pizzeria down the street, and the owners were convinced they wanted natural daylight. That kind of light makes diamonds look great. It makes fur look fantastic. It makes pizza look kind of gray. But that's what they bought. Now, it's really good pizza, so I don't care."

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Marvell Inside

Continued from page 40

Pantas defined the architecture, then moved on to simulate the digital circuitry; Sehat focused on the analog aspects of the design. The brothers hired four engineers to help out. By Christmas 1995 they had the first working chips.

Marvell now had a product but no customers. So Dai dialed information and got the number of every disk drive manufacturer she could think of. "Fortunately," she says, "in the storage market you only have about half a dozen guys."

The company sent samples to three drive companies. They all found the chip to be faster and cheaper and lower power—but, Sehat reports, they were reluctant to bet on a start-up.

Eventually, they convinced Seagate Technology to take a chance. Ken Burns, an executive at Seagate, told them that the company's next-generation drive would need a read channel at 240 Mb/s—could Marvell deliver?

Pantas recalls that, even though they had been designing to 180, the chip was already running at close to 240. They told Burns yes. In less than three months the Marvell team hit the 240-Mb/s mark, and Seagate became Marvell's first customer. "That changed everything," Pantas says.

MARVELL NOW HAD an easier time getting its next customers, particularly in the Japanese market, says Sehat. "The Japanese customers cared more about the technology instead of the perceived risk of dealing with a small company." Today, in terms of units sold, Marvell has about 60 percent of the market for hard drive systems-on-a-chip.

"This little start-up, with one product line, put Texas Instruments out of the read-channel business," Ohr says.

Marvell then turned its sights on the Ethernet industry because, as with the disk drive read channel, Ethernet chips extract analog signals from a noisy environment. The company got a jump start in 2000 by acquiring Galileo Technology, a company that built controllers for data networking. Today Marvell is the second largest supplier of Ethernet transceivers and switches.

Next came Wi-Fi. Most Wi-Fi products at that time were cards with an array of components, but Marvell again blew the competition away when it announced single-chip Wi-Fi in 2005. The Wi-Fi market today brings in about 20 percent of Marvell's revenue.

These days, Marvell, along with many of its competitors, is building not just simple processors but what the industry refers to as platforms. That is, it puts together in one package most of the key electronic components for a device. Flint Pulskamp, an analyst with market research firm IDC, says designing platforms rather than single chips makes it easy for the customer and also presents a higher barrier to competition. Marvell now has platforms for smartphones, including Android devices, Wi-Fi networking, and Ethernet communications. Its platforms are also in two of the three top game systems (Sony's and Microsoft's) and a number of e-readers, including the original Kindle. Earlier this year, right after the company introduced a tablet reference design it calls Moby for use in $99 tablet computers, the One Laptop per Child association announced that it would use the Moby design in its XO-3 tablet. Next on Marvell's agenda: LED lighting, which requires a surprising amount of control electronics.

Just as Sehat had done as a teenage tinkerer, a grad student, and a young circuit designer, he's continued to push Marvell's engineers to rethink conventional designs to get a leap in performance. Sehat's Berkeley office mate Lewis believes that's how the company gets the edge on its competition, by making countless little things slightly better. "You put enough of those things together, and you have a product that is significantly better," Lewis says.

IF MARVELL'S ASCENT sounds like the plot of a Disney musical, keep in mind that every good story has its moment of crisis. For the company, that point came in 2008, when the U.S. Securities and Exchange Commission accused the company of backdating stock option grants. The same charge was made against a number of tech companies at that time.

Jeff Palmer, vice president of investor relations for the company, explains it this way: "In the late '90s and 2000, when there was a land rush to hire people, potential employees asked for options at price points in the past. There is nothing illegal about granting stock options below market rate. The issue is if you don't document them in your [SEC] filings. This happened at many, many, many companies. We fought the charge, because we believed that we had done nothing fundamentally wrong, and none of the founders enriched themselves personally."

However, as chief operating officer, Dai was in the hot seat, dealing with issues she wasn't exactly comfortable with. "I'm a software engineer," she says. "I never even took a finance class. Finance, legal, all of those completely make a dark side."

Marvell eventually reached a settlement with the SEC. Without admitting or denying the allegations, it paid \$10 million in fines, and Dai herself paid \$500 000. In addition, Dai agreed to step down as chief operating officer; she now holds the hazy-sounding position of cofounder, vice president and general manager of communications and consumer business. She says she is not allowed to talk about the case but points out that the change in title hasn't changed what she does at the company, which she calls being the "caretaker" of the big family inside Marvell and its customers outside. "An unfortunate tsunami hit," she says, "but everybody knows who I am and what I do, and so life goes on."

TODAY MARVELL HAS offices in 15 countries, and its cofounders are billionaires. Yet at heart, Sehat is still an engineer, and the corporate culture reflects that.

"We are an engineering-driven company," Sehat says.

"A nerdy company," Dai says.

You see that in the hiring. A vast majority have electrical engineering degrees—and not just those doing design work. Investor relations vice president Palmer, for instance, holds a BSEE from George Washington University. "It doesn't mean that someone who doesn't have an engineering degree could not be hired as a marketing person," says Sehat. "It'd just make it harder."

Sehat describes his management philosophy as a combination of two famous Silicon Valley styles: the "only the paranoid survive" mantra of Intel's former CEO Andrew Grove, and Hewlett-Packard's "management by walking around," which encourages executives to interact more with their employees.

Both styles come naturally to Sehat. "We've always been paranoid, from day one when we started the company," he says. "We always thought the other guys could [beat] us. So we needed to build something even better."

"I'm a bit narrow-minded. I only see things in terms of electronics" —Sehat Sutardja

And his designers confirm that even now Sehat won't hesitate to roll up his sleeves and dive into the most difficult project. He keeps up on the technical literature and every week conducts random reviews of projects in the design stage. If his engineers tell him that a task will take two weeks, "Sehat will tell them it can be done in *x* number of hours or days," says Gani Jusuf, an early employee and now a vice president. "Newcomers think he is trying to put pressure on them, but he's not. It's that he is four steps ahead of everybody in quickness, and he can do it that fast."

And, says Jusuf, he "walks the walk. He may tell an engineer in a design review to change a layout. The designer will say, 'I can't do that in time.' And Sehat will go back to his office for a while, then come out with the new layout and say, 'Here you go.' "

LATELY, THOUGH, Sehat finds himself being forced out of his EE comfort zone and moving onto a more visible stage.

"I never wanted to be involved in politics, because I thought it was not productive for me or the company," he says.

But the economic and environmental impacts of the semiconductor technology he has worked so hard to advance have started to worry him. "We can now build practically anything in a chip or two, at low cost, for less than the cost of maybe two cups of coffee," he says. "And every one of these devices will consume energy. In the next 10 years we'll be building 50 billion, 100 billion units of these new devices, all consuming energy. And we'll be in trouble very, very quickly."

As part of an industry that is creating this energy-sucking monster, he feels obligated to try and tame it. "We don't have 10 years to solve this problem," he says. "We don't even have 5 years."

Sehat is now a regular visitor to Washington, D.C., where he's been pushing energy conservation standards for small consumer electronics devices. Marvell this year helped write the Smart Electronics Act, HR5070, introduced by U.S. Representative Michael Honda, a Democrat who represents the Silicon Valley area. The bill calls for the U.S. Department of Energy and the Environmental Protection Agency to draft testing protocols for such devices. Marvell is also working with the California governor's office on a similar initiative for the state.

As you might expect, Sehat has already taken an exhaustive look at existing power supply technology, and he doesn't like what he sees. The design hasn't changed in decades, he notes, even though it's now possible to build in circuitry that would keep the voltage in phase with the current and thereby improve efficiency. "Technology has advanced so drastically over the last 20 years that we can implement this function practically for free," he says. Of course, he isn't blind to the business opportunities; Marvell is busy developing circuitry for such improved power supplies.

Sehat is also using his personal fortune to support technology education: "With the support of higher education diminishing, I'm afraid [the United States] will fall behind countries like China." He and Dai have donated more than $20 million to Berkeley to complete the new headquarters for the Center for Information Technology Research in the Interest of Society—otherwise known as Sutardja Dai Hall. Their two sons now pass it daily as EE students there.

But his riches haven't changed his lifestyle. He and his wife carpool to the office most days (admittedly in a Mercedes sedan); they don't own a yacht or vacation home. They eat most of their meals at work, where the cafeteria usually offers a Chinese meal along with more typical Silicon Valley fare. They work until 7 or so and then drive home together, typically talking shop.

In the evening, Sehat often relaxes by turning on the SyFy channel, which he half watches while sketching circuit designs. Or he might kick back with the latest IEEE publication, whether it's *IEEE Spectrum* or the *IEEE Journal of Solid-State Circuits*. And that is pretty much the extent of his leisure activities.

"I'm a bit narrow-minded," he says. "I only see things in terms of electronics."

Can that strict engineering approach continue to work for Marvell? It's not the scrappy little start-up anymore; it is now a formidable company with shareholders to please and quarterly targets to meet. For Marvell to continue to grow, says Sergis Mushell, an analyst with Gartner, the time has come for it to lead. He believes the company now needs to identify a killer app and open a new market on its own, rather than focusing on incremental changes to existing products. "That's not an easy thing," he says. "Many companies get to this point and struggle."

"Having a CEO so involved on the engineering side" may make it tough for original ideas to percolate through the organization, he adds. But so far, he says, Marvell is heading in the right direction. The company, with its platforms for tablet computers, smartphones, and e-readers, is trying to create additional markets for mobile, low-power processors.

And, while Sehat and his cofounders could certainly afford to retire tomorrow, Marvell remains their singular passion. Says Dai, "This is just the beginning for us. Our mission is long term. There's so much we ought to do. It's a 48-hour-a-day job still."

For Sehat, the need to keep creating semiconductor-based technology springs from something even more basic. "I don't know anything else," he says. ❏

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For details on the positions and to submit your application, please go to:

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Review of applications will begin immediately
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www.ece.utah.edu.

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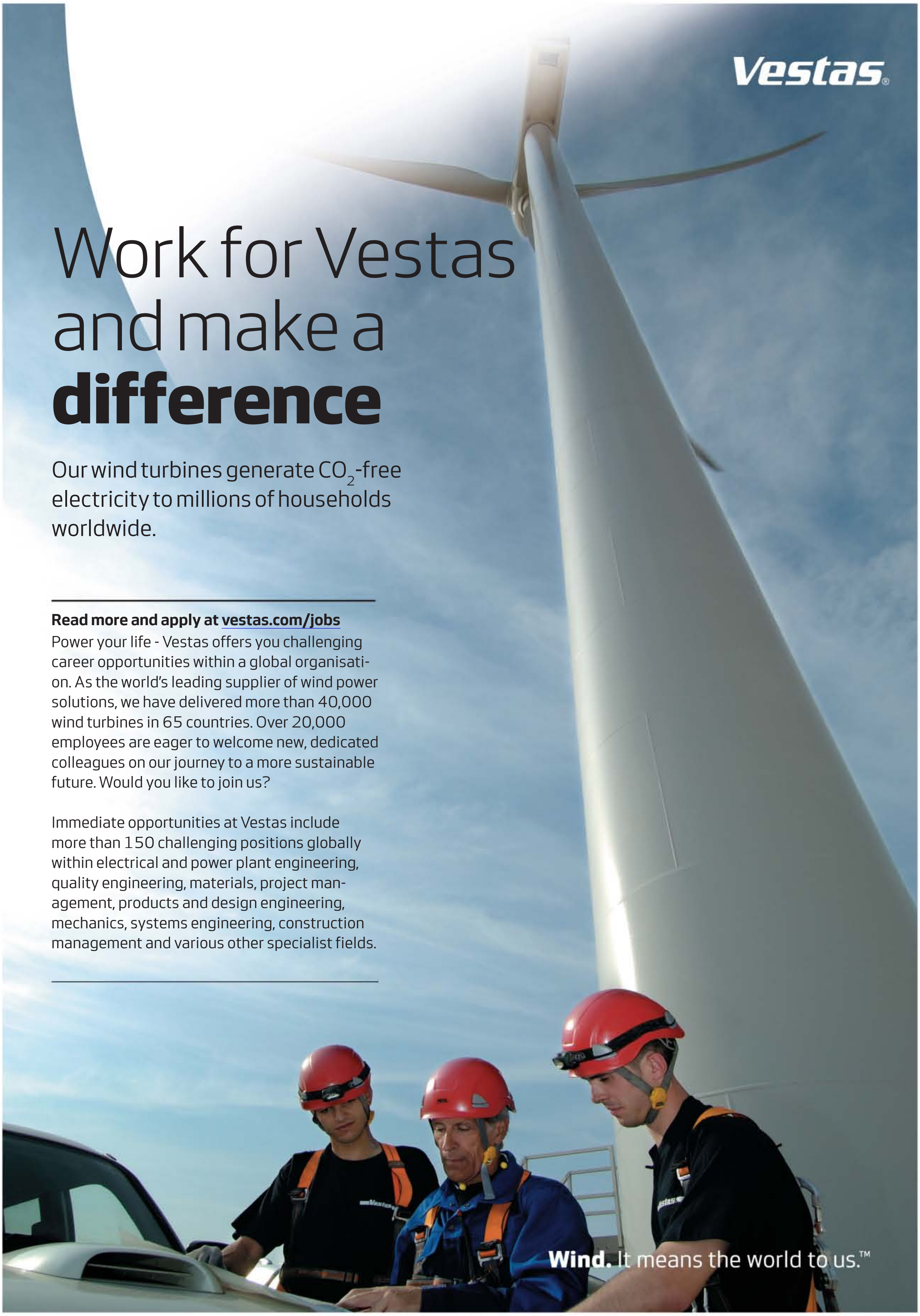
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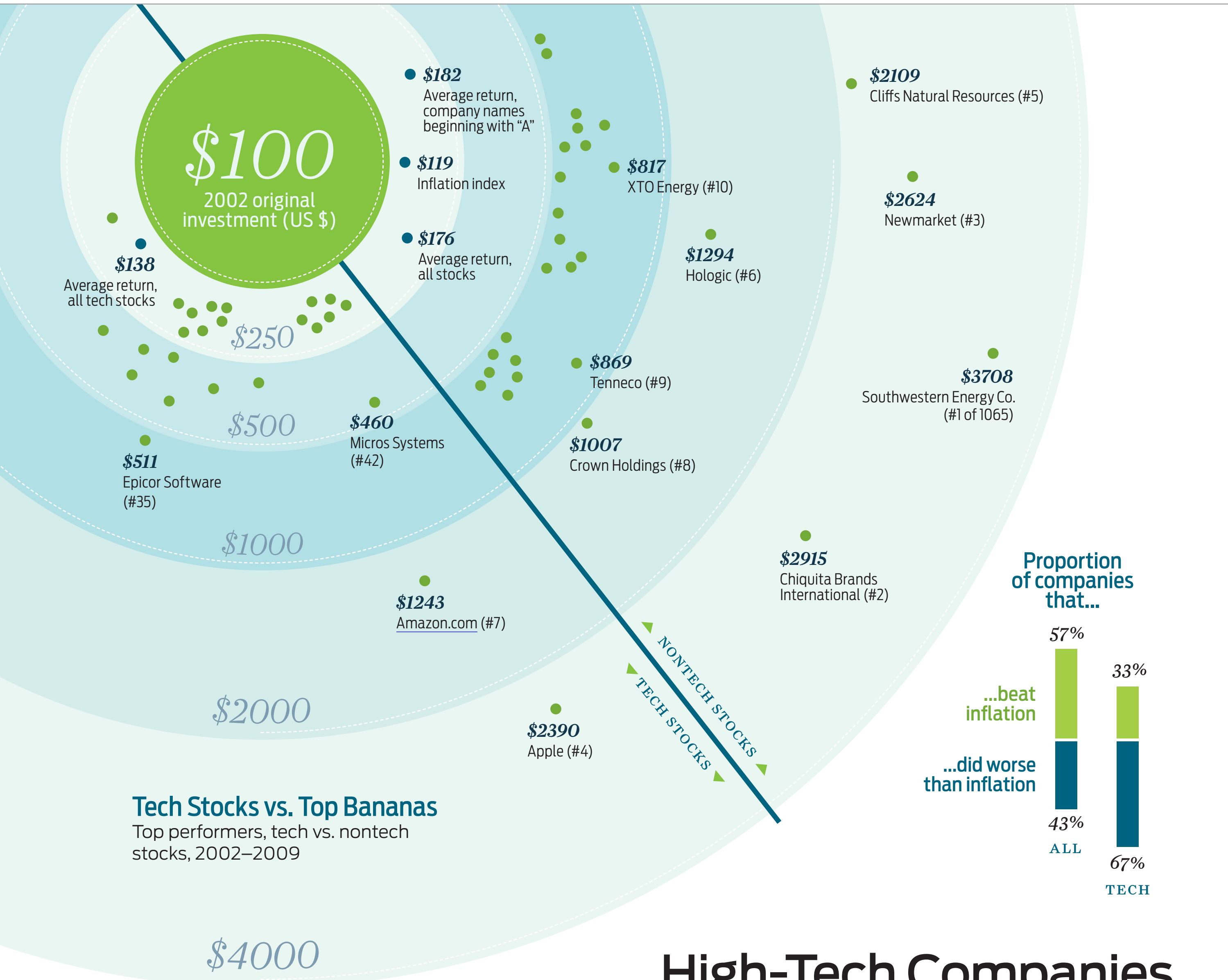


Tech Stocks vs. Top Bananas

Top performers, tech vs. nontech stocks, 2002–2009

High-Tech Companies Are Low-Grade Investments

YES, SUPERMAN, we know—crime doesn't pay. But neither do tech stocks.

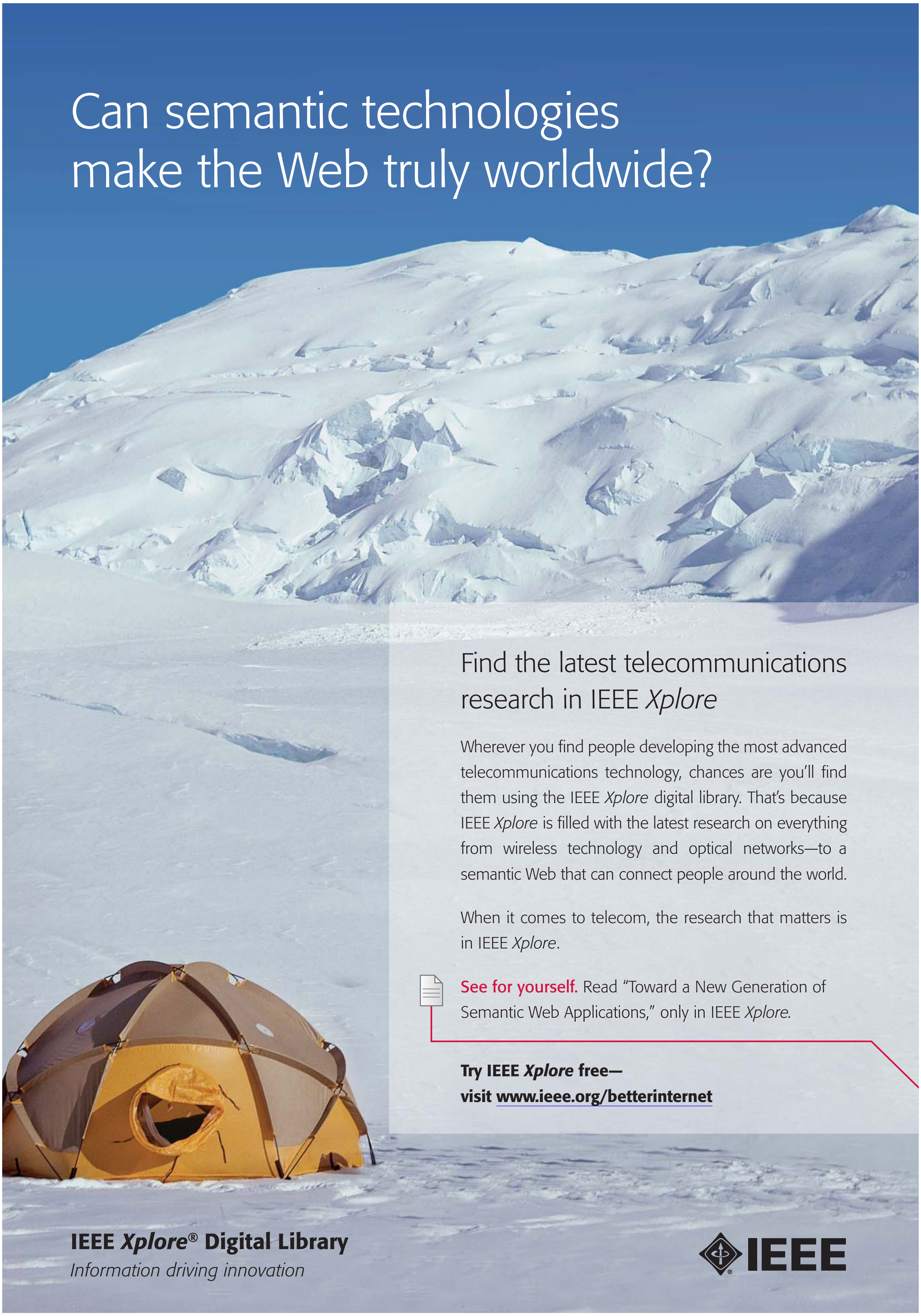
In an analysis for *IEEE Spectrum*, Kevin J. Murphy of the Marshall School of Business at the University of Southern California ran a simple algorithm that "invested" US $100 in the top 1500 companies listed in Standard & Poor's in early 2002—after the dot-com crash wreaked its havoc. And, assuming the investor reinvested all the stock's dividends, Murphy tracked the portfolio's value through the end of 2009, for the 1065 companies that were still listed.

Tech performed abysmally. Of the 118 tech stocks, 79 of them didn't even beat inflation. Just picking the first 118 stocks in alphabetical order beats the tech index by 25 percent. By comparison, the 110 mining and utilities companies on Murphy's index had an average return of $285 on the $100 investment, outperforming tech's $138 return by more than two to one.

Just about the only two standout tech companies were—no big surprises here—fourth-place Apple (which returned $2390 on the $100 investment) and seventh-place Amazon.com (which returned $1243). One genuine surprise was Chiquita Brands International, which came in second on Murphy's index, just behind mining and utility superstar Southwestern Energy Co. If you'd dropped $100 on this fruit company in 2002, you'd have had $2915 by the turn of the decade.

So, the adage is sort of right—an Apple a day...but even better, a banana. —*Mark Anderson*

Sources: Standard & Poor's S&P 500, SmallCap 600, MidCap 400 listings; S. Morgan Friedman's inflation calculator (http://westegg.com/inflation)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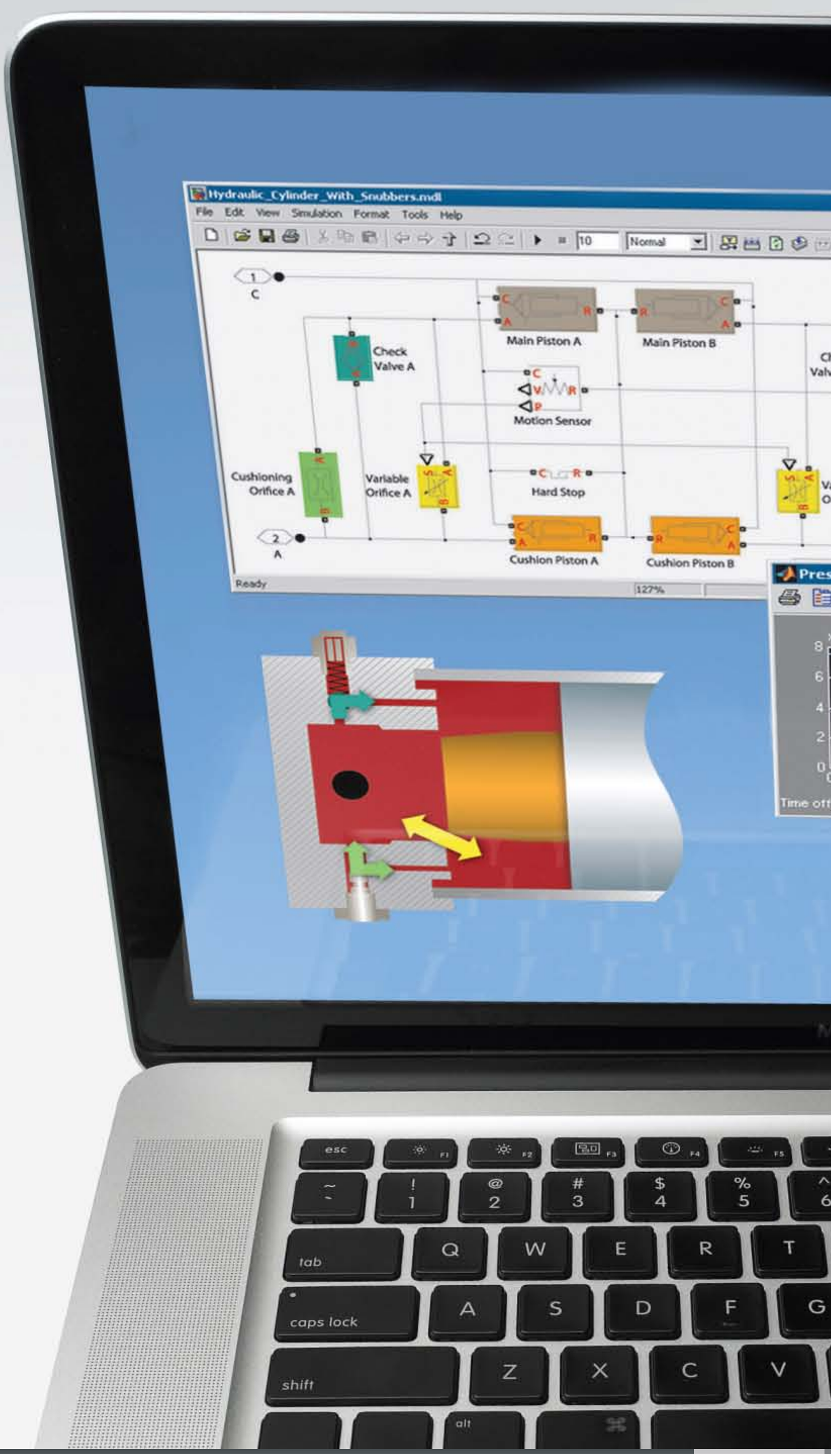
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