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IEEE SPECTRUM

THE MAGAZINE OF TECHNOLOGY INSIDERS

SEPTEMBER 2007

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RIC FULOP,
AND BART RILEY
OF A123 SYSTEMS

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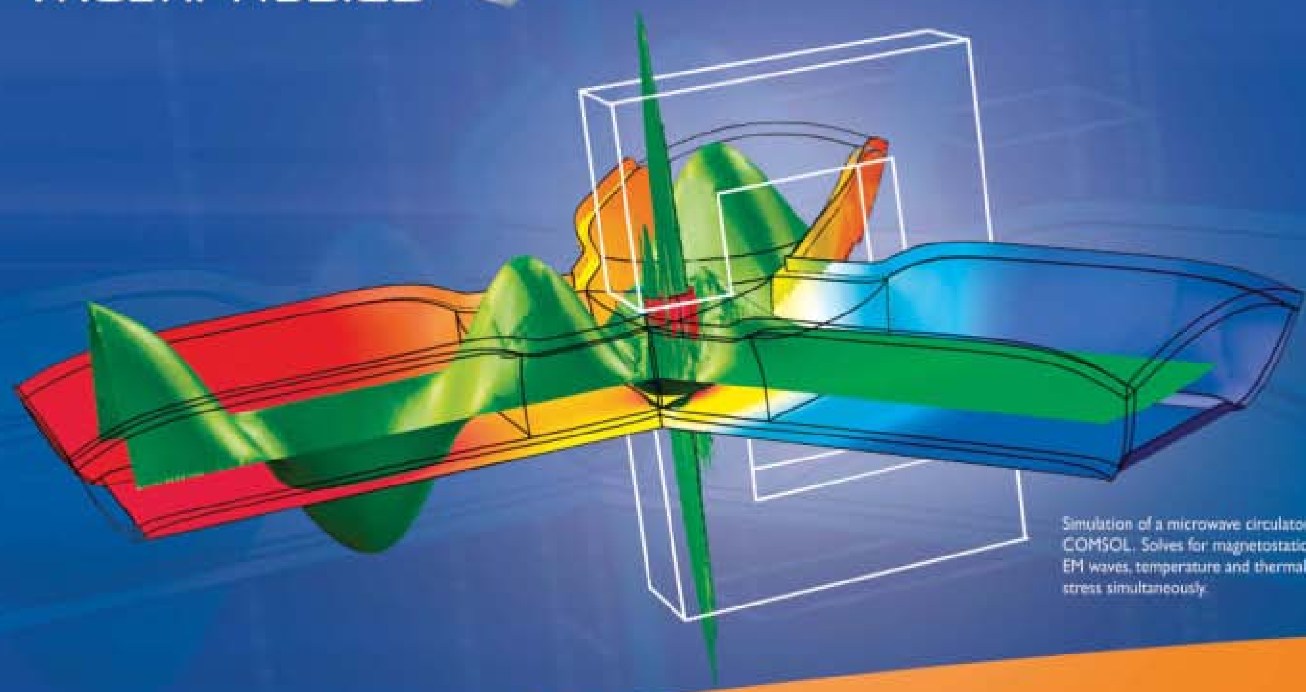

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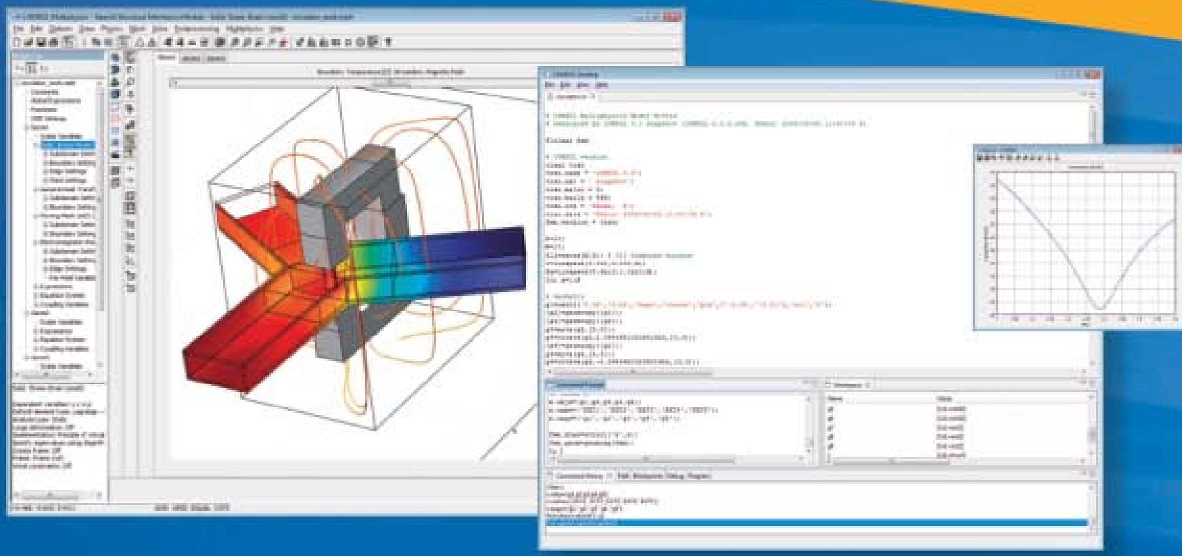

IEEE SPECTRUM SEPTEMBER 2007
VOLUME 44 NUMBER 9 INTERNATIONAL EDITION

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Engineer-explorer Bill Stone with his autonomous underwater robot.

This month at SPECTRUM ONLINE

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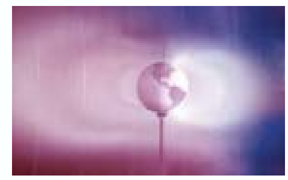

Killer Electrons From Space

Scientists are figuring out what causes storms of satellite-crippling radiation in space. Their efforts could help engineers predict the storms and protect spacecraft from them.

PORTRAIT OF A MATURE GRID MANAGER

With electricity deregulation, new authorities have been established in the United States and elsewhere to manage regional power systems. But not all are created equal. Join us on a virtual tour of New England's state-of-the-art Independent System Operator, in Holyoke, Mass.

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COVER: Photo by Joshua Dalsimer; Retouching by Statik Digital
THIS PAGE, LEFT: Randi Silberman; RIGHT: NASA Glenn Research Center

IEEE SPECTRUM

SEPTEMBER 2007

VOLUME 44 NUMBER 9 INTERNATIONAL EDITION

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Observations In Depth
Permanent, unmanned, underwater observatories are being developed by countries around the world.

WHAT SHOULD BE THE FIRST PROFESSIONAL DEGREE IN ENGINEERING?
The IEEE wants you to weigh in on whether it should follow the recommendations of several other professional associations and declare that a master of science or master of engineering should be an engineer's first professional degree.

CANDIDATES TAKE ON SIX KEY ISSUES
Find out what Marc Apter, Pedro Ray, and John Vig—the candidates for 2008 IEEE President-Elect—have to say about the issues that are important to you and the IEEE.

LEFT: L3 MARIPRO
RIGHT: TEKLA S. PERRY

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FROG: JEAN KUMAGAI

THE BACK STORY

Amphibious Adventure

It was a slow Thursday afternoon when *IEEE Spectrum* Senior Editor Jean Kumagai [above, left] popped into the cubicle of Photo Editor Randi Silberman [above, right] to ask if she'd like to come along on a trip to northeastern Mexico. The assignment was to cover the initial testing of an underwater robot in a deep sinkhole.

Silberman jumped at the chance. "Normally I sit at my desk talking to photographers about the amazing things I'm sending them off to do," she says. "This time I'd get to do those things myself."

And then she encountered Toilet Frog [right]. Arriving at the sprawling ranch where the robot team was based, she and Kumagai discovered an enterprising amphibian that had taken up residence in the ranch's septic system, swimming back and forth between its bathrooms. "Randi didn't seem to mind the frog that much," Kumagai says. "But I felt like every time I turned around, there it was—in the shower, on the kitchen floor, even in the toilet bowl. Very weird."

Despite those run-ins with the wildlife, they captured a great story. Says Silberman, "I never thought I'd find myself climbing down a cliff holding on to just a rope, then getting into a kayak and paddling around to frame the perfect shot." But she did all that, and more, to document the expedition. Her photos and Kumagai's text come together in "Swimming to Europa," in this issue.

Back in New York City, the two found themselves reminiscing fondly about the characters they'd met in Mexico. Even Toilet Frog. ■

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 News page is in *IEEE Spectrum*, Vol. 44, no. 9 (INT), September 2007, p. 10, or in *IEEE Spectrum*, Vol. 44, no. 9 (NA), September 2007, p. 12.

FORUM

"The prudent thing is to get rid of the hack immediately"
—Bruce Walker

SHOOT FIRST

In their fascinating article, "The Athens Affair" [July], the authors Vassilis Prevelakis and Diomidis Spinellis criticize Vodafone for deactivating the rogue software that enabled widespread eavesdropping on some of the most powerful people in Greece. I disagree with this criticism. After discovering the intrusion, officials had little choice but to shoot first (remove the hack) and ask questions later.

In hindsight, it might have been smarter to leave the rogue code in place, study it, and perhaps contact the people whose phones had been tapped, and then arrange a sting operation to catch the hackers. But this might work only if you know what the rogue code is doing—something, crucially, that you can't know when you first discover it.

Even the length of time the rogue code had been there was another thing the officials didn't know when the hack was uncovered.

What do you do in such a case when the code wasn't written to your requirements, wasn't tested by your testers, and doesn't belong in your system? The prudent thing is to get rid of the hack immediately.

Bruce Walker
IEEE Member
Los Angeles

I read with interest your article on the hacking of Greek cellphones. The reference to Clifford Stoll said he was at the Lawrence Livermore National Laboratory; he was at the Lawrence Berkeley Laboratory at the time when he discovered that one of the computers he was responsible for had been hacked. He determined that the intruder was looking for information on the Strategic Defense Initiative (SDI), and in response he set up a computer with a lot of bogus forms for grant applications and so forth—to make the everything look official.

He then created a fictional secretary to handle requests for information on the SDI and set a trap by putting references to the secretary only where a hacker could find them. When a request came addressed to the secretary asking for more information, he had the culprit! Stoll's book, *The Cuckoo's Egg*, on the episode in which he caught the KGB agents attempting to hack into U.S. computers, reads like a thrilling mystery.

William R. Patterson
IEEE Senior Member
Somerdale, N.J.

GOING FOR THE GUN

As a former rail-gun researcher, I want to congratulate Carolyn Meinel for writing a vivid description of recent rail-gun history ["For Love of a Gun," July]. I spent 10 years working with Ian McNab, Richard Marshall, and a full complement of scientists and engineers at the Westinghouse R&D Center back in the 1980's. I came away from the experience with a sobering appreciation for the challenges that will have to be met before we can deploy such guns.

Perhaps the most positive cumulative result of the many years of government-supported rail-gun research is that we have established just how difficult it is to develop useful launchers. Also, the work has given us a knowledge base that will help mitigate the repercussions of any surprise breakthroughs from clandestine programs in other parts of the world.

George T. Hummert
IEEE Member
Aiken, S.C.

INVISIBLE WOMEN

I just read the article "T-Rays vs. Terrorists" [July], and was quite annoyed at the second sentence in the article. It says, referring to advertisements for bogus "X-ray specs" years ago, that "They'd let you see through walls, boxes, and—best of all, for a teenager, anyway—clothing." What a jolt! Clearly, the authors of this article are talking only about male teenagers—and are writing only to male engineers.

It was disturbing to read this. I am disappointed with the editors of *IEEE Spectrum* for allowing such a blatant bias to be published. Such a sentence counterbalances the effect of many righteous articles about increasing the percentage of females in engineering. It shows the great distance we still have to go to alter the fundamentally masculine image of engineers in the eyes of fellow engineers as well as laypersons.

Judith E. Soukup
IEEE Member
Rockville, Md.

The executive editor responds: I regret the distress caused to reader Soukup. But her apparent assumption that a Y chromosome is necessary to be amused by the ability to see through clothing strikes me as, well, biased. Moreover, it may have escaped Soukup's attention that one of the authors of the article, Zoi-Heleni Michalopoulou, is a woman.

CORRECTION

In "How to Master a Seismic Disaster" [June], a map referred to the body of water between Japan and Korea as the "East Sea." Readers may have assumed that the figure's source, the Japan Meteorological Agency, also uses that designation. It does not; the JMA prefers "Sea of Japan." In the future, we will join other magazines in using the dual appellation "Sea of Japan (East Sea)." —*Ed.*

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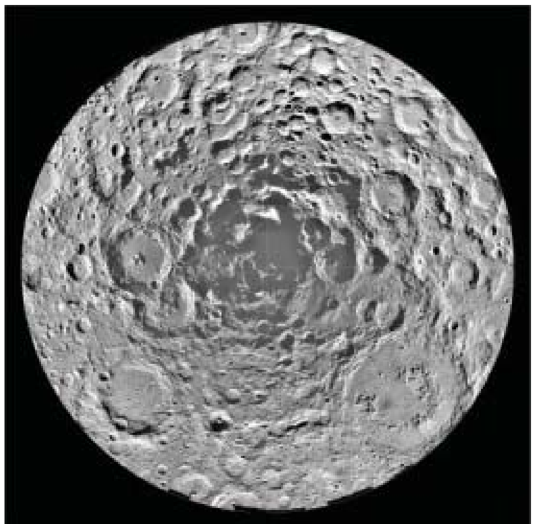
SPECTRAL LINES

Exploring the Extreme

Bill Stone, an engineer and renowned cave explorer, has been diving into the bowels of the Earth to get ready to explore the furthest regions of space. Stone's expeditions, covered in *National Geographic* and other magazines, have taken him and his teams into some of Mexico's longest and most dangerous underwater caves and tunnels, known as sumps. In 1994, at the end of a harrowing and much-documented expedition that claimed the life of a young diver, he and his then-girlfriend, Barbara am Ende, traveled more than 3.3 kilometers into the San Agustin Sump, the deepest point in Sistema Huautla in Oaxaca, Mexico. To get there, they had to get past eight other treacherous sumps, the last one some 1500 meters underground. Stone and am Ende found themselves in an enormous subterranean chamber 100 meters in diameter, where they spent several days. Their footprints are the only ones that have ever been left there.



Lunar mosaic of approximately 1500 images of the south pole of the moon, taken by the space probe *Clementine.*

U.S. GEOLOGICAL SURVEY/NASA

Stone is an exceedingly rare engineer. He not only designs and builds advanced technology, he uses it to explore the most extreme niches of this world—and others. His latest creation is the DEPTHX autonomous probe, whose testing is the subject of Senior Editor Jean Kumagai's story "Swimming to Europa" in this issue. Once again the scene of the action is Mexico, where Kumagai found a considerably mellower Stone than the notoriously hard-charging one of the Huautla mission 13 years ago.

But if age has mellowed Stone, it has not touched his passion for exploration. He's not just interested in sending an unmanned probe to Jupiter's ice-bound moon Europa. He wants to go to our moon—himself. According to Stone, 90 percent of the weight of present-day space vehicles, and much of the exorbitant cost of spaceflight, comes from the fuel needed to break through the Earth's atmospheric chains. He is convinced that if you could set up a "water-mining" operation on the moon you could use the water to make liquid oxygen rocket fuel and then port it back to a low-Earth-orbit "gas station," where new kinds of spacecraft could fuel up and take off for the stars.

Just how much water the moon holds is still debatable, but Stone is one of a group of scientists and technologists who are convinced that a vast icy lunar waterworks resides beneath the moon's south pole, at the Shackleton Crater, named after the intrepid Antarctic explorer Ernest Shackleton.

So Stone is hard at work raising money and interest in his Shackleton Crater Expedition, a complex and ambitious project to send what he calls "an industrial Lewis and Clark mining expedition," led by himself, to the crater by 2014. His plan calls for the spacecraft used in this mission to carry enough fuel for the outbound flight—but expedition members will need to make their own moon-water fuel to get back, providing proof-of-principle of his idea. And proof that it won't take a trillion dollars and 20 years to work.

Stone and other like-minded folks believe that space travel and space exploration should not be the sole purview of government agencies like NASA. The U.S. space agency is too crippled, they say, by bureaucracy and risk avoidance to make any significant progress in manned space exploration over the coming decades. Billionaires like Virgin Airways' Richard Branson and Microsoft cofounder Paul Allen are already supporting the development of suborbital passenger spacecraft and are looking for other ways to break into the space business. Stone hopes people like these will help bankroll his commercial moon-mining project.

What does NASA think of all this? Not much. With the specters of *Apollo 13* and the *Challenger* disaster haunting its halls, it is reluctant to even consider putting its crews at such great risk. But Stone is following in the "no guts, no glory" footsteps of the great explorers, like Shackleton, who believed that while careful preparation was essential to successful exploration, the danger of going where no human had ever gone before was also intrinsic to the effort.

At the end of the Technology Entertainment Design Conference talk he gave in Monterey, Calif., earlier this year, Stone showed a slide of the ad Shackleton is said to have placed in a London newspaper seeking volunteers for his 1914 Imperial Trans-Antarctic Expedition, which sought to cross the southern continent: "Men Wanted: For Hazardous Journey. Small Wages, Bitter Cold, Long Months of Complete Darkness, Constant Danger, Safe Return Doubtful. Honour and Recognition in Case of Success."

Twenty-eight men signed on. If Stone has his way, we've no doubt there will be men and women who will be ready to join him. Is it lunacy? Of course it is. But then again, perhaps the Great Age of 21st Century Space Exploration is about to begin. Thank heavens for lunatics like Stone. ■

NEWS

TEKLA S. PERRY

The Zero-Zero Hero

David Kaneda's San Jose office building will use zero electricity, produce zero carbon dioxide, and still be a comfortable workplace

It may be a first: an office building with a net electricity use of zero or less, that burns no fossil fuels for heating and produces no greenhouse gas, and that makes the people working there at least as comfortable as those in conventionally heated and cooled buildings. The building, in San Jose, Calif., opens in October, and if all goes according to plan, it will raise the bar for designers of energy-efficient buildings worldwide. Though other so-called z-squared buildings exist, they are highway rest stops, nature centers, and event locations, not office structures with computers and printers and cubicles full of employees.

"We've hoisted the flag and said we're the first," says David Kaneda. "No one yet has stepped forward to question that." He owns the San Jose building, and his Santa Clara, Calif.–based firm, Integrated Design Associates (IDeAs), did the electrical and lighting design and will occupy the ground floor.

The building was once a windowless bank, designed in the 1960s when banks were meant to be riot-proof concrete bunkers. Today, with the remodeling nearly completed, it is modern art: the exterior is broken up with rows of windows and swaths of blue and gray paint, while solar panels adorn the roof, with skylights pushing up in between.

Kaneda embarked on the project of renovating the old bank in September 2005, with the goal of creating an environmentally friendly building that could earn a Platinum rating—the highest—from the U.S. Green Building Council, an association of builders in

POWER: David Kaneda shows off the solar panels and skylights of his new building [left]. The skylights are sometimes supplemented with efficient fluorescent lights [top]. Meanwhile, water in underground pipes keeps things cool [bottom].

MIKE KAHN/GREEN STOCK MEDIA (2)

Washington, D.C. At that time, global climate change was not in the forefront of public consciousness, and the council's standards were not much in the public eye. So Kaneda thought he was being very forward-thinking when he proposed to renovate the bank to meet the council's specifications for building materials, water use, indoor air quality, and—most important—energy use.

But when Kaneda hired architect Scott Shell, from EHDD Architecture, in San Francisco, to work on the project, Shell went even further, suggesting they design a building with no net electricity usage and no carbon dioxide emissions.

"It was a shock to me when he said that," Kaneda recalls. He didn't know of any commercial buildings that had gone that far.

The idea appealed to Kaneda, and the two decided they would disconnect the natural gas pipes running to the building and find heating alternatives. They would stay on the electric grid but install enough photoelectric panels to cover the entire energy load—about 30 kilowatts, generating more electricity than the building uses during the day but pulling a small amount off the grid at night. Since they'd be limited by the size of the roof, they'd have to be clever about energy use.

"To cut down on energy use, you've got three areas to address," Kaneda says, "lighting, heating and cooling, and plug load—that is, the computers, printers, microwave ovens, and other things you plug into the wall."

To reduce the amount of energy used for lighting, Kaneda's builders sawed through the concrete perimeter of the building to install windows and skylights. Special window glass lets visible light through but blocks infrared and ultraviolet light, keeping the office cool. An overhang on the south side shades the windows from direct sun; on the east side, electrochromic glass controlled by a sensor darkens the windows when sun hits them directly and makes them transparent the rest of the day. Because the ceilings are high, the skylights bathe much of the office space in a diffuse light; in areas where the skylight illumination is too strong, Kaneda is experimenting with different types of diffusers.

The building also uses low-energy fluorescent bulbs, some of which are hooked up to switched circuits, while others are on dimmers. Kaneda wasn't able to get any good data on which method is more energy efficient, so he plans to collect his own data, which will be invaluable to others embarking on similar projects.

For heating and cooling, Kaneda chose a geothermal heat pump, which takes advantage of the fact that at some point below the surface, the ground remains a constant 10 °C all year round. In Northern California, this point is only about 1.8 meters below ground level; Kaneda installed water pipes that snake throughout the property, an area that will eventually have a landscaped courtyard and a bocce court. When the water flows into the building, it goes through a heat exchanger that collects the heat from the ground in winter and pulls heat out of the building in summer.

Designers of energy-efficient buildings often stop at this point, but for Kaneda, once the first two areas of energy use had been addressed, the amount of energy allocated to computers and other plug-in devices looked huge. All the appliances he purchased for the common room meet the U.S. Department of Energy efficiency goals, and all his employees' computers will have LCD screens, the lowest-power option. Light and motion sensors will turn on electric lights when daylight gives way to evening and employees are still working, but employees will be able to adjust their personal light levels from their desktop computers. Arming the building security system, which is supposed to happen when the last person leaves for the night, will automatically cut off the power-sucking printers—Kaneda's own large-format printer, the worst power vampire, draws 40 watts in standby mode.

Kaneda won't know for sure just how efficient the building will be until he and other tenants—yet to be determined—move in later this fall, but he's confident he'll be putting more energy into the grid than he takes out. Though he has yet to set a policy for tenants, he hopes to attract companies that are equally concerned about the environment.

If Kaneda wins the Green Building Council's approval, his will be among the few Platinum buildings in Northern California (only about 40 exist in the United States as a whole). But whether his will truly be a z-squared building is a matter of debate, since no official definition exists.

Is simply producing more energy than a building consumes enough to call it

NEWS

z-squared? Or does all the energy consumed need to be green energy? If all energy consumed has to be green, how is this guaranteed? Is buying "green power" from the utility company enough? This may mean only that it purchases enough green energy to cover users' needs but that it doesn't send that actual energy to them. Or would it be better to buy carbon credits to offset any electricity imported from the grid, based on the utility's average greenhouse-gas emissions per kilowatt generated? Paul A. Torcellini, a senior engineer with the National Renewable Energy Laboratory in Golden, Colo., notes that in real life some of the electricity you buy is bound to have been generated at the cost of greenhouse-gas emissions.

Torcellini points out that the building stock in the United States is grow-

BIG DEALS IN BANGALORE: Venture capitalist Promod Haque [right] listens as Claudia Fan Munce, IBM Venture Capital Group managing director, strategizes with IBM India's chief scientist, C. Mohan.

AIJAZ RAHI/AP PHOTO

Indian Start-ups Lure Silicon Valley Cash

Tech giants invest in Bollywood, e-government, and more

Having discovered India's inexpensive engineering talent years ago, nearly every big tech company has a subsidiary there. Now the venture capital (VC) groups of these multinationals are discovering India's independent start-ups. Venture capital investment in India is on the way to a substantial increase this year, with US $341 million committed in the first half of 2007. That follows VC's nearly doubling in 2006 to $508 million spread over 90 deals. Nearly 15 percent of the 2006 money came from the venture capital divisions of companies like Cisco Systems, Google, IBM, Intel, and Yahoo, according to Arun Natarajan, CEO of Venture Intelligence, a Chennai-based firm that tracks VC investments. That's a much higher proportion than in the United States, where in 2006 big companies accounted for less than 8 percent of VC financing.

The amount of VC funds coming into India from big corporations is increasing on top of a general growth in foreign VC investment, he says. The research services company, Evalueserve, in Gurgaon, India, says that 40 VC firms are planning to invest $4.4 billion in India in the next four to five years.

"We will continue to see more money flowing into India," says Promod Haque, managing partner of Norwest Venture Partners (NVP), a Palo Alto, Calif.–based VC firm that has coinvested with Cisco, IBM, and Intel. "This is definitely part of a global trend, but India offers some unique opportunities." In a survey of U.S. venture capitalists released in July by Deloitte Touche Tohmatsu and the National Venture Capital Association, India stood with Canada, China, and Israel as the country most favored by VC investors. Respondents wrote that India is particularly attractive due to "its emerging entrepreneurial environment" and R&D and engineering opportunities.

India's traditional strengths, notably inexpensive and available talent, are now backed up by a growing domestic market and the emergence of start-ups with transnational business models, says Haque. Add to that an increasing penetration of mobile phones and broadband Internet connections, and India looks very attractive.

Traditional VC outfits work by pooling money from wealthy individuals and institutional investors such as pension funds and foundations, and investing the money in start-ups. VCs typically play an active role in the management of the firms they invest in. Any return on investment—usually from the start-up being acquired or going public—doesn't come for five to seven years on average.

Corporate VCs get their funds from the parent company itself. Firms like Intel, which are subject to investor pressure to profit in the short term, use their VC divisions to make longer-term investments. "Corporate venture arms can leverage the strategic and operating resources of their parent corporations," says NVP's Haque. "And they often fund companies that are related to their own strategic competencies," making India's booming technology sector a natural fit.

INTEL CAPITAL leads the pack of corporate investors. It began strategic investments in India in 1998 but announced a $250 million India Technology Fund in late 2005 to focus on technology start-ups. Soon after that, it set up smaller funds for China ($200 million), the Middle East and Turkey ($50 million), and Brazil ($50 million). Intel Capital has invested in 10 start-ups since it began India Fund. "We invest in companies that complement Intel's technology initiatives and accelerate the computing and telecom infrastructure build-out in India," says Sudheer Kuppam, Intel Capital managing director for Australasia, India, Japan, and Southeast Asia. More infrastructure in India means a biging faster than builders are deploying energy-efficiency technology. As a result, with buildings accounting for just about 18 percent of the country's energy consumption, the absolute amount of energy used is increasing one-and-a-half percent per year. So "we either need to save more or build more power plants," he says.

Kaneda is already developing another z-squared structure, this one for the La Jolla, Calif., research building of the J. Craig Venter Institute, a biotech firm based in Rockville, Md., that is seeking to create artificial life and use genomics to solve a wide array of pressing global problems. With the name of the famed genome pioneer, J. Craig Venter, over the door, that building will get a lot of notice, even if the former San Jose bank remains known only to tech insiders.

—TEKLA S. PERRY

ger market for Intel's products.

The impact of corporate VCs is potentially bigger than what traditional VC firms can deliver. "When companies like Intel come on board as venture capitalists, there's a huge boost to the credibility of the start-up, as these VCs have a very high diligence process. They evaluate a start-up much more stringently than a traditional VC firm," says Sriram Raghavan, president of Comat Technologies, in Bangalore. Earlier this year, Intel invested about $4 million in Comat, which is developing e-government software. Once a firm gets money from the VC division of a big company like Intel, adds Raghavan, it can draw on the company's expertise to fine-tune its technology strategy.

IBM, is a latecomer to India, though the company has relationships with more than 1300 VC-backed projects worldwide. "We are just getting started here; the VC ecosystem in India is in start-up mode," says Drew Clark, director of strategy at IBM VC Group in Menlo Park, Calif. IBM has invested in three Indian companies so far and is evaluating more than a dozen proposals. It is scouting for opportunities, both in the country's proven outsourcing area and in companies serving India's growing domestic travel, retail, and health-care markets.

IBM's VC business model is unique. It does not make direct financial investments but forges partnerships with start-ups and offers its customer base, experience, and above all, market standing to expand a company's businesses. IBM, says Clark, uses start-ups to drive innovation around open-source software, where IBM is staking out a leadership position.

In India, IBM's partnership with NVP's portfolio companies Virtela Communications and Persistent Systems is paying off. Virtela and IBM have jointly sold networking services to hundreds of customers worldwide. Meanwhile, Persistent, which provides outsourced software product development, has helped IBM serve its customers better. "When our customer requires a customized product such as a database or management services, Persistent, with its on-demand skills, helps us do that," says Clark.

CISCO SYSTEMS exemplifies a different approach. "Typically, Cisco uses investments to learn about new markets and participate in market transitions that add more value to the network," says Sameet Mehta, director of India Investments and Acquisitions at Cisco. For now, that has meant investing in the entertainment industry, which according to a Confederation of Indian Industry–KPMG report is growing 20 percent annually and will reach $13.5 billion by 2010.

With an eye on putting content and digital media over an IP network, Cisco recently invested in Nimbus Communications, a Mumbai-based TV production company. Cisco hopes that one day Nimbus might stream video worldwide. "India is one of the largest producers of movies in the world and has over 300 TV channels. While there is a vast repertoire of content, there is very little in terms of legacy distribution," says Mehta, who thinks India could move quickly toward direct distribution of content.

Having invested more than $70 million in less than two years, Cisco plans to put another $25 million to $30 million into India over the next few months. Some of these investments are likely to become full acquisitions by Cisco later on, says Alok Shende, vice president of IT practice at research firm Frost & Sullivan, in Mumbai.

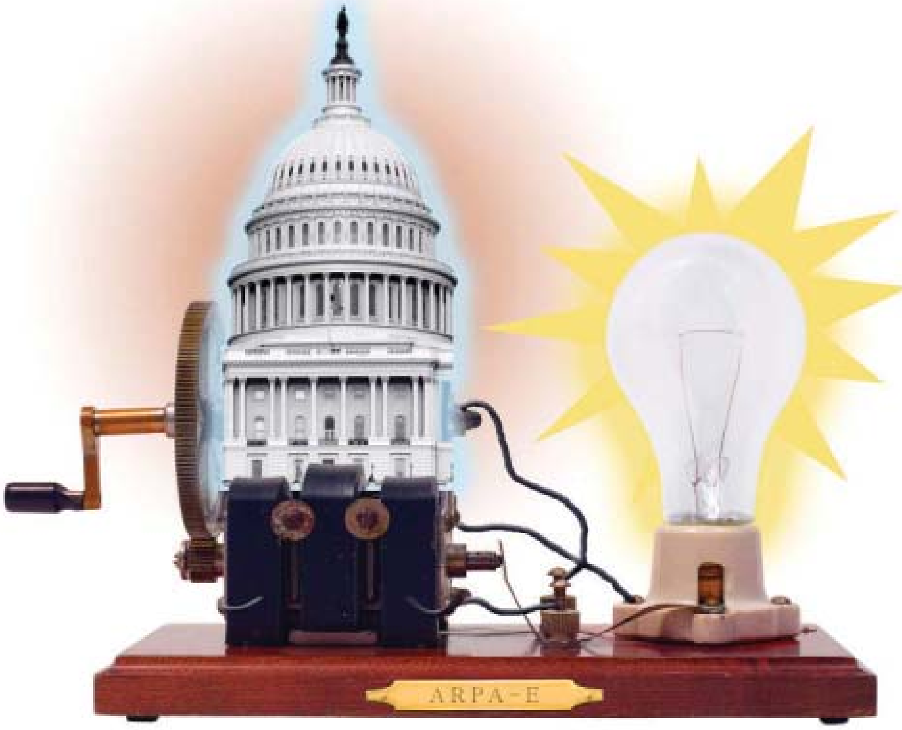
Most of the corporate VCs are investing in middle or late-stage start-ups, and little money has trickled down to early-stage start-ups. Google intends to fill the gap by investing in three Indian early-stage venture capital funds and by supporting a group of Indian entrepreneurs and investors called Band of Angels.

Other technology companies such as Nokia, Philips, and Siemens have VC divisions interested in India as well. Siemens Venture Capital, which started operations in June 2006, is now looking to invest in one or two companies in India every year.

—SEEMA SINGH

Tech Titans and Their Indian Interests

CORPORATE VCs	RECENT DIRECT INVESTMENTS	AREAS OF INTEREST
Cisco Systems	Bharti Telesoft, Indiagames, Nimbus Communications	Online gaming, mobility, broadband content, digital media, technology infrastructure, advanced communications technology
Google	Band of Angels, Erasmic Investment Ventures, Seedfund, VentureEast TeNeT Fund	Internet and mobile services, other technologies allied to Google's mission
IBM VC Group	InstaCall, Persistent Systems, Virtela Communications	IT and communications services; software; technologies for health care, retail, and travel
Intel Capital	40 companies since 1998; 10 since India Fund was formed in 2005, including Comat Technologies, Ilantus Technologies, Insilica, Maya Entertainment, Vignani Technologies	Digital media; hardware; software services for business, home, mobility, health, Internet; semiconductor manufacturing
Yahoo	BharatMatrimony.com	Content-based services



Power Up

Could an agency modeled on DARPA recharge U.S. energy R&D?

NEWS

A bill passed by the U.S. Congress last month and signed into law by President George W. Bush on 9 August creates a special R&D unit within the Department of Energy modeled on the Pentagon's Defense Advanced Research Projects Agency (DARPA). Like its Defense Department analog, Advanced Research Projects Agency–Energy, or ARPA-E, is meant to engender a research elite to develop high-risk, high-reward technologies, but specifically in energy. Critics of the legislation complained that the proposed agency lacked a clearly defined mission, established sources of funding, and the ability to put its findings into practice. Supporters have countered that without a new agency in place, none of those issues can even be addressed.

The idea for ARPA-E came from a 2005 National Academy of Sciences report called "Rising Above the Gathering Storm." The report criticized the state of American competitiveness in the global market, specifically condemning government inattention to baseline research and development. The U.S. Government Accountability Office found that federal investment in energy technology R&D has declined by 85 percent since 1978, when adjusted for inflation. The report spurred House Science Committee chairman Bart Gordon (D-Tenn.) and other political heavyweights to sponsor legislation that would create a DARPA-like agency.

DARPA—famously credited with helping develop the Internet, weather satellites, and GPS—was established in 1958 as part of the U.S. response to the Soviet Union's launch of the *Sputnik* satellite. The agency is a svelte 240 employees within the DOD behemoth. Legislators envision ARPA-E as a similarly small, autonomous agency whose personnel will be replaced about every four years to discourage bureaucratic lethargy. Like DARPA, ARPA-E will fund both university and industry programs. The agency's director will bypass all the usual protocols to report directly to the Secretary of Energy. Program managers will be given a great deal of autonomy to jump-start promising projects and terminate failing ones just as quickly.

Critics like David Goldston, a former staff director of the House of Representatives Science Committee, are not impressed. He believes that ARPA-E is popular just because the idea is visible, not because of its intrinsic merits. Critics say four major questions about ARPA-E remain unanswered:

- Is a new program for energy research and development necessary?
- Is DARPA really the best model?
- How can ARPA-E's mission succeed when the means have not been provided, in the form of money or the ability to turn its findings into new regulations?
- What specific problems will ARPA-E try to solve in order to reduce foreign energy dependence?

Testifying at the first of many hearings on the ARPA-E bill, former DOE advisor Melanie Kenderdine, now an associate director at the MIT Energy Initiative, said that ARPA-E's objective is not easy to distinguish from that of the DOE's Office of Science, which funds basic research across a broad array of fields. But House Science staffer Christopher King, who worked on the ARPA-E legislation, argues that little of that office's research has energy technology applications.

The energy department once had an Advanced Energy Projects division, which, until it was abolished in 1998, was the incubator for cutting-edge energy research. Started in 1977, it funded what Ryszard Gajewski calls the "infants and orphans" of energy research. Gajewski, a former director of the division, says that the time from proposal to funding was sometimes as little as two months, even though the division relied on peer review of proposals, which DARPA does not do.

Will the DARPA model work at another agency? Critics have serious doubts. For one thing, DARPA has one customer, the Pentagon, which buys the products that result from its innovations; ARPA-E will promote the development of products that would have to be taken up throughout the economy to make a difference. But adoption of its innovations will depend on vagaries of policy-making far beyond its specific purview or even that of the Energy Department itself.

For example, ARPA-E might successfully identify revolutionary fuel-saving technology for vehicles but fail to see it break into the market because Congress or the White House declined to tighten fuel economy standards.

Adequate funding, of course, will be crucial to ARPA-E's success. Since 2006, various legislative incarnations of the bill authorized annual appropriations anywhere from US $300 million to $1 billion. Where will that money come from? "I would guess that an ARPA-E will have to be funded at the expense of existing DOE programs," says William Happer, who ran science programs at the DOE in the early 1990s. But King notes that a bill adopted in January would set up a fund for clean energy research—including ARPA-E—using money from discontinued oil and gas subsidies.

As for the question of what specific problems ARPA-E can try to solve, its

LOU BEACH

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advocates said dwelling on that would put the cart before the horse. Through July, House Speaker Nancy Pelosi (D-Calif.) was still concentrating on getting the legislation passed before hammering out a plan for funding the agency or determining how to use its findings. "That's point C," said senior Pelosi energy aide Amy Fuerstenau, speaking back in July, "and we're still trying to get to point A."

Longtime critic Goldston thinks that this strategy invites long-term failure. "What happens in an agency in the initial year or two sets the culture in that agency for decades to come, and it's very hard to change," he says.

A CAUTIONARY TALE of what could happen to an ill-conceived agency, as critics see it, was in the creation of another DARPA clone at the Department of Homeland Security. HSARPA ended up getting lost in the giant, newly created homeland security bureaucracy, unable to function as the nimble, red-tape-cutting unit envisioned when it was set up as part of the Homeland Security Act of 2002.

But does ARPA-E have to end up that way? King says HSARPA veterans helped modify the ARPA-E legislation to avoid some of the pitfalls, especially a lack of autonomy, that hobbled the homeland security research agency.

Much of the Energy Department's research, in particular that undertaken at national laboratories, is universally recognized as essential. But the pace of research is often glacial, and the culture is notoriously risk-averse. High-risk projects demand a certain tolerance for failure, and congressman Gordon says that the DOE has none. Meanwhile, responsibility to shareholders makes private industry cautious, and university research depends mostly on federal funds. But by acting as an independent manager and venture capitalist, ARPA-E could get the three sectors to collaborate.

Consequently, ARPA-E could kick-start projects that no other single entity would dare to support alone. Whereas the DOE advances mainstream biofuels and advanced solar research, for example, ARPA-E could step in to fund promising but orphaned contenders like solar paint or alternative biofuels feedstock, like kudzu. "It takes an integrated program to do biofuels right," says Steven Koonin, who directs BP's $500-million-per-year R&D effort. "The DOE has not been able to do that." An alliance with the Department of Agriculture might be needed for alternative biofuels research, for example.

THE ABILITY TO REACH across departments might be the agency's best attribute. Former DARPA director Frank Fernandez says that DARPA consistently collaborates with the military services, other DOD agencies, the CIA, and the Department of Justice, among others. "This is because DARPA can only take ideas to the prototype stage," he says. After that, another entity has to take over. "I would think that this kind of collaboration would be an essential part of ARPA-E's business plan," Fernandez says. In fact, Fernandez hopes to see DARPA and ARPA-E work together on projects of mutual interest.

The bill creating ARPA-E, H.R. 2272, has been dubbed COMPETES, for Creating Opportunities to Meaningfully Promote Excellence in Technology, Education and Science. Its more comprehensive provisions include sharp increases of funding for the National Science Foundation, the National Institute of Standards and Technology, and DOE's Office of Science; more than $33 billion in authorized spending, during the fiscal years 2008–10, by government agencies on science, technology, engineering, and mathematics; and more support for teacher training programs in those areas. —**SARAH ADEE**

JAMES OBERG

No Exit

Through this submarine-like hatch, volunteers for a 500-day simulated mission to Mars will transit from one train-car-size module to another in a mock-up of a Mars-faring spacecraft. The Institute of Biomedical Problems, in suburban Moscow, is now completing preparations to lock a group of people into the simulator in an effort to identify psychological problems that may arise during very long space missions. The main living module sports cozy wood paneling to seem Earthlike. But the decor is unlikely to make up for the isolation from all but your bunkmates. Phoning home won't help. It takes up to 15 minutes for radio signals to reach Earth from a Mars-bound craft, so all the voice and data lines into the simulator will be tape-delayed.

The crew will practice various psychological support techniques while scientists from the Russian and European space agencies monitor them remotely. Researchers will also be testing the crew's mental health in simulated emergencies. More than just a punishing stress test, the exercises will also assess the adequacy of remotely monitoring the physiological and psychological health of space travelers experiencing unprecedented isolation. In contrast to the International Space Station, which is frequently visited by Russian and American space vehicles carrying supplies and spare parts for emergencies, absolutely nothing will be added to the simulated spacecraft after it "departs" from Earth early next year. —**JAMES OBERG**

For a tour of the simulator, go to http://www.spectrum.ieee.org/sep07/marsxtra

THE BIG PICTURE

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426 000 Discarded Cellphones

We live in a consumerist society. The numbers are staggering, whether it's how many cellphones and plastic bottles we discard, cigarettes we smoke, paper and plastic bags we use at the supermarket, or painkillers we pop. How can we imagine the quantities involved?

If you're Seattle artist Chris Jordan, you pick a number, such as the number of cellphones that are retired in the United States every day, and figure out a way to show all 426 000 of them. Here, each speck of gray represents a phone, clearly visible in the original 150- by 275-centimeter picture.

Here's how you build an image of 426 000 cellphones. (1) Get 400 actual phones. (2) Pour them into a wooden frame on your studio's floor. (3) Photograph from directly above. (4) Stir. Make a similar but not identical photograph. (5) Repeat 198 times. (Each of the 200 images will be used five or six times.) (6) Spend the next two weeks manically trimming, by hand, around the edges of each of the 200 photographs, airbrushing out all the fractional phones. (7) Cut and paste 1065 times, moving the individual photographs around for the best visual effect and to keep the five or six identical copies as far away from one another as possible. Finally, (8) send a DVD with your 1-gigabyte file to a specialty shop in New York equipped with a Canon inkjet printer with a 60-inch-wide roll (152 cm) for printing, mounting, and framing. (9) Ship the framed artwork to the Von Lintel Gallery, in New York City.

Jordan's Web site, http://www.chrisjordan.com, contains images from the complete exhibit, "Running the Numbers," that included *Cell Phones, 2007*.

Photo by Chris Jordan

BUZZ! DRILL! RRRIP! Three A123 execs wield DeWalt's potent new line of tools, which pack the company's lithium-ion cells. From left: CTO Bart Riley, CEO David Vieau, and Ric Fulop, VP of business development.

HYBRID ELECTRIC CARS NEED MUCH BETTER BATTERIES—

TRANSPORTATION

"We knew from the start that we wanted to do auto batteries," says Ric Fulop, a 30-something entrepreneur with an electrical engineering degree and a curly mop of brown hair. "But we also knew that automakers only buy from companies with volume production and real customers."

It's a version of the old chicken-and-egg problem that has confronted would-be tech entrepreneurs for decades. But Fulop and company came up with a novel solution: "We had to do power tools first."

In 2001, Fulop, then 26, set up A123 Systems in Watertown, Mass., with three partners, taking the position of vice president of business development. Late last year the company's new design for lithium-ion batteries hit the market in a line of power tools aimed at professional builders from the DeWalt Industrial Tool Co. The batteries operate at 36 volts, twice the voltage of their predecessors, and hold 130 watt-hours per kilogram—twice as much as standard nickel-metal-hydride cells.

Lithium-ion cells are poised to take an increasing share of the auto battery market, just as electric drive seems set to begin a long, slow climb to become, at last, a serious power-train option. But what's rarely understood is how much that second revolution depends on the first.

The auto industry transformation began modestly enough a decade ago with the Toyota Prius, the now wildly successful gasoline-electric hybrid. And if A123 and dozens of like-minded companies and research groups can deliver on the promise of lithium-ion batteries for vehicle propulsion, in four to 10 years plug-in hybrids could be capable of going substantial distances on electricity alone. Enthusiasm for the plug-ins being tested now, along with the 15- to 65-kilometer pure-electric range projected for their successors using lithium-ion battery packs, has raised hopes. Some analysts dare to contemplate the re-emergence of a mass-market electric car, perhaps within a decade.

Chalk it up to changing attitudes as much as breakthrough inventions. High gasoline prices have given regulators and drivers alike a reason to smile on hybrids. And investors in the currently fashionable green tech sector love new energy-storage technologies, so critical to electric-drive vehicles.

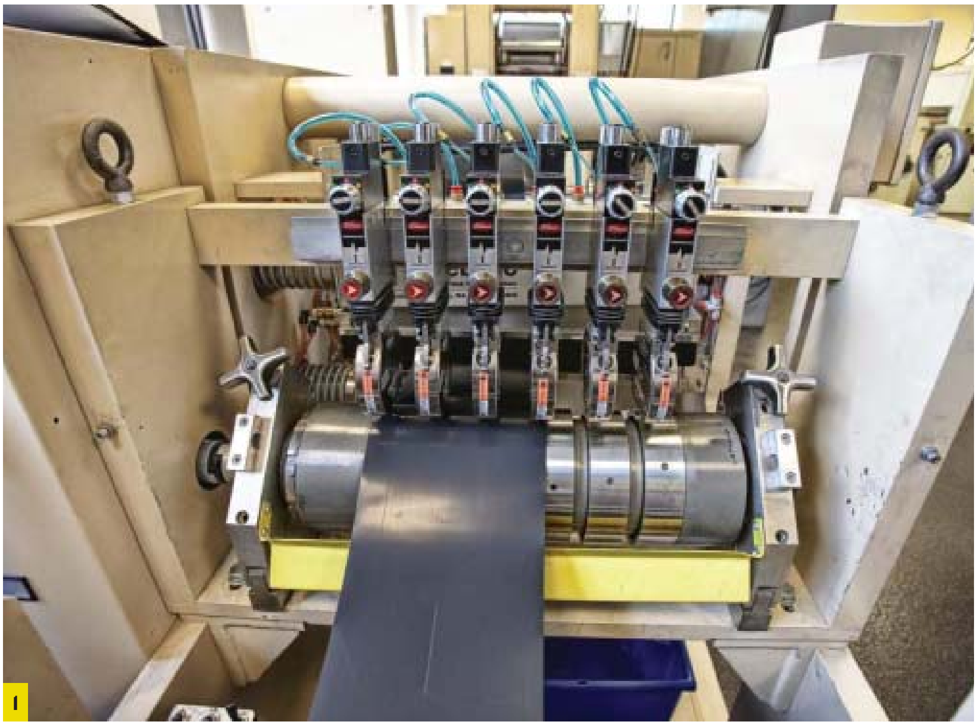
There are plenty of technical challenges—in the cells themselves, in the battery packs where they reside, and in the cars that will have to be engineered around them. The first to meet the challenges will be in the driver's seat of tomorrow's cars. A123, with its modest staff of 300 scientists and engineers, says its unique proprietary technology gives it a shot.

"The first vehicles to use lithium-ion batteries will come in 2009," Fulop declares. "In 2010, there'll be several. By 2015, most of the world's hybrids will use them."

A123 already has contracts to supply batteries to several European and American automakers, Fulop adds coyly, declining to identify the companies. He points out that early this year A123 received one of General Motors' first commissions for R&D work on lithium-ion batteries.

LITHIUM BATTERIES TAKE TO THE ROAD

AND A123, A PLUCKY MASSACHUSETTS START-UP, SAYS IT'S GOT THEM BY JOHN VOELCKER




BATTERY FACTORY: At its R&D lab in Watertown, Mass., A123 makes and tests small batches of lithium-ion batteries, relegating its large-scale manufacturing to facilities in Asia. (1) A machine splits a reel of electrode into strips narrow enough to fit the width of the final battery. (2) Rolls of electrode foil sit in racks on a wall, like fabric in a store. (3) Most materials are safe enough and tough enough to work in the open air, as in this example. (4) However, to store the more sensitive components, such as powders and electrolytes, researchers must have recourse to the low-oxygen, low-humidity, dust-free environment inside this glove box.

In fact, in June, GM raised the stakes, announcing two more R&D contracts: one to Compact Power of Troy, Mich., which plans to use cells from Korean battery maker LG Chem, and the other to a division of the German auto parts maker Continental, which plans to build battery packs incorporating A123's cells.

EXPERTS AGREE that lithium-ion cells will power coming generations of cars—hybrid, plug-in hybrid, and pure electric. At first the car companies will put the new batteries in just a few standard hybrids, to test the waters, or they'll use them to fill market niches, like the one for such dazzlingly fast sports cars as the Tesla Roadster [see "Top 10 Tech Cars," *IEEE Spectrum*, April]. Later they'll put them in plug-ins—at first, in standard parallel designs, which drive the wheels with either the motor or the engine or some combination of the two. Then, perhaps, they'll move on to the more radical series design, in which the electric motor drives the wheels, leaving the engine no other role than to recharge the batteries.

Cars won't come until the batteries are affordable, and batteries won't be affordable until the automakers purchase a lot of them. This year, though, the world's top two automakers made firm commitments to lithium-ion technology.

Toyota, the world's biggest and most profitable car company, said that late next year it will put lithium-ion batteries in an unspecified hybrid vehicle. It will also test a fleet of plug-in hybrids, using nickel-metal-hydride cells, that are able to run a few kilometers on batteries alone. Today's Prius can do that for only a couple of minutes, and then only at speeds of less than 50 km/h.

General Motors is playing catch-up—but with a vengeance. Late this year, it expects to finally launch its first hybrids able to run in all-electric mode, if only for a minute or two. GM recently said it will "soon" offer a true plug-in, with an all-electric range of 16 km (10 miles), although it hasn't committed to a launch date, saying that the batteries aren't yet ready. GM is also planning to build a true series hybrid—the Chevrolet Volt, first shown as a concept vehicle in January.

Why aren't the batteries ready for prime time? There are lots of reasons, including cell life and cost, but perhaps the biggest of all is safety. Remember last year's vivid videos of flaming laptops? Nobody was hurt, but the resulting recall of millions of lithium-ion batteries was a black eye for Sony and other major vendors. If a lithium-ion powered minivan carrying a family were to burst into flames, the resulting fiasco could set the industry back a decade. And it's no use arguing that something like 250 000 gasoline-powered cars catch fire every year in the United States alone. New products are held to a higher standard.

Safety is key, and it all comes down to preventing fires and explosions. These catastrophes happen when a cell shorts out, gets hot, and starts an exothermic oxidizing reaction that kicks the temperature to hundreds of degrees Celsius in a fraction of a second. The heat then shorts out adjacent cells to produce a runaway thermal reaction that can be spectacular (just ask Sony). And, unlike a gasoline fire, the conflagration can't be smothered, because it gets oxygen from the cell's intrinsic chemistry.

Field failures occur once in every 5 million to 10 million of the most common lithium-ion cells, those known as the 18650 design, according to Brian Barnett, a technology analyst at Tiax, a consulting firm. Of course, the more cells there are in a battery pack, the greater the chance of a problem. Although it's clear that impurities introduced during manufacturing are largely to blame, the mechanism remains unclear.

There are several ways to make the new technology safe enough for cars. One, perhaps transitional, approach is to link large numbers of small cells in networks—as the Tesla does—with safeguards to ensure that a problem in one cell cannot propagate to others. A123 and some other start-ups instead chose to focus on the fundamental reactions in the cell.

PREVIOUS PAGE: BATTERY: A123 SYSTEMS

3

4

FIRST, A LITTLE CHEMISTRY. (Don't worry—it's so straightforward that chemists like to call lithium-ion "the physicist's battery.") Like any battery cell, this one has two electrodes sitting in an ion-rich solution, the electrolyte [see diagram, "Anatomy of a Cell"]. The electrodes are typically very close, so a polymer film, called a separator, prevents contact and a possible short circuit. A switched external circuit connects the electrodes to draw power, and the electrochemical reaction begins.

Ionized elements in the anode—in this case, including lithium—are tugged by the electric potential that is inherent in their chemical relation to elements in the opposing electrode, the cathode. The ions move through the electrolyte and the separator. Those arriving at the cathode give up electrons; those coming to the anode accept them. Electrons travel through the external circuit, producing a flow of charge complementary to the flow of ions. During recharge, current is forced into the cell, reversing the process.

Cell shapes vary widely, from thin discs hardly larger than a pinhead to high-power specimens the size of a small fire extinguisher. The consensus view in the auto industry is that battery packs will consist of up to 100 large-format cells of 20 to 50 ampere-hours apiece—each cell perhaps 50 millimeters wide and 200 mm long—grouped into modules that include sensors and electronics. The modules feed data to an electronic battery management system, which performs the crucial function of enabling cells of varying power and voltage to work together as a unit.

The Tesla alternative, packaging thousands of inexpensive commodity cells, requires far more sensors and control software than would be practical for mass-market vehicles.

There is no one lithium-ion battery. Several chemical designs compete, each with advantages and drawbacks. "No chemistry will be the perfect one," says Klaus Brandt, the chief executive of Gaia, a German subsidiary of Lithium Technology Corp., of Plymouth Meeting, Pa. "Different chemistries will find different niches that vary with cost, performance, and safety."

The anode is typically made of graphite, but the cathode composition varies widely from design to design, and as much as any other factor it determines a battery's capacity. The critical feature is the rate at which the cathode can absorb and emit free lithium ions; this parameter in turn largely determines the power density. Each of several competing cathode materials has a different mix of cost, durability, susceptibility to temperature, and so forth. Cobalt is more reactive than nickel or manganese, meaning it offers high electrical potential when paired with graphite anodes, permitting higher voltage. However, cobalt, like nickel, is expensive. Manganese is cheaper, but it is slightly soluble in electrolytes—which means a shorter useful life.

The most important cathode contenders:

Cobalt dioxide is the most popular choice today for small cells. It has been on the market for 15 years, so it is proven and its costs are known. It has high electrical potential and the highest energy density—up to 600 Wh/kg. On the other hand, when fully charged, it is the most prone of all the cathode alternatives to oxidation and subsequent thermal runaway. Its internal impedance—the extent to which it "pushes back" against an alternating current—also increases with both calendar time and cycling. Cobalt dioxide cells are manufactured by dozens of Chinese, Japanese, and South Korean companies.

Nickel-cobalt-manganese is somewhat easier to make. Substituting nickel and manganese for some of the cobalt raises the electrical potential only slightly, but it's enough to let manufacturers tune the cell either for higher power or for greater energy density, though not both at the same time. (Remember that total

ALL OTHER PHOTOS: JOSHUA DALSIMER

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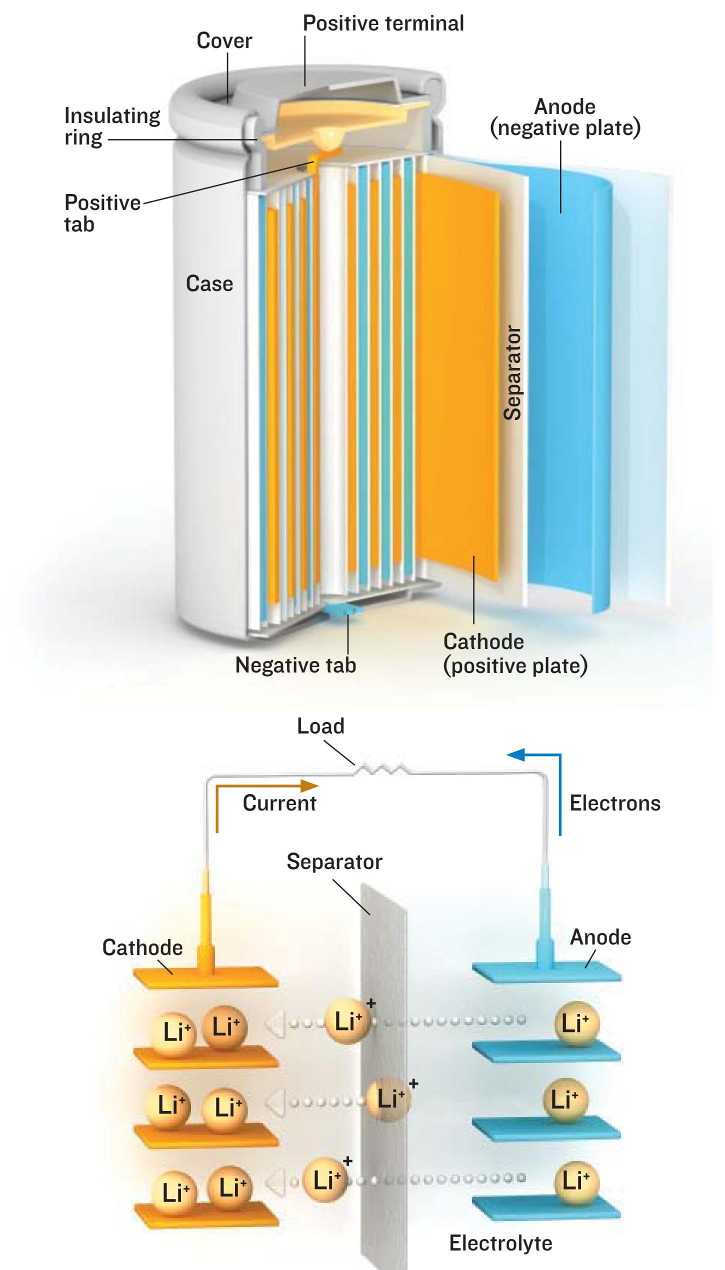

Source: ©2006 HowStuffWorks

ANATOMY OF A CELL: In a lithium-ion cell, the two electrodes are held apart by a separator, all of it wound spirally into a cylindrical shape and bathed in an electrolyte. When the circuit is closed, the anode gives off electrons via the external wire, delivering power and creating positive lithium ions that travel to the cathode. On recharge, current is forced into the cell, reversing the process.

energy determines the vehicle's range, whereas available power determines its acceleration.) It is susceptible to thermal runaway, though less so than cobalt dioxide. Its long-term durability is still unclear, and nickel and manganese are both pricey at the moment. Manufacturers include Hitachi, Panasonic, and Sanyo.

Nickel-cobalt-aluminum is similar, with lower-cost aluminum replacing the manganese. Companies manufacturing NCA cells include Toyota and Johnson Controls–Saft, a joint venture between a Milwaukee company and a French firm.

Manganese oxide spinel offers higher power at a lower cost than cobalt, because its three-dimensional crystalline structure provides more surface area, permitting more ion flow between the electrodes. The drawback is an energy density only slightly better than 450 Wh/kg. GS Yuasa, LG Chem, NEC-Lamilion Energy, and Samsung offer cells with such cathodes.

Iron phosphate may well be the most promising new cathode, thanks to its stability and safety. This is what A123 is using in its batteries. Other manufacturers include Gaia and Valence Technology, in Austin, Texas. The compound is inexpensive, and because the bonds between the iron, phosphate, and oxygen atoms are far stronger than those between cobalt and oxygen atoms, the oxygen is much harder to detach when overcharged. Therefore, when it fails, it does so without overheating.

Unfortunately, however, iron phosphate doesn't conduct well; to compensate, engineers have to add dopants. Even then, the cells work at a lower voltage than cobalt, so more of them must be chained together to drive a motor. That means iron phosphate battery packs need more interconnections and sensors to control the system.

One way around that problem is A123's use of nanostructures in the cathode. This proprietary method produces better power and longer life than earlier generations of iron phosphate cells, says Andy Chu, a researcher at A123.

As phosphate molecules in the cathode acquire and give off lithium atoms—undergoing lithiation and delithiation—the phase boundary between the two states shifts, just as the boundary between cold water and ice does during freezing. In A123's nanostructures, Chu says, the molecular lattices of the two states are structurally more similar to each other than in other phosphate cells, so atoms need less time to rearrange themselves. That means lithiation can proceed faster, delivering more power.

Moreover, because the lattice spacing of the two phases is closer, the physical stress on the cell is reduced, especially in deep discharge and charge. The cells should thus last longer.

"The batteries have performed as advertised by A123," said a third-party tester who requested anonymity because he wasn't authorized to speak to the news media. He noted that even when the cells were subjected to severe abuse, including extreme overcharging, they failed in a "relatively benign fashion."

One shadow hanging over iron phosphate chemistries is the extent of the coverage of patents for work done by the pioneering researcher in the field, John Goodenough, now of the University of Texas at Austin. A123 insists that its work does not violate the patents. Gaia, on the other hand, purchases only materials manufactured under license to the patent owner.

ONE CHARACTERISTIC FLAW of lithium-ion batteries, anode plating, comes when a recharging cell dumps lithium ions faster than the anode can absorb them. This problem can be caused either by low temperatures, which slow the rate of diffusion, or by overcharging, which slows the rate of absorption. One of the jobs of the battery management system is to keep overcharging from ever happening.

Plating is bad for a number of reasons, particularly because it further reduces absorption, increasing the concentration of carbon ions until they begin to react with the oxygen in the electrolyte. The oxidation—equivalent to that in a burning lump of coal—creates a lot of heat, which in turn increases the rate of deposition.

A123 says its carbon anode combines the high rate of charging provided by graphitic carbon with the long life of nongraphitic types. It won't give details of its proprietary formulation, saying only that it fine-tunes the size and structure of the particles.

Altair Nanotechnologies of Reno, Nev., wards off plating by coupling standard cobalt oxide cathodes with anodes made of lithium titanate spinel rather than graphite. The spi-

BRYAN CHRISTIE DESIGN

nel won't react with oxygen, and it also charges fast and lasts long. However, the energy density—at the current, early stage of development—is only half that of standard cobalt cells, and it is little better than that of nickel-metal-hydride cells.

The second-toughest problem after thermal runaway is limited life span, as measured by both the calendar and the number of charge-discharge cycles. A123's Fulop says the cycle-life goals are easy to meet, but the calendar-life ones will be harder.

Cobalt-based cells for portable electronics lose as much as 20 percent of their capacity each year, starting from the day of manufacture. That may be tolerable for cellphones and other portables that are replaced every three or four years, but not for a car, which is expected to last 15 years.

The California Air Resources Board requires a vehicle's power train to last for 10 years or 150 000 miles (240 000 km) with the original components. GM has said, meanwhile, that it expects battery packs for its Volt concept car to last for at least 4000 full-discharge cycles. That's good but might not be good enough. At one charge-discharge cycle per day, the pack would last for 11 years—though it's the rare car that runs 365 days a year for a decade.

Worse yet, auto and battery makers don't have the luxury of spending 10 years testing lithium-ion packs. "Ideally," says Mark Verbrugge, director of GM's materials and processes laboratory, "we'd have half the life span to test it. But we don't, so there's no clean answer." Meanwhile, automakers are "oversizing" their battery packs to ensure they'll power the car even after projected degradation. Of course, that strategy adds cost and weight.

THEN THERE'S THE FINAL HURDLE: COST. At the moment, 12-V lead-acid batteries cost US $40 to $50 per kWh. Nickel-cadmium and nickel-metal-hydride cells for portable electronics cost $350/kWh; lithium-ion cells for the same market go for $450/kWh. Move to hybrid vehicles, though, and the price for longer-lived, more rugged nickel-metal-hydride batteries shoots up to about $700/kWh. That's more than double the $300 target set by the U.S. Advanced Battery Consortium for automotive lithium-ion packs.


THEY PUT THE JOLT IN THE VOLT: A123's dynamic trio pose beside Chevrolet's Volt, a serial hybrid concept car that uses their company's batteries.

Manufacturers expect to reach that target by 2015, but in the earlier stages of production the price will likely be several times higher. How low must the price fall before a manufacturer will commit to even a low-volume purchase? No one will say, though every manufacturer surely has a threshold in mind. As GM's Verbrugge summarized with a straight face, "Cost lower—always better."

World politics plays a role in some of those costs, especially prices of the raw materials. Lithium is not a "strategic metal," unlike nickel—whose price is surging as demand for stainless steel grows—so the cost of the metal per kilowatt-hour is lower for lithium than for nickel-metal-hydride. Right now, Chile and Argentina supply much of the world's lithium carbonate, but Bolivia and China also have large reserves.

Geography does matter in another way, one that may give A123 an advantage: its headquarters and research labs are in the United States. No automaker wants to depend on a supplier in a distant land, especially one whose loyalties lie with a competitor. Take Ford: it purchased nickel-metal-hydride battery packs for its Escape Hybrid SUV from Japan's Sanyo Electric Co., which had developed them for Toyota. But if battery supplies get tight, Sanyo's ties to Toyota surely will outweigh Ford's needs.

With North American and European companies intent on nurturing battery companies in their own backyards, A123 is focusing its sales and marketing efforts in those regions. And clearly that focus has started to pay off.

A123 IS CONFIDENT IT CAN COMPETE with the big boys. It is fully global, concentrating its research and development in North America and manufacturing in Asia. Already Europe's Continental will build A123 cells into battery packs, and Fulop itches to provide details of A123's other contracts.

How, then, is development going? The goal remains the same: raise cell power beyond today's 3.5-V maximum, as high as the company's nanostructure phosphate chemistry will permit, while working toward cell life beyond 10 years and 5000 full-discharge cycles. If A123's cells can deliver the power and energy of the best cobalt varieties with far less danger of a spontaneous meltdown, the company could carve out a big, profitable share in the auto components industry. A123 won't reveal the details of its R&D, of course, but it has said it expects further significant improvements in chemistries and molecular structures.

For a company whose first products reached consumers less than a year ago, A123 is on a fast track. DeWalt cites builders who say they can finally replace corded tools, because the 36-V line now provides all the torque they need. In fact, A123 has ignored most inquiries from potential buyers, instead focusing on existing customers and future markets. That's a luxury few companies enjoy.

Clearly the next five years are critical. Fulop notes that at this year's conference on advanced auto batteries, several companies declined to discuss current and future developments. "The submarines have gone underwater and turned on their sensors," he says cheerfully. "Everyone's preparing their attack." Asked what keeps him up at night, Fulop is startled. "The big challenges are behind us," he says. "We're well capitalized. We've got numbers of customers. Our products are good for this application."

Then his voice rises. "What excites me is to finally see our batteries in actual vehicles, after so many years of work," he says with a grin. "That's cloud nine." ■

ABOUT THE AUTHOR

JOHN VOELCKER, *IEEE Spectrum*'s automotive editor, has covered automotive technology for 25 years.


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TECH EXPEDITION

Swimming to Europa

A robot designed to explore Mexican sinkholes is pointing the way to Jupiter's watery moon

By Jean Kumagai

Photographs by Randi Silberman

It's a hot late-spring Friday on a cactus-studded cattle ranch in Mexico, and nothing is happening. Nothing, in fact, has been happening for going on a week now, and it's starting to get tedious.

Ordinarily, the group of scientists, engineers, and students who have gathered here might have enjoyed a respite from their otherwise crazy schedules. But they didn't come here to catch up on their reading, play the guitar, or take long, leisurely walks. They came here to work.

Their goal is to field-test one of the most intelligent and agile underwater robots ever crafted, a possible predecessor of a machine that might someday swim the vast, ice-crusted ocean of Jupiter's mysterious moon Europa. Called DEPTHX, for DEep Phreatic THermal eXplorer, the 1.3-metric-ton machine can maneuver freely, draw detailed, three-dimensional maps of its watery surroundings, and collect solid and liquid biological samples as it senses changing conditions in its environment. Most important, it does all that without any guidance from human operators.

Such autonomy would be essential if the robot ever does swim on Europa—which may be warm enough, thanks to geothermal activity, to have given rise to some sort of life. Human control of a robot sub that far away isn't an option: radio waves don't effectively penetrate water. Even if they did, a round-trip radio signal would take 2 hours or more, making remote control unlikely.

But today, on this sweltering retreat near the Gulf Coast of Mexico, with cicadas buzzing and a hazy sun beating down, Europa seems a long way off. At the moment, the robot is up on blocks, and the clock is ticking. Every project involving complex machinery experiences the odd delay out in the field. The weather won't cooperate, a part breaks, software crashes. Such problems are expected and can be worked through. This delay, though, seems to defy rational remedy.

A permit from the Mexican government that will allow the crew to continue their activities has been caught up in a tangle of diplomatic grandstanding. For more than a week, phone calls, e-mails, and faxes have been flying back and forth in an attempt to extract the permit from the proper authorities. Many of the researchers will soon have to leave, as other work and family responsibilities call them home. If the team doesn't get the go-ahead by 5 p.m. today, they'll have no choice but to pack up the robot and leave.

It's not looking good.

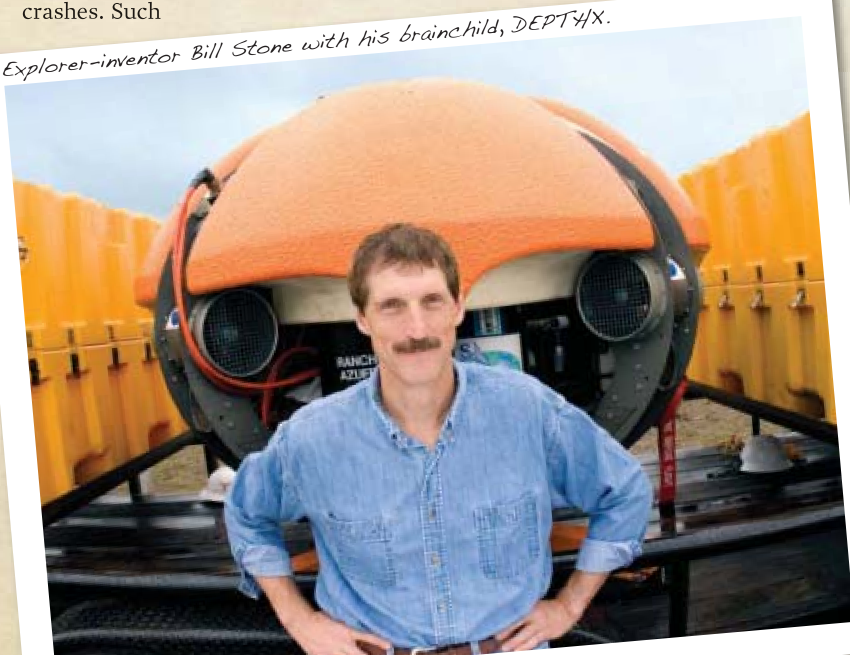
DEPTHX is the brainchild of Bill Stone. With a Ph.D. in structural engineering from the University of Texas at Austin, Stone worked for 27 years as a researcher at the National Institute of Standards and Technology, in Gaithersburg, Md., where he specialized in industrial automation. Since 2005, he's also had his own company, Stone Aerospace, in Austin, which has been focused exclusively on building the DEPTHX robot.

Of the countless engineers who as children read the fictional adventures of Tom Swift and dreamed of becoming the fearless explorer-inventor, Stone is arguably the one who actually did it. Tall and lanky, with hawkish features and piercing blue eyes, he is probably best known for his exploits, chronicled in *National Geographic* and other magazines, in some of the world's deepest and most dangerous caves. Not uncommonly, those expeditions revolved around sophisticated technology of his own design and construction.

He'd spend weeks underground, pushing to, and occasionally beyond, the limits of endurance. Many of the DEPTHX team members, in fact, are old caving buddies of his. Marcus Gary, the project manager and a geology Ph.D. candidate at UT Austin, is a caver. So are John Kerr, lab manager for Stone Aerospace, and Vickie Siegel, a geologist and part-time staffer.

Fascinated with caves since childhood, Stone learned to scuba dive just so he could explore water-filled caverns. Frustrated with the limits of diving gear, he spent years and most of his savings designing a rebreather, an intricate and ingenious piece of engineering that recycles a diver's respired air, scrubbing out the carbon dioxide and adding oxygen and other gases as needed to let him stay submerged for up to 24 hours.

Explorer-inventor Bill Stone with his brainchild, DEPTHX.



ALL ILLUSTRATIONS: LAURA H. AZRAN

Stone had also long dreamed of space travel. As a younger man, he applied repeatedly to enter NASA's astronaut-training program and eventually made it far enough to be interviewed at the Johnson Space Center, in Houston. In his 2002 book *Beyond the Deep*, Stone identifies the point in that interview when his candidacy went south. He had just articulated his vision of establishing a permanent base on the moon. NASA at the time had no interest in such ventures, and one of the interviewers told him so. "Well, sir," Stone blurted out, "then God help the United States of America."

Robotics, exploration, and space travel: drawing on his three passions, Stone began thinking seriously about designing an underwater planetary probe about five years ago. It built on work he'd done in the late 1990s, when he had put together a diver-steered sonar apparatus called the Digital Wall Mapper, which successfully surveyed Florida's vast freshwater Wakulla Springs. A planetary scientist named Dan Durda, of the Southwest Research Institute in Boulder, Colo., heard about that work and asked Stone if he could do the same for exploring Europa. "Piece of cake," Stone told him, with customary bravado.

It took another year to fashion a proposal to NASA's liking—unlike the Wakulla mapper, this robot would have to operate autonomously, and it would have to collect biological samples in addition to taking stock of its aquatic environs. In October 2003, the funding came through: US $5 million over three years.

"Then I had to figure out how to build it," Stone says.

The robot floats in El Zacatón, a deep sinkhole in Mexico.

Though he didn't yet know what the robot would look like, Stone knew exactly where he would test it out: in a series of deep sinkholes, or cenotes, at Rancho La Azufrosa, about 400 kilometers northeast of Mexico City. Scuba divers and geologists have long been fascinated with the site, but detailed studies were lacking.

The deepest cenote, called El Zacatón, held a particular significance. In 1994, Sheck Exley, one of the world's premier cave divers and a good friend of Stone's, died while attempting to reach 1000 feet (305 meters). When they pulled his body out of the water, wrapped in his descent line, his dive computer read 268 meters. No human since has succeeded in plumbing Zacatón's depths.

Limestone cliffs reach up 25 meters above Zacatón's smooth surface. Flurries of butterflies flit among the wildflowers at the cenote's lip. Buzzards circle overhead, and the lime-green parrots that live in the cliffs screech at the intruders in their midst. In the afternoon sun, the warm water turns milky, the result of microbes that metabolize the sulfides in the water. After dusk, they'll release the sulfides again, and powerful fumes will rise up into the night sky.

If Zacatón weren't pulling double duty as a test bed for advanced robotics, it would be studded with tiny islands of tall grass, called zacate, that float freely on the water. For the robot's safety, though, the zacates have been corralled at one end behind a yellow rope. A canopied dock festooned like a NASCAR racer with all the logos of the project's participants sits nearby; during missions, the programmers and robot wranglers use the dock for monitoring the vehicle's progress. A tall white construction crane perches on one cliff. When the time comes—if the time comes—to fire up the robot, the crane will gently lower the vehicle to the water's surface.

During earlier runs in January and March, the robot had mapped La Pilita, a smaller, urn-shaped cenote just down the dirt road from Zacatón. The team had returned with high hopes of pushing DEPTHX to its limits, fully exploring Zacatón and perhaps some of the other nearby cenotes.

On its initial run at Zacatón just days earlier, before the snafu over the permit, DEPTHX had descended all the way to the bottom, registering a tentative depth of 318 meters. To put that in perspective: if you submerged New York City's Chrysler Building in the sinkhole, just the last meter of its elegant spire would stick out of the water.

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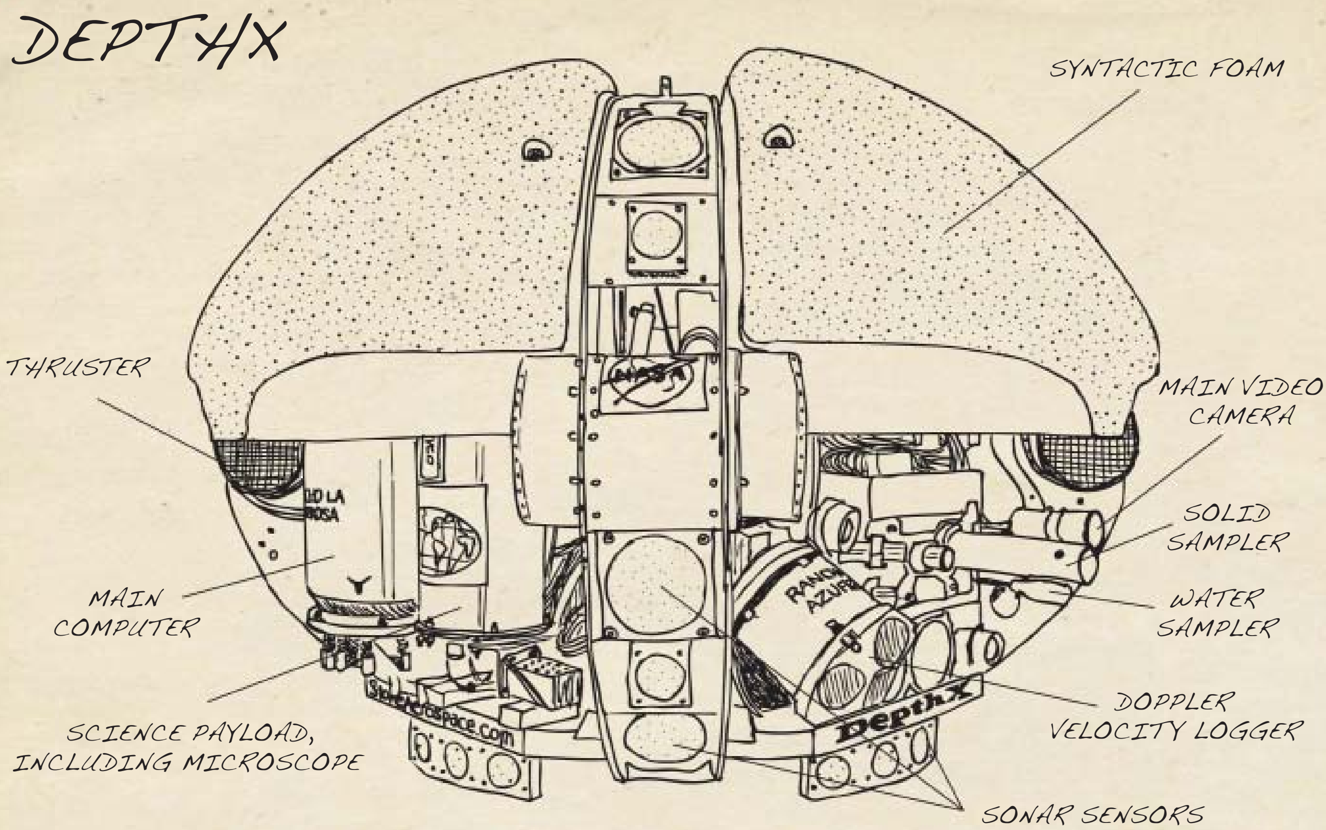

But the sonar map that DEPTHX drew was tantalizingly incomplete. There appeared to be a passage at the deepest point leading off to one side. Stone has been exploring deep caves in Mexico for decades, and he's seen passages like this before. "If this is what I think it is," he says, "it could go on for hundreds or thousands of meters." The robot would need more time in Zacatón to tell them if the passage was real.

And more time, too, to complete DEPTHX's scientific mission—namely, exploring the biology of the sinkhole. Zacatón's walls are covered with a thick slimy coating of microorganisms, while other microbes float freely in its sulfurous water. The plan is to have the robot gather solid and liquid samples at various depths. Later, DNA analyses and studies of the water's chemistry would tell scientists much about life in the cenotes. This exercise would also be a vital step for exploring Europa, whose ocean may harbor life.

There's never been an aqueous robot quite like DEPTHX. Most autonomous underwater vehicles look the same, Stone says. "Some have fat midsections, some are more elongated, but they pretty much all look like weird torpedoes." We're sitting in a cramped, airless room that's become his temporary headquarters at the ranch. The temperature outside is climbing past 32 °C, and it's even hotter in here, but Stone doesn't seem to notice. He's fired up, and he could go on for hours.

"Their design is dictated by their mission: traveling in straight lines at relatively high speed to survey the ocean floor or gather bathymetry data," he continues. But for exploring uncharted territory, that shape can get you in trouble. You can back yourself into a tight spot where you can't turn around.

Two years ago, a team at the University of Southampton, England, learned that lesson the hard way. Their autonomous robot, named Autosub, was exploring the ice shelf below Antarctica. "It was 17 kilometers in, under 200 meters of ice, when it got itself into a position where it couldn't figure out which way was home," Stone says. And so the $10 million robot parked itself, sent out an emergency signal, and waited. And waited. "The scientists back on the surface could still pick up its signal, but there was no way they could go in and rescue it." It's presumably still there, somewhere below the ice.

DEPTHX, by contrast, is designed not for high speed but for complicated maneuvering in unfamiliar environments. Hence its shape: a squashed sphere with no protruding parts to catch on things. "We used to have a Wi-Fi antenna on top," Kerr says. "But during one

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run we surfaced under the chase boat and it snapped off." And if one of the robot's six thrusters goes out, it can just rotate around and use the others.

With its top half encased in pebbly orange syntactic foam, for buoyancy, the robot looks kind of like a giant tangerine. The vehicle's shape was also dictated by its mapping software, known as SLAM, for simultaneous localization and mapping.

SLAM "is designed to solve a chicken-and-egg problem," says David Wettergreen, an associate research professor at Carnegie Mellon's Field Robotics Institute, in Pittsburgh, which was responsible for DEPTHX's software—all 100 000 lines of it. "To build a map, you have to know where you are, but to know where you are, you need a map." SLAM does both things simultaneously, creating a 3-D map as it moves along and then positioning itself within the map.

Variations of SLAM are commonly used in robotics, and they typically rely on identifying distinct features in the surroundings, like a doorway or a tree, viewing those features from many points, and then triangulating the robot's relative position. But underwater environments have few recognizable features—a slime-covered wall looks very different when viewed from the front and from the sides.

So Nathaniel Fairfield, a Ph.D. student at Carnegie Mellon who wrote the SLAM algorithm for DEPTHX, designed the software to look not at discrete objects but at the shape of the environment as a whole. To do that, the robot uses 56 sonars, mounted on two circular steel frames that intersect at the top and bottom of the vehicle. As the robot descends through the cenote at the leisurely pace of 1 meter per second, it also spins around about once per minute; each sonar fires up to four times per second, allowing the beams to "paint in" the surroundings.

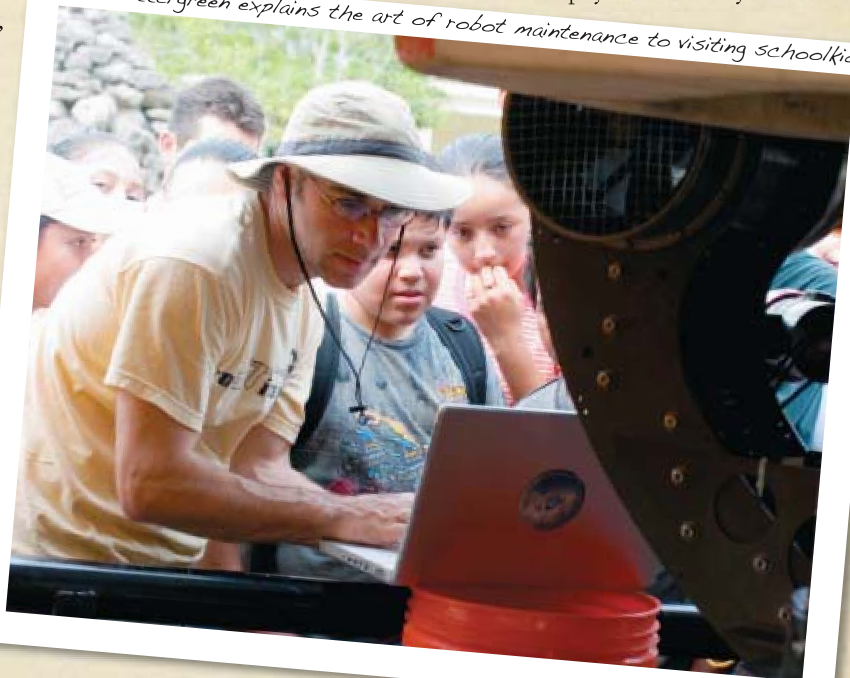
Controlling the sonars and the 19 other subsystems on the machine are 36 onboard computers. Power is supplied by a pair of lithium-ion battery packs that will run for up to 5 hours between recharges. Much of the hardware is enclosed in pressure-resistant aluminum housings, to protect the contents from being crushed by the external water pressure. Other components are built into oil-filled housings, which balance the outside pressure while keeping water out.

DEPTHX's other key piece of software gives the robot autonomy, allowing it to make decisions about when and where to move. The Carnegie Mellon programmers paid particular attention to how the robot deals with faults. "We have contingency plans for all kinds of failures, like all the sonars turning off at once, or one battery giving out, or the robot losing its way," Wettergreen explains. "If something goes wrong, and it's at the bottom of the cenote, with its batteries running low, it can't just stop and wait. It has to do something sensible"—initiate a controlled ascent, for example.

Autonomy also means the robot has to decide on the fly where and whether to gather biological samples. The machine starts by characterizing its surroundings. Sensors continuously measure the water's salinity, temperature, pressure, and chemistry. "Changes in any of these conditions are where we'd expect to find biological activity," says Ernest Franke, an engineer from Southwest Research Institute, where the robot's sampling arm and science autonomy system were designed and built.

The robot then "trains" itself by taking a baseline water sample. The liquid is inspected under an onboard microscope, and a subroutine counts any moving objects (likely microorganisms), tracks their paths, and measures their speed. Another subroutine tells the robot's video camera to take a baseline reading of the cenote's slime-covered walls, measuring their color, intensity or saturation, and texture.

The result of each subroutine is a statistical classifier, a value that averages all the parameters, much as your credit score is computed from details such as your age, salary, and mortgage payment history. These two classifiers—one for water, the other for the walls—are then compared with subsequent readings the robot takes. When it spots a significant difference, suggesting a rise in biological activity, it takes a water or solid sample. For the latter, the robotic arm extends about 2 meters and punches a pinky-size chunk from the cenote wall. To gather liquid, a water sipper on the arm fills up plastic bags. After the robot surfaces, the team will remove the specimens and freeze them in liquid nitrogen for later analysis.



David Wettergreen explains the art of robot maintenance to visiting schoolkids.

Any robotic probe that swims on Europa will have to do all that—and much more. Stone has no doubt that machines will eventually have the requisite smarts, though. Europa will still be there in 10 or 20 years, he notes. "We have time."

Today, with the robot sitting on the back of a truck, all hands are scrounging around for projects to keep themselves occupied. Franke plugs an oil leak that's

A construction crane lowers DEPTHX into the sinkhole.

The bisecting rings of sonar sensors are visible during the robot's descent.

sprung up in the sampling arm. Dominic Jonak and George Kantor, both of Carnegie Mellon, tweak the robot's control and navigation software. Kerr replaces the sulfide sensor and mounts a pair of 100-watt lamps, for additional illumination at Zacatón's murky depths, as well as a lead-acid battery pack to power them.

Throughout the day, local schoolchildren and picnickers arrive at the ranch to gawk at the robot, which has gotten wide coverage in the Mexican media. The Spanish speakers on the DEPTHX team obligingly give them the grand tour.

When they've run out of useful tasks, some people go for a dip in the cenotes, while others hang out in the shade of a palm-covered palapa, an open-sided gazebo that functions as the team's computer room, dining hall, and after-hours jamming studio. Robin Gary, a geologist married to Marcus, cooks up a hearty meal. Over beers, people trade war stories about their favorite death-defying experiences in the field: lightning storms, carbide-lamp explosions, not showering for 62 days in a row. Someone breaks out a guitar. Nobody can seem to remember all the lyrics to "Hotel California," but that doesn't stop them from trying. As another day passes with no word on the permit, what else is there to do?

If you're still not convinced that scoping out Mexican sinkholes is the logical jumping-off point for exploring one of Jupiter's moons, just ask Richard Greenberg. He's a professor of planetary sciences at the University of Arizona, in Tucson, and author of *Europa, the Ocean Moon*.

"I'm here as a sort of reality check," Greenberg says, sitting on a beach chair in the late-afternoon heat. He's been fascinated with Europa since at least 1977, when he joined the imaging team for NASA's Galileo mission, which orbited Jupiter and its moons for nearly eight years, beginning in 1995. The space probe's most intriguing discovery was the likely existence of a vast ocean beneath Europa's icy crust.

"It's the only other celestial body that we know of that has an ocean," Greenberg says. The water covers the entire surface to a depth of perhaps 160 km. So even though Europa is only about the size of Earth's moon, it has twice as much liquid water as all of the oceans of Earth combined.

Scientists believe there's a good chance that something is alive in that watery world. "It's one of the most likely places for us to find extraterrestrial life," Greenberg says. "All the basic ingredients that life might need are there." Ingredients like sunlight, organic molecules delivered by asteroid or comet, and radiation from Jupiter's magnetosphere. If life exists, he says, "it could just be micro-organisms, but with an ocean that deep it could be much more complex."

To get to that ocean, though, means somehow penetrating the several-kilometer-thick ice sheet that encapsulates the moon. Fortunately, the ice is networked with cracks, some of which extend deep below the surface. "If you landed 'smart,' and you got next to a crack in the ice that went down to the ocean, you could sample oceanic material that had sloshed up to the surface—or even send a probe down through that crack and into the ocean," Greenberg suggests. DEPTHX is the first incarnation of what such a probe would look like.

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John Spear, for one, wouldn't mind if life on Europa turned out to be entirely microscopic. He's a microbiologist by training, and, it must be said, by disposition. "There are 600 kinds of micro-organisms living in your mouth," he informs me when we first meet at the ranch. I hadn't even considered the possibility, but brushing my teeth is now a whole new experience.

Based at the Colorado School of Mines, in Golden, Spear searches for microbes that live in so-called extreme environments—geysers in Yellowstone National Park, volcanic hot springs in Kamchatka, and hypersaline lagoons in Baja California.

Show him a warm, sulfurous cenote and he is a happy man. "I knew that when we explored these water-filled limestone holes, we wouldn't be looking for big fish or bugs or plants," Spear says. "We're looking for the microbes, because those are the most likely things to be found throughout the cenote, on the walls from top to bottom and also within the water column."

George Kantor [left] and Dominic Jonak share a joke during night duty.

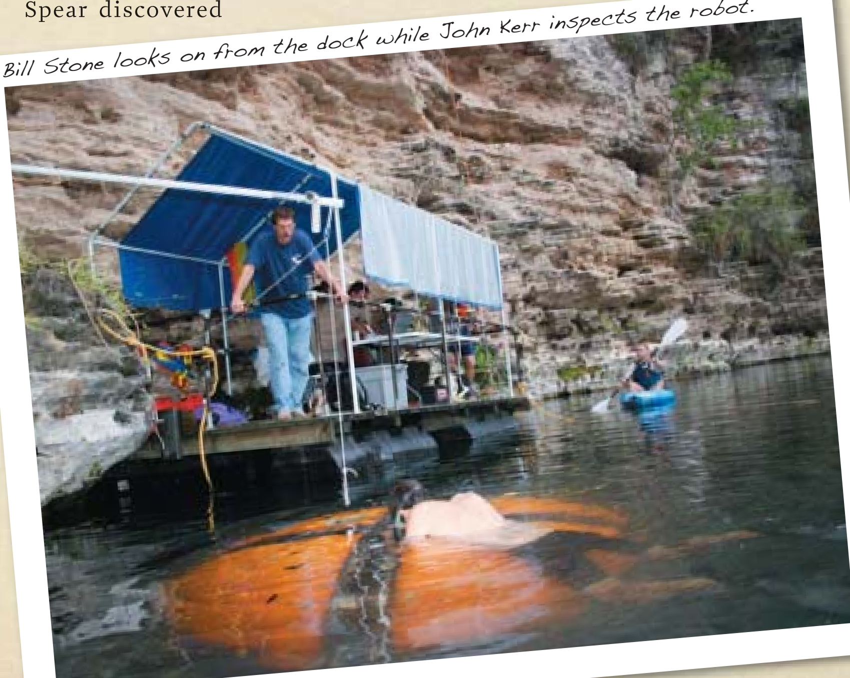
Gathering samples in the field is mostly done by hand, he adds, but at Zacatón, the robot would have to serve as his proxy. "I wanted the machine to be me—to be a field microbiologist," Spear says. "When I'm in Yellowstone, I smell things, I look at things, I touch things—you can even taste them if you want."

But building a machine that can replicate even a single human sense is pretty hard. So DEPTHX was designed to act as a sort of simple-minded assistant. It can collect samples in the cenote, but the actual analysis would happen later.

Spear and his students will look for DNA in the samples, with the hope of discovering new types of bacteria. They've good reason to be optimistic. Two years ago, a legendary deep diver named Jim Bowden descended to about 90 meters in Zacatón and brought back some specimens. Spear discovered six new divisions of bacteria in the haul.

If you're not a biologist, you may not realize how huge that was. To put it in perspective, you have to think of organisms not by the old Linnaean taxonomy of animals, plants, and such, but by the newer three-domain system: eukaryotes, which include all complex life forms, from us to protozoa; bacteria; and archaea, which are sort of like bacteria. "Within the domain of bacteria, there are about 110 main kinds, or divisions," Spear says. "We found six new ones."

That kind of diversity in micro-organisms exists pretty much everywhere, he adds. "It could be garden soil, it could be your ear canal. But to find six here was a good start. We think we're going to find more."



Bill Stone looks on from the dock while John Kerr inspects the robot.

The 5 p.m. deadline comes and goes, as the orange sun dips toward the palm trees. The more fragile components have already been stripped off the robot, which now sits strapped to its flatbed trailer, ready for the journey back to Austin. Some members are packing gear into their pickup trucks. Others hang out beneath the palapa, where some consolatory tequila swilling and singing go on. Stone heads out to one of the cenotes for a swim. "Heard anything?" somebody calls out. "Not a goddamn thing," he says, shaking his head as he walks off. The mood is somber: this wasn't how things were supposed to end.

Then, at 2 minutes before 6, a shout and a whoop emerge from the vicinity of Marcus Gary's room. Seconds later, he's out on the lawn, delivering the good news: the permit has finally come through.

DEPTHX surfaces after a midnight dive.

There's a brief moment of stunned incredulity, followed by some quick mental recalibration—after several weeks on the site, many of the researchers had been getting used to the idea of returning home. But there's no question that they will go back to work.

In 30 minutes flat, the robot is reassembled and towed down to the lip of Zacatón. The Carnegie Mellon programmers run further diagnostics on the control software, and just before 7:30, with the light fading and the parrots screaming, the crane slowly maneuvers the robot into the water. Looking on, Stone wonders aloud which of the many favors he called in finally shook the permit loose. "I'm going to be writing thank-you notes for months," he says happily.

The crew will spend the next 5 hours, and then the next three days, exploring Zacatón and its sister cenotes, Caracol and Posa Verde. In all, they squeeze in six shifts, running around the clock, with just enough time between shifts to recharge the vehicle's batteries. They send the sphere down to Zacatón's bottom and confirm the 318-meter depth. Alas, what had looked like an opening to the side was just noise on the earlier sonar map. The sampler grabs microbial specimens at three depths; Spear is already preparing for a busy summer.

"We did everything we set out to do," Wettergreen says, back in his office in Pittsburgh in early June. "Of course, we would've liked to do more dives, take more samples. But the robot continued to improve. We hit all the bullets."

For all its accomplishments, DEPTHX won't enjoy a long senescence in the National Air and Space Museum, or anywhere else. Before long, Stone and company will begin scavenging its parts for the next big step on the road to Europa. Sometime in 2008, a robot called ENDURANCE will be plunked down into Antarctica's icy Lake Bonney and start creating the first detailed 3-D map of the 2-km-long body of water.

The project's name is, of course, an acronym: Environmentally Non-Disturbing Under-ice Robotic ANtarctic Explorer, if you must know. But it also harkens back to Ernest Shackleton's ill-fated ship, which became hopelessly mired in the Antarctic ice in 1915. Modern transportation and permanent base stations have made exploring the polar continent somewhat easier, but the robot ENDURANCE and its team will still face deprivation and nasty weather.

Like Europa, Lake Bonney is covered with ice year-round, so just getting the robot into the water will require melting a hole through several meters of ice, a process that takes about three days. All of the robot's components will have to be sterilized beforehand; otherwise the lake and its microbial inhabitants might be inadvertently exposed to foreign elements. The lake's varying levels of salinity—which fluctuate from freshwater at the surface to four times that of seawater at the bottom—will create weird refraction and reflection patterns for the sonars. "It's like shining a laser through a bunch of glass of different densities," Stone explains. "So we'll have to develop an algorithm that takes into account the layering."

He currently envisions a tetherless vehicle about 1.4 meters long and weighing in at 80 kg. In addition to onboard sonars and sensors, the machine will have a robotic doppelgänger, which Stone calls a "dropsonde spooler." At various points of interest, the dropsonde will feed out from a fiber-optic spool of cable, take measurements, and get reeled back in like a fish.

Somehow, Stone and his engineers will need to pull all that together by next winter, when the team plans to test the machine in a lake in Wisconsin. They'll then ship the craft to Lake Bonney for a first run in late fall of 2008 and a final run the following year. NASA is funding the project, led by Peter Doran of the University of Illinois at Chicago, at less than half the level that DEPTHX got. "Budgetwise it's about as tight as you can get," Stone says. "We'll be working flat out" to make the 2008 expedition.

But if they succeed at Lake Bonney, the next, and penultimate, stop on the Europa express will be Lake Vostok. This enormous freshwater lake, some 600 meters deep and 4 km below the Antarctic ice, would be "in all respects the stage test for Europa," Stone says.

And then on to Europa. "That mission will be the greatest intellectual accomplishment of all time," Stone says, and he seems to mean it. "It's something we should strive for." ■

TO PROBE FURTHER
Field notes, photos, and other information about DEPTHX are available at the following sites: Stone Aerospace, http://www.stoneaerospace.com/news-/news-latest.php; the Field Robotics Center at Carnegie Mellon University, http://www.frc.ri.cmu.edu/project/depthx; and the University of Texas, http://www.geo.utexas.edu/zacaton/depthx.
To see our slide show and video clips from the expedition in May, go to http://www.spectrum.ieee.org/sep07/depthx.

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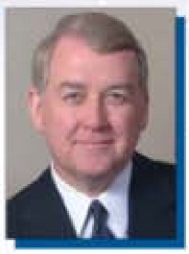

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SECOND IN A 2-PART SERIES ON QUANTUM COMPUTING

DOT-TO-DOT DESIGN

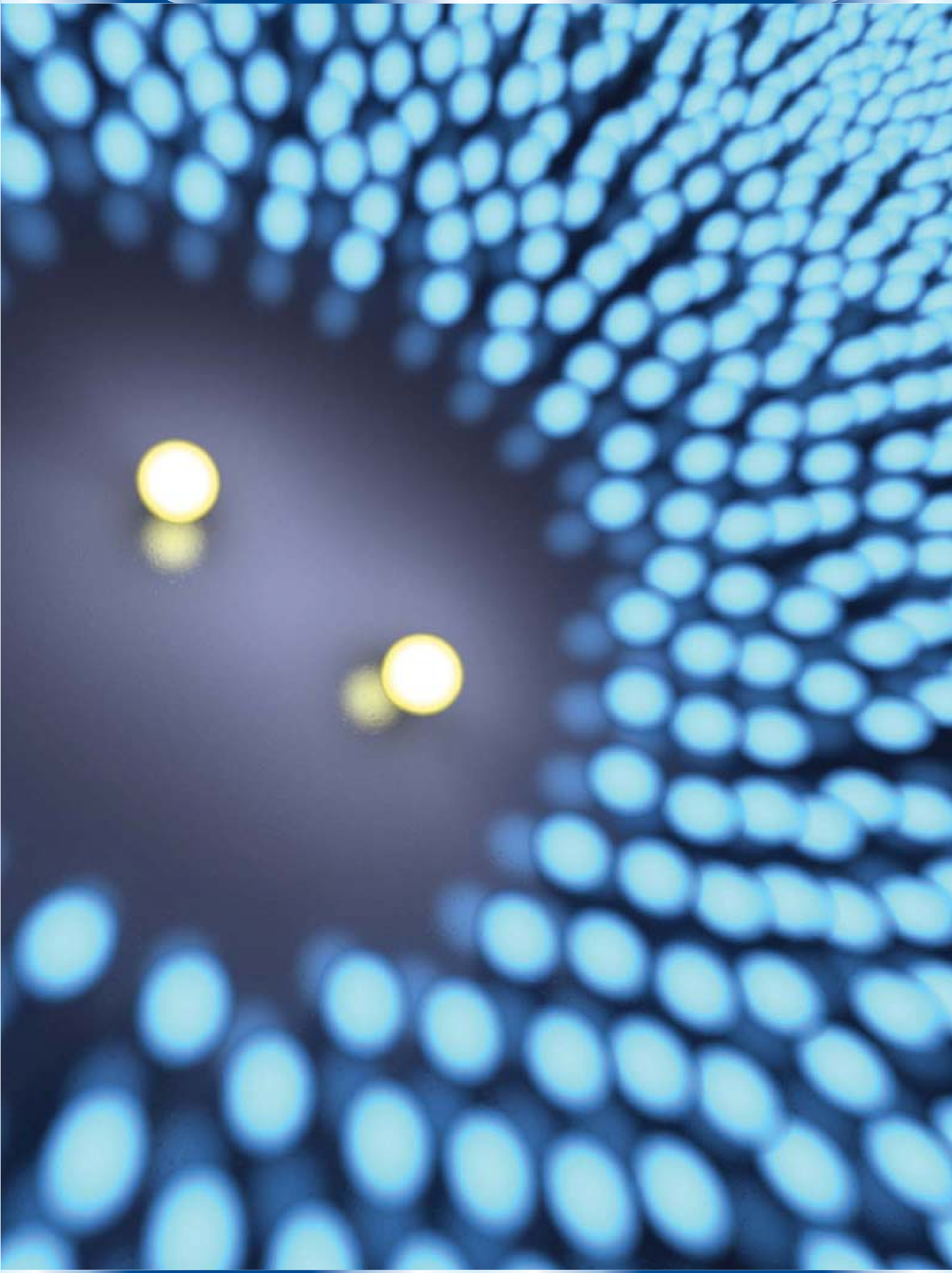
RESEARCHERS ARE CONNECTING TINY PUDDLES OF ELECTRONS IN A CHIP AND MAKING THEM COMPUTE—THE QUANTUM WAY

THREE AND FIVE! The result was correct. After spending long nights in the lab during the spring of 2001 tweaking and fixing a roomful of equipment, my colleagues and I at Stanford University and the IBM Almaden Research Center had built a computer that could successfully calculate the prime factors of 15. To be sure, you don't need a computer for that—a fifth-grader could give you the answer. What was so remarkable about our machine was that it computed not by toggling a bunch of transistors but by manipulating deep quantum-mechanical properties of individual atomic nuclei. In doing so, this quantum computer prototype factored 15 in a fundamentally different way, and in fewer steps, than any conventional computer was capable of doing.

Six years later, we're still hunkered down in labs—albeit different labs, having dispersed to various research institutions throughout the world—and we're now seeking to build bigger and better quantum computers. We want a computer that can factor not 15 or 21 or 35 but 300-digit-plus numbers. Such a system would in principle be able to break today's most advanced cryptographic codes and could be used to engineer new ways of protecting data. A quantum computer would also easily simulate physical models that today's top supercomputers can't handle—calculating the quantum energy levels of atoms, for example, or simulating the behavior of conventional transistors as they shrink to diminutive dimensions where the laws of quantum mechanics rule. Quantum computers may also speed up key types of search problems in which the correct solution must be found among a vast number of trial solutions.

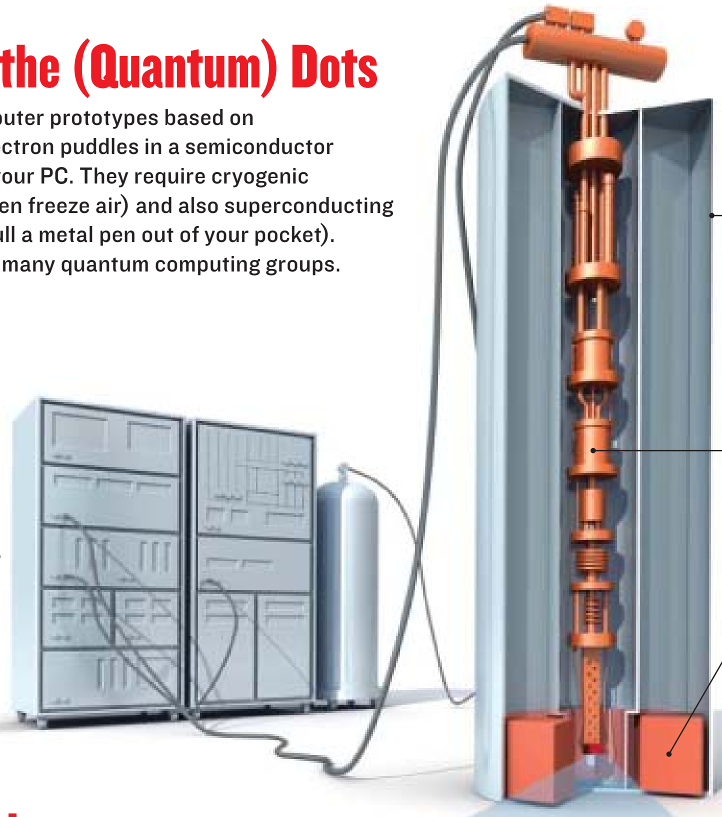
As we look forward to such possibilities, we often look back to that first Stanford-IBM machine. It taught us a couple of important lessons. The first was that the quantum-mechanical property we used to store the computer's data proved an excellent choice. This property is spin, a kind of intrinsic angular momentum exhibited by atomic nuclei, electrons, and other particles.

BY LIEVEN VANDERSYPEN



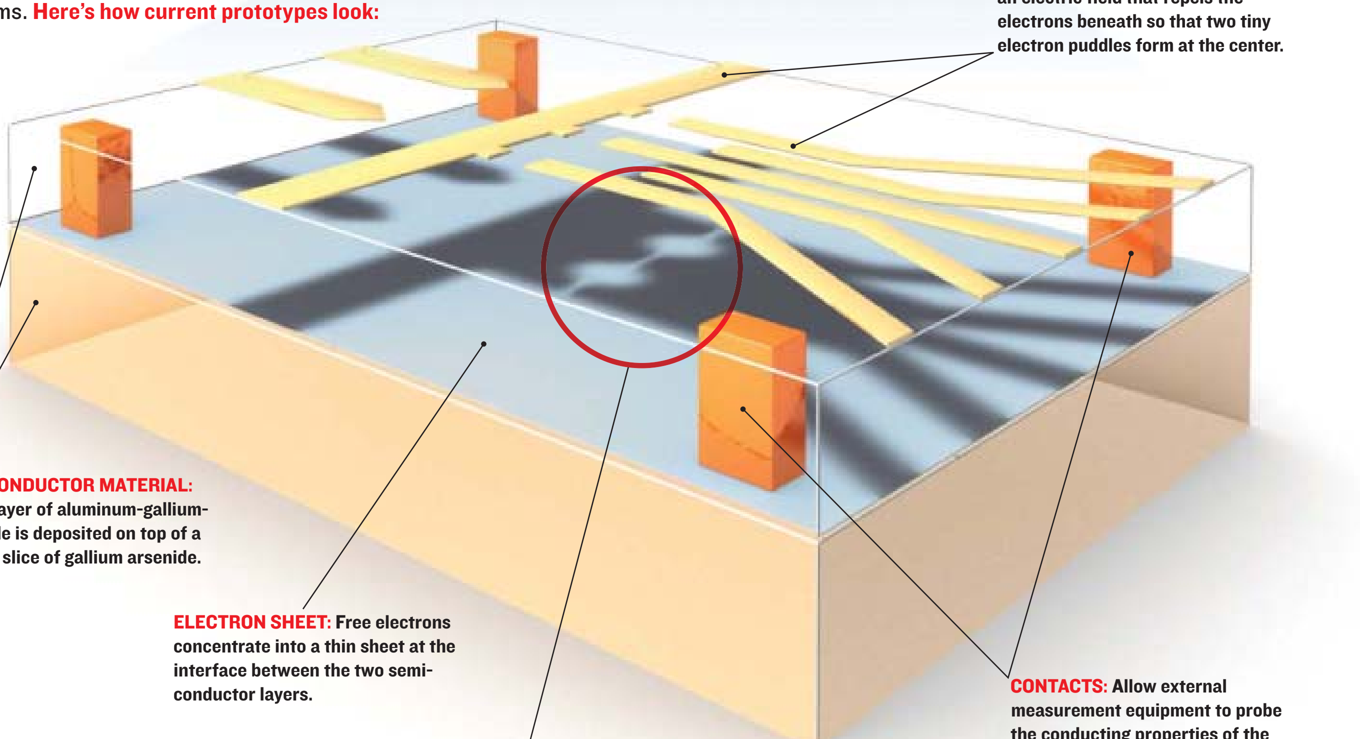
Connecting the (Quantum) Dots

Current quantum computer prototypes based on **quantum dots**—tiny electron puddles in a semiconductor material—are not like your PC. They require cryogenic systems (which can even freeze air) and also superconducting magnets (which can pull a metal pen out of your pocket). Here's a setup used by many quantum computing groups.



Quantum Chip

A quantum computer would need hundreds of quantum dots to perform useful operations. So far, current prototypes have two or just a handful of dots. But researchers hope that chip-making techniques will allow them to scale up their systems. **Here's how current prototypes look:**



The second lesson was that the way we used spin posed some big challenges. The core of our quantum computer consisted of a custom-synthesized organic molecule in a solution. It had five fluorine and two carbon nuclei whose spins we used to store seven units of information, called quantum bits, or qubits. We blasted the molecule with radio-frequency pulses to alter the spins according to the computational steps of the factoring algorithm. To read out the qubits, we used nuclear magnetic resonance, or NMR, to generate a frequency spectrum of each spin. It worked beautifully for seven qubits, and in fact that system remains the only one to have factored a number to this day. But designing molecules suitable for more complex calculations became just too hard.

If we wanted a quantum computer that we could scale up, we needed a system that would let us precisely manipulate tiny bits of energy, that could be effectively shielded from external interference, and—most important—that could be built by replicating tiny identical building blocks within a small area. We needed something less like a test tube—and more like a microchip.

TO SCALE UP OUR QUANTUM COMPUTER, WE NEEDED SOMETHING LESS LIKE A TEST TUBE AND MORE LIKE A MICROCHIP

A SEMICONDUCTOR quantum computer is now the goal of dozens of research groups worldwide. In the last few years, these groups, including my own at Delft University of Technology, in the Netherlands, have made rapid progress in creating qubits based on materials and processes similar to those used in the microelectronics industry to manufacture standard processors and memory chips. [See "The Trap Technique," *IEEE Spectrum*, August, for the first part of this report.]

The advantage of a solid-state design over the NMR approach is the ability to fabricate large arrays of miniature electronic devices that can be individually addressed and interconnected—just as we do with transistors in an integrated circuit. One promising approach to such a solid-state system was put forward by Daniel Loss of the University of Basel, in Switzerland, and David DiVincenzo of the IBM T.J. Watson Research Center, in Yorktown Heights, N.Y. In their January 1998 paper, "Quantum Computation with Quantum Dots," in *Physical Review A*, they proposed trapping individual electrons in semiconductor structures called quantum dots and then using the electrons' spins as qubits.

With typical dimensions from a few nanometers to a few micrometers—about the size of a virus—a quantum dot is a tiny area in a semiconductor that can hold anything from a single electron to several thousand. To make a quantum dot that's suitable for a quantum computer, you start with a half-millimeter-thick wafer of gallium arsenide and cover it with an even thinner, 100-nm-thick layer of silicon-doped aluminum-gallium-arsenide. Free electrons will concentrate at the interface between the two materials, forming a thin electron sheet. Next, you attach a set of gold electrodes to the top layer and apply negative voltages to them. The electrodes will repel electrons in the sheet underneath and create small islands of electrons isolated from the rest.

Creating such electron puddles is relatively straightforward, but manipulating electron spin is a different matter. Like charge and mass, spin is considered an intrinsic property of electrons, and yet it remains somewhat mysterious. We can measure spin because it interacts with an external magnetic field, much as an ultrasmall magnet rotating about its own axis would. But unlike with a real magnet, when we measure an electron's spin orientation, there will be only two possible outcomes: the spin and the external field are pointing in the same direction, or they are pointing in opposite directions. These two possibilities are also referred to as spin up and spin down, respectively.

More interesting—and bizarre—is that spin can also exist in a combined state of up and down. This superposition state is one of the things that set quantum computers apart from classical ones. A three-bit conventional memory, for example, can hold any combination of three bits at a time: 000, 001, 010, 011, 100, 110, 101, or 111. But using qubits, and representing spin up as 0 and spin down as 1, you can do much better: a three-qubit memory can hold all those eight states simultaneously. As a result, if you perform a calculation using those three qubits, you in effect perform a calculation on all eight states at once. As you add more qubits, this quantum parallel processing increases exponentially.

To perform quantum computations, however, you need to link the qubits somehow. The way researchers do that is by using the quantum phenomenon of entanglement. Two entangled spins can exist in a superposition of, say, up-down and down-up. You don't know which electron has which spin until you measure it. But as soon as you measure one spin, that means the other spin must have the opposite value. How do they "know" which way to point? Scientists devised ingenious experiments to test entanglement and concluded that entangled particles don't carry a "preprogrammed" behavior. Instead, according to quantum mechanics, the pair of electrons forms a single entity. Each electron's spin by itself has no definite orientation until one of them is measured, no matter how far apart they are. Einstein rejected this notion and famously called it "spooky action at a distance."

Spooky indeed. But those are the rules of quantum mechanics, and we might as well use them to our advantage. Quantum researchers not only accept spin's weirdness, but they also embrace it. They think of spin as a vector in a mathematical domain called a Hilbert space. Basically, this vector describes the probabilities of obtaining spin up or down when a particle's spin is measured. The researchers perform a host of mathematical transformations to those vectors to concoct quantum computing algorithms. But as physicist Asher Peres has put it, "Quantum phenomena do not occur in a Hilbert space, they occur in a laboratory." And it's in the lab that our group and many others set out to build a practical quantum computer.

OUR STARTING POINT was Loss and DiVincenzo's proposal and related concepts. Clearly, it would be too difficult to build a whole computer at once. So the idea has been to develop a set of basic functions that any working system would need. These are an initialization mechanism to set all of the qubits to a known state before computations begin, a readout scheme to measure the individual spins, and a set of spin-manipulation techniques capable of carrying out any possible quantum computations.

Here's the basic design: the core of the machine will consist of a single chip, which will sit inside an ultracold receptacle called a dilution refrigerator, which in turn will be encircled by a powerful superconducting magnet. (As DiVincenzo once said, "This is not going to be a laptop computer!")

Whereas a conventional microchip is packed with transistors, the quantum-computing chip will be packed with quantum dots. The dots—dozens, hundreds, or perhaps thousands—will

ALL ARTWORK: BRYAN CHRISTIE DESIGN

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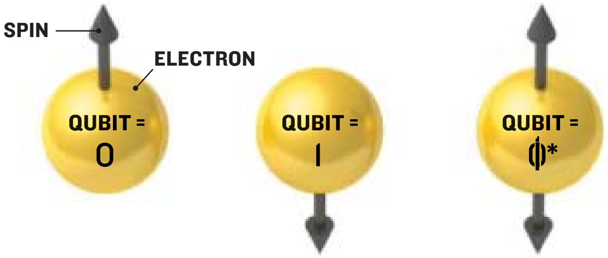
A New Spin on Computing

To perform quantum computations you need quantum bits, or qubits. One possibility is to use a quantum-mechanical property of electrons called spin. Whereas a conventional bit can be either 0 or 1, a qubit can be 0, 1, or both at the same time, a state called superposition.

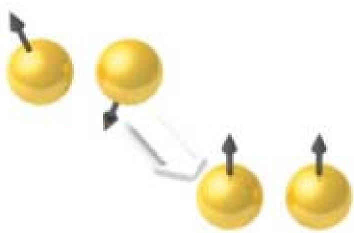


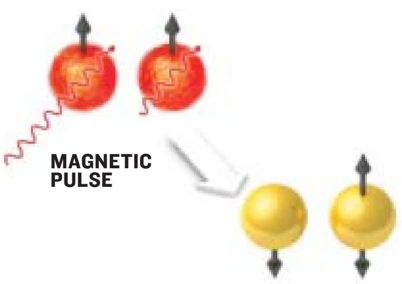
*Superposition of 1 and 0

Spinning It

To compute with qubits, your computer needs to be able to perform four critical tasks.

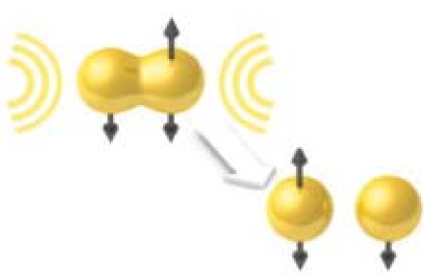
INITIALIZATION: Before computing, you need to initialize the qubits. This is necessary because spins initially point in random directions. A system based on ultracold temperatures and powerful magnetic fields orients all spins in the same direction: up.

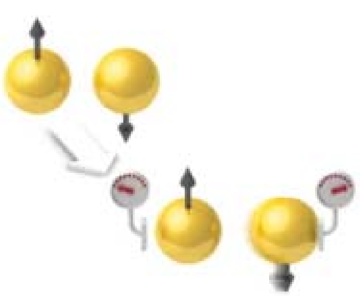




ROTATION: An oscillating magnetic pulse applied to an individual electron can reorient the direction of its spin. The duration of the pulse determines the final direction. The left spin was switched from up to down, and the right spin was put in a superposition state. Rotation is required to load the initial data and perform single-spin operations in quantum algorithms.

SWAP: Voltage changes to electrodes push the electrons closer together, and their quantum properties become coupled. By being separated after a precise period of time, the two electrons will have swapped their spins. Rotation and swap are basic operations that let you carry out any quantum-computing algorithm.





READOUT: After carrying out a quantum algorithm, you need to read out the qubits. Voltage changes to electrodes can push electrons out of their dots. Only the electron with "spin down" makes the jump, because it has a more energetic state. A highly sensitive electrometer detects a current increase, indicating a spin-down electron. No change in current means "spin up."

each hold one electron. Electrodes near each dot will control how its electron interacts with its neighbors.

The first step consists of initializing all of the electron spins to a known state, say, up. The computer will then "load" the initial data: it will leave some spins pointing up, make some point down, and put others in superposition up-down states. The computation comes next. By varying the electrodes' voltages and applying magnetic fields, it will manipulate individual spins or pairs of spins. These manipulations correspond to sums, multiplications, and other operations specified by a quantum algorithm. The final step is reading the output qubits.

We're far from being able to build such a system. The chips developed to date are still too rudimentary, having at most a few quantum dots. Also, even though the basic functions have been successfully demonstrated, integrating them into a single system will take lots of time in the lab. To understand why, it's worth looking at each in more detail.

Consider the task of placing a single electron in each dot. Today that's a routine operation, but it took Leo Kouwenhoven at Delft and Seigo Tarucha at the University of Tokyo a lot of effort to accomplish that. In 1996, these two researchers demonstrated how to apply negative voltages to metal electrodes near a quantum dot to expel the electrons from the dot one by one until just a single electron remained. By comparison, a conventional memory chip uses 10 000 to 100 000 electrons to store one bit of data. So manipulating a single electron was no small achievement.

Having isolated one electron per dot, it's then necessary to set their spins to the same initial state. The superconducting magnet generates a static magnetic field of several teslas that acts as a frame of reference for the spins in the dots. You also need to cool the whole thing to keep the electrons from wiggling around too much. Hence the dilution refrigerator, which circulates a mixture of helium isotopes to remove heat from its surroundings, cooling the chip to about 30 millikelvins. Under these conditions, the spins will assume the lowest energy state, which by convention is spin up.

Measuring the spin of each electron was long considered difficult, because its interaction with external fields is so tiny. In 2004, my colleagues and I found a way around this problem. The trick is to measure the spin indirectly. To do that, we pulsed the electrodes near a quantum dot with 0.5-microsecond, 5-millivolt signals. These pulses give the electron just enough energy to make it slop out of the dot if its spin is down, but not if its spin is up. That's because in a magnetic field, a spin-down electron has a higher energy than a spin-up one. The presence or absence of a single electron in a dot in turn changes the current flowing through a nanoscale electron channel next to the dot by about 300 picoamperes. We measured this tiny current using highly sensitive electronics, which told us the spin state. We got the correct answer about 82 percent of the time, and that performance could be boosted to around 99 percent using even faster and lower-noise electronics.

By 2004 researchers attempting to build a quantum computer out of quantum dots had accomplished two main tasks: initialization and readout of spins. These were important steps, but the essence was still missing: the quantum dots didn't compute.

IN CONVENTIONAL COMPUTERS, any operation you would wish to perform to a group of bits—the AND, OR, and NOT operations of Boolean logic—can be implemented using a universal digital logic gate. One example is the NAND gate, and you can make one with a couple of transistors and resistors. But NAND gates, or any other conventional gate for that matter, can't be used for quantum computations, because they can't handle bits in superposition states. A new type of gate—a quantum gate, capable of operating on superposition qubits—is needed.

Theorists have already identified several universal quantum gates, as well as sets of gates. One such set consists of a spin-rotation gate and a spin-swap gate. The first lets you rotate a spin by a controlled amount. It could be a full flip from up to down, for example, or half a flip to a superposition state. The other gate lets you couple the spins of two electrons, making them swap their states. In the past two years, experimentalists have successfully demonstrated these two gates using quantum dots.

First came the spin swap. In 2005, a team led by Charles Marcus at Harvard coupled two neighboring spins using a phenomenon called the exchange interaction. To understand this, you have to think of electrons not as particles with well-defined locations but rather as waves with fuzzier positions and energy levels. Electrons as waves are described mathematically by wave functions, equations that define the behavior of electrons in terms of probabilities. When two electrons are very close to each other, their wave functions partially overlap, and they can exchange their spins.

The breakthrough, reported in the 30 September 2005 issue of *Science*, was that the researchers controlled the duration of the overlap by tweaking the voltage on an electrode separating the dots. When the exchange interaction was switched on for a precisely timed interval—just a few hundred picoseconds—the two spin states were swapped. And when the exchange interaction was switched on for half as long, the spins were "half swapped," assuming an entangled state.

ALL OF THE ESSENTIAL INGREDIENTS FOR A QUANTUM COMPUTER HAVE BEEN REALIZED. NOW WE NEED TO INTEGRATE THEM

The other quantum gate is the spin-rotation gate. My colleagues and I had struggled since 2003 to create such a device, and last year we finally succeeded. The method we devised relies on magnetic resonance, the same technique we used to manipulate the atomic nuclei of organic molecules in the 2001 Stanford-IBM prototype. Magnetic resonance, which is also used in hospitals for medical imaging, is based on the fact that when spin is in a static magnetic field, it wobbles about the axis of the field with a certain speed—picture a top wobbling about its axis. Now, if you apply an oscillating magnetic field with the same frequency as the wobbling, the spin can be gradually rotated. Again, this rotation can be a full flip from up to down or down to up, or a partial rotation, say, from up to a superposition, depending on how long the magnetic field was applied.

One challenge we had to overcome was to generate on-chip an oscillating magnetic field of around 1 millitesla. Even that small a field heated up our device. Another problem was reading the spins; the oscillating magnetic fields unavoidably generate stray electric fields, which kick the electron out of the dot. After trying many chip designs, we found a configuration that minimized those problems, and we're now able to rotate the spin in every possible direction. This achievement, which we reported in *Nature* (17 August 2006), was the first time the spin of a single electron was controlled using a semiconductor nanostructure.

So researchers are able to control single and coupled spins and put them in specific superposition states, but how long would the spins remain that way? Not long at all, as it turns out. Electron spins in quantum dots are strongly disturbed by the spins of the atomic nuclei in the host semiconductor. The result: computation errors. We know that such errors begin to crop up after just tens of nanoseconds from the time you put your spin in a desired state.

Some clever tricks exist to lengthen this so-called coherence time. One involves a technique called spin echo. After creating a spin superposition, you wait a short period of time and then apply a control pulse that rotates the spin 180 degrees. You then let the same amount of time elapse, and the errors accrued during the two intervals will cancel out each other. By correcting the spin this way, the coherence time can be extended to a few microseconds. This is still rather short, but for now it is sufficient to proceed.

IN THE FOUR YEARS of research on electron spins in quantum dots, all of the essential ingredients for a quantum computer have been realized. The next steps are clear. First, we need to integrate all of the basic functions into a single system. Then we need to expand the system from two quantum dots to a large array of dots.

And we need to find better ways of overcoming the environment's effects on the fragile spin states—the most fundamental challenge we researchers face now. One possibility is to construct the quantum-computing chip out of materials that have no nuclear spin, such as isotopically pure silicon-28 or carbon-12. Eventually we'll need to reduce the number of errors to at most one in every 10 000 elementary operations. At that point, we could use a technique called quantum error correction to guarantee reliable calculations.

As we progress, a particularly profound theme that we'll explore in depth is entanglement. We will need to come up with better ways of detecting that this connection is actually there, that two spins are indeed entangled. Entanglement is routinely studied in laboratories using photons and optical equipment, but controlling this ghostly linkage between scores of electrons in a fingernail-size chip still remains uncharted terrain, ready to be explored in the next few years.

Given the many uncertainties ahead, we still don't know exactly where quantum dots and electron spins will take us. Based on the progress of the last several years, though, we venture to say that the creation of a practical quantum computer may be possible within the next few decades. To get there, we'll keep on connecting the (quantum) dots. ■

ABOUT THE AUTHOR

LIEVEN VANDERSYPEN is an associate professor at Delft University of Technology's Kavli Institute of NanoScience, in the Netherlands.

TO PROBE FURTHER

Visit "The Delft Spin Qubit Project" Web page for more technical details: http://qt.tn.tudelft.nl/research/spinqubits.

For an overview of the field, see "Prospects for Quantum Computing" by David P. DiVincenzo (2000 IEEE International Electron Devices Meeting) and "Challenges for Quantum Computing with Solid-State Devices" by Robert W. Keyes (*IEEE Computer*, January 2005).

An extensive review of spin in few-electron quantum dots is available at http://arxiv.org/abs/cond-mat/0610433.

SOFTWARE

BET ON IT!

CAN A STOCK MARKET OF IDEAS HELP COMPANIES PREDICT THE FUTURE? BY STEVEN CHERRY

In August 2004, Todd Proebsting, a researcher in Microsoft's platform and services division, was approached by a manager in the company's testing organization who had spent months helping to create a piece of software to be used by other Microsoft programmers. Although it was an internal product, the software still had a rigid development schedule and an official launch date: November 2004, just a few months away.

The manager had heard a talk by Proebsting about something called a prediction market, a sort of stock market for ideas, in which Microsoft employees would in effect place bets on predictions, instead of on racehorses or football teams. A lot was riding on the timely completion of the testing software. "You said that a market could be used to predict schedules," the manager said. "I want to know when my team will finish writing the software."

Proebsting created a market with six possible bets: that the product would ship before November, in November, in December, in January, in February, or later than February. His pool of bettors included members of the development team itself, other developers, and program managers from related teams, as well as internal "customers"—the programmers within Microsoft who would use the software. He showed them all how to use the market, gave them each US $50 with which to wager, and then sat back and watched prices fluctuate.

"All six months were started equally at 16 2/3 cents on the dollar," Proebsting says, meaning that you only had to bet that amount to win $1 if you were right. "Within seconds, the pre-November market went to $0.00 and never moved from there." So much for beating the deadline. "The November date went down to 1.2 cents in about 3 minutes." So much for meeting the deadline.

"The director of the group came to see me. He asked, 'What have you done?'"

"No one believes your product will ship on time," Proebsting told him. The director replied, "No one on the team is telling me this."

After discussing things with his development team, the director came to accept what the market was "saying." He decided to cut some of the software features that were holding things up. "And the price of the markets started to reflect that—the November price rose," Proebsting says. "Then the internal customers got wind of the fact that some of their favorite features were being cut and demanded their features back. So the market then reflected that!" In other words, the markets that predicted the software would be very late went back up. "In the end," Proebsting says, "the product shipped in February, which is what the market predicted."

ArcelorMittal, Best Buy, General Electric, Hewlett-Packard, Nokia, and Samsung have all begun tapping into the "wisdom of crowds" to help them predict public reaction to new products, the future price of a commodity, or sales revenue in the next quarter. In the past few years, the technique has really taken off, with at least a dozen start-ups competing for business in the field. Some offer software and services to help companies tap the wisdom of

ILLUSTRATIONS: VIKTOR KOEN

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their workers or the outside world. Others create markets that allow anyone to go to a Web site to bet or even to pose a question that can be bet on.

Chris F. Masse, a financial consultant in Sophia Antipolis, France, who specializes in prediction markets, says that by 2010, "10 percent of Fortune 500 companies will have gone public about their use of internal prediction markets, and probably another 10 percent will be testing some projects."

Among the leaders in the emerging field are Consensus Point, in Nashville, which counts GE and Best Buy among its clients, and Inkling, a Chicago start-up that designs internal markets. Computer-game manufacturer Electronic Arts, in Redwood City, Calif., uses Inkling to predict industry assessments of its products. There is, inevitably, an open-source software for prediction markets: the Zocalo project, which is run by software engineer Chris Hibbert and affiliated with North Carolina State University.

Meanwhile, the number of public markets is growing at an astonishing rate. You can already predict the popularity of Web sites, new movies, computer game hardware, financial instruments, and the eventual success of a book proposal or a musical artist's first CD. You can bet on the success of sports stars or entire teams in an absurdly varied number of ways—including how many goals a team will score in a season and the number of fans who will attend its games. You can guess how many inches of snow will fall in New York City's Central Park in December, when Osama bin Laden will be captured, and the outcome of a 2008 Senate race. At Smarkets, based in Austin, Texas, you can even buy shares representing relative sales of Amazon products, guessing if the retailer will sell more books, iPods, or 500-thread-count sheets next month.

Prediction markets have caught on so well in the United States that they've even attracted the attention of the state and federal regulators who oversee lotteries, casino gambling, and racetrack wagering. So in May of this year, a group of distinguished economists including Nobel laureate Kenneth Arrow, of Stanford, issued a statement asking that prediction markets be exempt from gambling regulations. In the statement, the group declared that "using these markets as forecasting tools could substantially improve decision making in the private and public sectors."

Users bet on one outcome (the month of a product launch, a political candidate, or a sports team) more than another, which establishes a favorite and a long shot, just as in a horse race. As explained by financial journalist James Surowiecki, who wrote the 2004 book *The Wisdom of Crowds*, "under the right circumstances, groups are remarkably intelligent, and are often smarter than the smartest people in them."

Prediction markets aren't perfect. They failed spectacularly to predict Howard Dean's startling 2004 defeat in the Iowa caucuses and Michael Jackson's high-profile acquittal in 2005. In the 2007 National Collegiate Athletic Association men's basketball tournament, they trailed 30 different expert sports analysts. But all in all, they consistently do better than other methods of predicting events. In May, Intel published the results of a comprehensive 18-month study of prediction markets. It found that they were as least as accurate as official forecasts by Intel management, and often better by as much as 20 percent.

PREDICTION MARKETS GOT THEIR START almost 150 years ago in the form of wagering on presidential elections. According to researchers Paul W. Rhode and Koleman S. Strumpf of the University of North Carolina, Chapel Hill, there were "large and often well-organized markets" in the period between 1868 and 1940. Rhode and Strumpf's study found that the market did "an admirable job in forecasting elections in a period before scientific polling."

In 1988, the University of Iowa College of Business revived the tradition of wagering on presidential elections with the world's first electronic prediction market. Since then, researchers there have set up increasingly complicated markets to study their behavior and accuracy. In its first three elections, the Iowa Electronic Markets were off by an average of only 1.37 percent.

By 2006, electronic markets were predicting some elections in the United States with stunning success. A commercial marketplace, Tradesports, let the public wager on all 33 U.S. Senate contests held that year. Not a single public opinion poll predicted all 33 correctly, but the bettors at Tradesports collectively did. The site even forecast the Virginia and Montana contests, which were decided by mere tenths of a percent—a few thousand votes out of hundreds of thousands.

"THE WINNERS ARE ATTRACTED BY LOSERS, JUST AS WOLVES ARE ATTRACTED BY SHEEP"

Formal research in prediction markets goes back at least to the storied economist Friedrich Hayek. As early as 1948, Hayek wrote about the ways that free markets emit information. By the late 1980s, Robin Hanson at George Mason University, in Fairfax, Va., and other researchers elsewhere had begun to study market behavior under controlled laboratory conditions.

So how do prediction markets typically work? First of all, they use real money. That's important for keeping bettors honest. The price you pay is set by the market's opinion on the odds of that outcome. If, for example, you have to pay 33 cents for a bet that former U.S. Senator Fred Thompson of Tennessee will be the Republican candidate for president of the United States next year (the price in mid-July), and 40 cents to bet on Rudolph Giuliani, former mayor of New York, then the market says there is a 1 in 3 chance of Thompson getting the nomination, while Giuliani's chances are 2 in 5.

Corporate prediction markets work the same way. Real money or some other trinkets are still necessary, because they reduce the chances that participants will lie, out of boredom or to advance their agendas in some way. Using real money is a double-edged sword, however—it can also motivate people to manipulate the market, by virtue of being able to influence the outcome of events in the real world. For example, in the Microsoft market, if enough money were on the line, a programmer could deliberately introduce bugs into the code that would affect its release date, just as a college basketball star can throw a key tournament game. For that reason, and because companies don't want to run afoul of insider trading laws, some markets limit the amount of money involved. Others use fake money, issuing modest prizes or honoring the winner in some other way.

In corporate prediction markets, the company involved usually subsidizes the wagers by giving participants initial stakes, real or otherwise. But even though they're not risking their own money, the bettors generally don't lie or misrepresent their beliefs with their bets. It's human nature to want to win more money. And in addition to the financial reward for success, prediction markets are public forums, and winners can take pride in their success.

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The first experimental corporate markets were at Hewlett-Packard Co., in Palo Alto, Calif. From 1997 to 1999 a researcher there, Kay-Yut Chen, with the help of Charles R. Plott, an economics professor at Caltech, let selected individuals bet on future sales of some of the company's printer products. They found prediction markets to be "a considerable improvement over the HP official forecast."

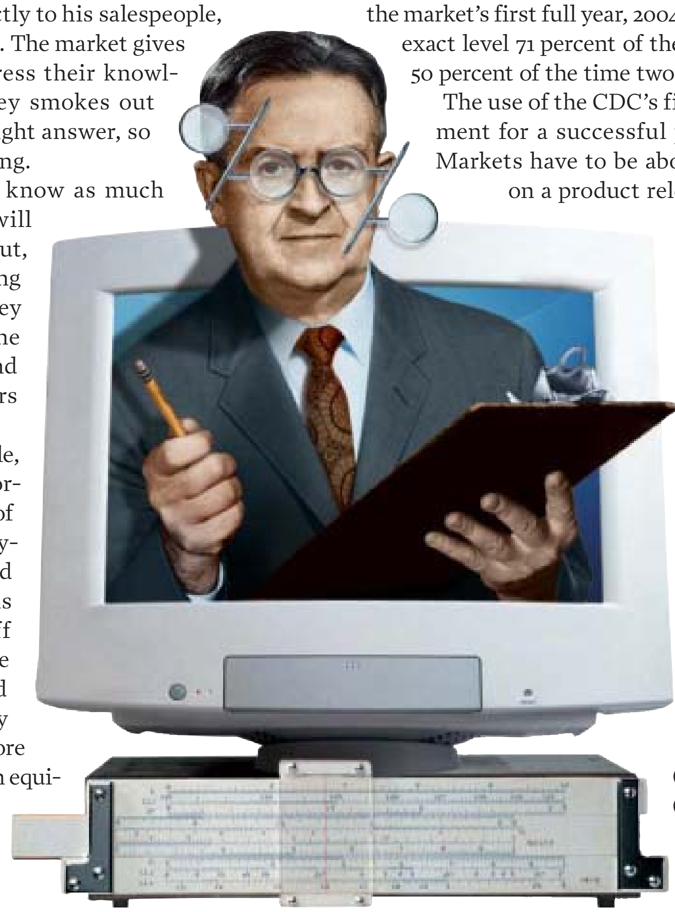
HP is no longer merely experimenting with prediction markets. Today, a market is used to predict the future cost of dynamic random access memory chips. "HP is the largest DRAM buyer in the world," says Leslie Fine, a game theorist who works in the Information Dynamics Lab at the company's HP Labs. "DRAM accounts for between 7 and 10 percent of the price of a new computer. Our profit margins are often less than that, so we're intensely interested in its price." Prior to using a betting system, Fine says, about 25 managers used to attend "endless meetings" each month to forge the next corporate prediction, which was then used by those who purchase the chips.

Last year, Fine and her colleagues assembled a group of 14 executives, "none of whom should have had the big picture." After 3 hours of training in prediction markets, she set them loose on an internal company Web site, where they spent about an hour a month making their bets. The result? Besides spending far less time, the executives were more accurate. The endless meetings had produced predictions that were, on average, 4 percent off from the actual future prices of DRAM, while the prediction markets missed by 2.5 percent.

PREDICTION MARKETS WORK SO WELL because they ferret out those confident enough to back up their beliefs with cash. Suppose a marketer wants to predict what his company's sales figures will be in the next quarter. He can set up a prediction market that puts the question directly to his salespeople, marketers, accountants, and others. The market gives those people an incentive to express their knowledge. The hope of winning money smokes out people who think they know the right answer, so the group of bettors is self-selecting.

Of course, some people don't know as much as they think they do, and some will make lousy bets. But as it turns out, that's a feature, not a problem. As long as there are people with both money and expertise, they will trump the bad betting of the ill-informed and overconfident with additional wagers of their own.

In the Microsoft case, for example, if the manager who believed, incorrectly, in the original release date of November bet accordingly, the payoff for November would go down, and the payoff for all the other months would go up. That higher payoff would raise the stakes for the people who were sure the product would ship later than November, and they would bet more money on one or more of those other months. Eventually, an equilibrium would be reached—which might not be different from the state of the betting before the bad November bet was made.



A market that consisted only of experts who were always right wouldn't see much action, because bettors couldn't win much. Imagine a poker game where almost all the cards are face up and everyone is a good player. As soon as the player with the best hand makes a raise, the other players drop out.

One way to inspire more betting is for the house to throw some initial money into the pot or to give the players some chips. That's why most corporate markets give employees an account with which to start betting. That stake is a subsidy of sorts, as is "sucker" money—the betting of the ignorant. As Hanson notes, "the winners are attracted by losers, just as wolves are attracted by sheep."

The importance of a diverse user pool for the success of a prediction market can hardly be overstated. If everyone has a similar mind-set or is using the exact same information, each person will predict events uniformly, and like the poker game with all the cards face up, the betting will be minimal at best.

Consider a market set up at the University of Iowa in Iowa City to predict outbreaks of influenza. The market was established because while organizations such as the U.S. Centers for Disease Control and Prevention track actual outbreaks of influenza, there was no good way of predicting them.

Betting in the Iowa influenza market is by invitation. If only epidemiologists participated, the market would suffer from similar mind-sets and information. So the researchers also invited doctors, nurses, and pharmacists, giving the market fresh information and a different set of perspectives.

Each week the CDC ranks influenza activity on a scale of 1 to 5. Bettors wager on which of the CDC's levels will be reported in a given week, up to five weeks in advance. The market runs throughout the flu season, from September to April. According to a study published this year in the journal *Clinical Infectious Diseases*, during the market's first full year, 2004–2005, it correctly predicted the exact level 71 percent of the time one week in advance and 50 percent of the time two weeks ahead.

The use of the CDC's five levels satisfies a key requirement for a successful prediction market: specificity. Markets have to be about measurable outcomes. Bets on a product release need specific time frames, such as the month-by-month market Microsoft set up. Sales figures can be divided into ranges, as the HP printer product markets were.

Last year, a poorly worded contract by Tradesports caused a ruckus when some bettors lost money. Tradesports had set up a market to predict whether North Korea would test a long-range missile—which was defined as sending a missile beyond the country's airspace. Those who bought that contract, which expired on 31 July 2006, thought they had won when a North Korean missile flew 442 kilometers (275 miles) into the Sea of Japan (East Sea). However, the contract also specified that the source of the confirming information had to be the U.S. Department of Defense, which declined to release any specifics about the test. Despite a White House statement that confirmed the missile "went out about 275 miles," Tradesports awarded the contract to those who bet against a successful test.

Vague or ambiguous outcomes are an ongoing problem at Inkling, the Chicago start-up, which also runs a Web site that lets anyone create a market. The company has more than 1200 active or completed markets, according to cofounder Adam Siegel. But about 450, or three out of eight, are "collecting dust"—no one is making wagers. Siegel says the most common problem is a bad question. Some are problematic because they ask for opinions instead of predictions. "We get a lot of 'Will my wife get pregnant?' How would anyone know enough to say?"

MANY PREDICTION MARKETS use a format known as a double auction, in which buyers and sellers submit bids. Such a market resembles a newspaper's stock listings, with "ask" and "bid" prices.

For example, on a particular night in mid-July, the Atlanta Braves were favored to win a baseball game the following night against the San Diego Padres. To have the chance to win $1 betting on them, you had to wager 57.5 cents (the ask price). If you had already made a wager on the Braves and wanted to sell it, though, you would get only 57 cents (the bid price). At any given time, the price—in this case, 57.5 cents—tells us the market's prediction: the Braves will win, and the likelihood is 23 out of 40 (575/1000).

As in the stock market, the bid price is what someone will give you when you want to sell, and the ask price is the one at which someone will sell you the item you want to buy. A large gap between them represents a lack of what is called liquidity, and it's usually a result of there being too few buyers and sellers overall or too many of one or the other.

In 2002 and 2003 George Mason's Hanson wrote a pair of papers that suggested a new way of running a prediction market that avoids the gap between bid and ask prices; it lets users simply bet on what they think the future will hold. Hanson named it the Logarithmic Market Scoring Rule Market Maker, but other researchers have whittled that down to Hanson's Market Maker.

When users come to a prediction market that uses the Market Maker, they can just buy or sell whatever the system is offering. Even if there's only one bettor, he or she can still make a trade at any time. The market uses an algorithm to make up a price of its own and takes the trade. The algorithm contains variables that include the amount of money that bettors have collectively spent so far, the number of shares outstanding, and the maximum amount of money the Market Maker is willing to lose. The more money it is willing to lose, the more market liquidity there is, meaning that bettors can buy more shares at or near

So Many Markets

MARKETS (Typical Bets)	**EXAMPLE MARKET**, July 2007
ABC7 TV, San Francisco (Local and national events) http://abc7.inklingmarkets.com	Will Ed Jew complete his current term on the San Francisco Board of Supervisors?
BlogShares (Fantasy blog stock market) http://blogshares.com	Popularity of Slashdot, Boing Boing, Flickr, etc.
The Buzz Game (High-tech products, concepts, and trends) http://buzz.research.yahoo.com/bk/index.html	Relative popularity of social networks (MySpace, FaceBook, LinkedIn, etc.)
Case Game (Popularity of Web sites) http://www.urladex.com	Popularity of Gizmodo.com
The Financial Times (Likelihood of future financial, political, and news-driven events) http://www.ftpredict.com	Will there be a U.S. air strike against Iran by September 2007?
Inkling Markets (Just about anything) http://inklingmarkets.com	A Google-Apple merger by the end of 2008?
Media Predict (Movie grosses, book proposals, unsigned bands) http://mediapredict.com	First week movie grosses for *Harry Potter and the Order of the Phoenix*
News Futures (Politics, sports, finance) http://newsfutures.com	How soon will U.S. troops begin leaving Iraq?
Popular Science (Tech-business wagers) http://ppx.popsci.com	Blu-Ray vs. HD-DVD
Protrade ("Where sports fans buy and sell teams and players like stocks") http://www.protrade.com	Toronto Blue Jays vs. Boston Red Sox on 12 July
The simExchange (Sales of game hardware, software) http://www.thesimexchange.com	How many copies will *The Darkness* sell in June?
Smarkets (Buy and sell shares pegged to Amazon products) http://www.smarkets.net	Number of white 500-thread-count cotton sateen queen sheet sets sold next quarter
Storage Markets ("Collective market intelligence by the storage industry") http://www.storagemarkets.com	How many tape libraries and autoloaders will ship in 2011?
Trendio (Search terms in search engines) http://www.trendio.com	Will the popularity of the word "mortgage" go up or down?
VideoIPO (Which videos will get viewed the most on YouTube?) http://videoipo.tv	Popularity of the video "Did Tim Donaghy and crew fixed game 3 of Suns-Spurs?"
Wagerline.com (A sports-book simulation) http://www.wagerline.com	Philadelphia Phillies vs. Chicago Cubs
Washington Stock Exchange (Political events) http://www.thewsx.com	Will a third-party presidential candidate get over 10 percent of the popular vote in 2008?

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the current price without causing massive price swings.

Suppose the wager in question is whether a Democrat will win next year's U.S. presidential election, and you want to wager in the affirmative. You'd win $1 if a Democrat wins, and nothing if the Democratic candidate loses. When the first trader comes along and wants to buy, say, 10 shares, the algorithm kicks in to determine how much the trader has to pay for them. According to David Pennock, who is in charge of prediction markets at Yahoo Research, plugging in a value of $100 as the maximum that the Market Maker is willing to lose, the algorithm will generate a price, in this case, $5.12 (that is, $0.512 per share).

Hanson's Market Maker is in effect another subsidy used to create an effective prediction market. As such, it's a reasonable thing for a corporation to do. After all, anything a company does to suss out hidden pockets of expertise involves some explicit or tacit expense, whether it's taking a poll or scheduling monthly meetings. A commercial exchange such as Tradesports, however, is in the business of making money; the fact that it generates useful information is only an incidental benefit. Hence, it continues to use the more cumbersome—but frugal—method of separate bid and ask prices. In contrast to a Market Maker, Tradesports doesn't take any stake in the bets.

"MAYBE IT WON'T WORK THIS TIME; MAYBE THE CROWD WILL BE STUPID"

HedgeStreet, a San Mateo, Calif., exchange devoted to foreign currencies and real estate, as well as gold, oil, and other commodities, also uses bid and ask. It claims to be the first retail market for certain types of trades, such as derivatives, which are in effect wagers on the future price of something, such as gold, without trading the commodity itself. Its markets, which operate under the oversight of U.S. regulatory agencies, blur the distinction between a prediction market and more traditional financial exchanges.

One market with an interesting structure is run by Media Predict, of New York City. Media Predict users can bet on events such as first-day movie grosses. For example, on 9 July, two days before the release of the film *Harry Potter and the Order of the Phoenix*, trading was at $56.80 (each dollar represents $1 million in ticket revenue). If you bought at that price and the movie grossed $70 million on its opening day, you would win $13.20. If ticket sales were only $50 million, you would lose $5.80. In addition, the site's users can review book proposals or music from unsigned bands and make wagers on the likelihood that they will be popular and successful. Such markets are springing up all over. At the Sim Exchange, for example, gamers predict the sales of console hardware and upcoming video games [see table, "So Many Markets"].

Companies can set up their own markets by hiring a company such as Inkling, or by using increasingly sophisticated software designed for the purpose. Or you can roll your own, using the Zocalo project's open-source code.

DESPITE ALL THE THEORETICAL AND PRACTICAL EVIDENCE of their usefulness, many companies are still reluctant to use prediction markets. Hanson notes that corporate managers would often rather retain control over decisions, even if a market would be more accurate. And an accurate prediction of, say, a product release date can undermine a manager's efforts. "If you act as if you can still make a deadline, even if you know you can't, you can get people to be more productive," he says. "Moreover, some corporate decisions have less to do with data than coalition building." Still, prediction markets are gaining acceptance. For example, HP researcher Fine says her company's consulting arm has begun a trial with Pfizer, the giant pharmaceutical manufacturer, to predict the success of new drugs while they are in the earliest stages of development.

Henry Berg, who runs the Information Markets group within Microsoft, notes that in many cases a company has no formal prediction methods in place. "An organization adopting prediction markets needs to make two major adjustments: deciding to start making formal predictions about the future and choosing to use prediction markets as the mechanism," Berg says. "In my experience, the first adjustment is greater than the second."

Author Surowiecki says prediction markets "threaten the established order." For example, it would be interesting but unlikely for a company to ask its workers about the consequences of the chief executive being forced to step down. If the workers bet the firm's stock price would rise, that would suggest they thought it would be a good idea.

Prediction markets are not only subversive, they're controversial in other ways. There's no better example than FutureMAP, a 2003 attempt to create some markets at the U.S. Defense Advanced Research Projects Agency. FutureMAP's markets were devoted to political questions—the political stability of Jordan; North Korean nuclear missile attacks; whether Yasser Arafat, then the head of the Palestinian Authority, would be assassinated. It was to have two components: a private market, like the ones created by HP and Microsoft, for analysts at the CIA and intelligence agencies; and one for the general public. FutureMAP quickly ran afoul of public opinion. Members of Congress found it offensive and ghoulish, and they quickly terminated the program.

Surowiecki also says prediction markets are counterintuitive. Sometimes, even he finds crowd thinking hard to believe. When *The Wisdom of Crowds* came out, he would tell the audiences at his book signings an anecdote in which a crowd at a 1906 English county fair collectively guesses the weight of a slaughtered ox. Then he would do a comparable experiment by having his audience guess the number of jelly beans in a jar. "I always had a thrill of fear," he says. "Maybe it won't work this time; maybe the crowd will be stupid. It always does work. But I spent two and a half years researching this, and I still have those thoughts." Nonetheless, he says that if managers can get past their doubts, they can create markets that foretell problems while there's still time to do something about them.

If prediction markets seem awfully close to out-and-out gambling, it's worth noting that stock markets were originally thought of the same way, and many financial instruments since then have been similarly condemned, including short selling, whereby you make money when a stock goes down instead of up; options trading; commodity futures; derivatives; and, most recently, hedge funds. Hence the concern expressed by economists such as Nobel laureate Arrow that we not lose the social utility that prediction markets offer.

Futures markets help farmers decide how much wheat and orange juice to produce. So, too, prediction markets might soon help media executives decide which books and movies to greenlight. After all, it was ordinary consumers who made the Harry Potter books and movies successful.

It's not surprising that Internet-based mechanisms can be found to tap into the wisdom of the masses. What's surprising is that there's a way to draw it out so quickly and efficiently. And that it works so well. ■


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protection solaire SPF 30+
Broad Spectrum
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with Nano Zinc-Oxide
Clean Green Vegan
Chemical-Free
ALL-NATURAL
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Nutri-Nano™
CoQ-10
3.1x
DIETARY SUPPLEMENT
50 SOFTGELS
SUGAR, SALT AND STARCH FREE
Pure Nutri-Nano™
NANOTECHNOLOGY
PUREOLOGY
NANOWAX

NANO PARTICLES WITHOUT MACROPROBLEMS

QUICK AND DIRTY ADVICE FOR KEEPING NANOTECH CLEAN

BY BARBARA KARN & H. SCOTT MATTHEWS

LITTLE BY LITTLE, nanotechnology has crept up on us. From a mostly academic exercise 20 years ago, it has swiftly progressed to the point where the technology is just about everywhere: in fact, there may very well be engineered nanomaterials in the clothes you're wearing at this very moment. If they were sold to you as wrinkle-free or stainproof, the fibers were almost certainly treated with nanotech processes that stave off stains and creases.

More than 500 products on the market today incorporate some kind of nanotechnology. With nanotech, sunscreens protect better against ultraviolet rays, paint can block cellphone signals, glass windows remain streak-free, washing machines can kill harmful bacteria, food storage bags can keep their contents fresher, tennis and badminton rackets are stiffer and lighter, and dietary supplements can claim to help ward off colds, flu, and anthrax. Toothpaste, hockey sticks, engine oil, and even a breast cream have all gotten the nano treatment lately [see photo, "Fair Warning?"]. By 2015, according to the U.S. National Science Foundation, such goods and services could add more than US $1 trillion per year to the global economy.

The news, however, is not all good. There is a growing body of evidence that nanotechnological chemicals and related substances could pollute the air, soil, and water and damage human health. Preliminary studies from Arizona State University suggest that nanoparticles accumulate in the food chain and could cause problems later on. But if we act quickly, nanotechnology presents a distinct opportunity: we have a chance to deploy it properly—from both environmental and health perspectives.

This is an opportunity the semiconductor industry missed. Research into possible environmental and health implications of solvents and other chemicals, including arsine and trichloroethylene, wasn't done at the birth of the industry, before such toxic substances were widespread in the environment. If it had been, we might not be stuck with polluted sites left by manufacturing plants.

For nanotechnology, the chance to act responsibly won't be there forever. New nanomanufacturing processes are being brought online every day, and if we're not careful, we could be jolted years from now by unintended consequences and messes to clean up. What's at stake is potentially greater than the

DAVID CLUGSTON

billions of dollars in health and environmental costs particular to nanotech: for the first time, industrial society has the opportunity to usher in a new paradigm for dealing with the blights that until now have been seen as inevitable in big new industries. Instead of cleaning up the waste stream at the end of a product's or process's life, regulators and manufacturers—usually aware of the health and environmental issues they are facing—can solve many problems by preventing pollution before it occurs. For example, simply not using a material that's a known environmental hazard or designing processes that run at lower temperatures can prevent pollution problems.

And so it is with nanotechnology: our experience with small particles suggests that some of the nanoparticles we are already manufacturing could cause problems. We need to look at nanotechnology broadly, anticipate its adverse effects, and prevent problems. Prudently avoiding a crisis is always better than trying to repair damage later on.

NANOPARTICLES CAN BE SMALLER BY A FACTOR OF 1000 THAN THE AIR POLLUTANTS WE ARE JUST NOW BEGINNING TO UNDERSTAND AND REGULATE

WHEN WE TALK about nanotechnology, we mean that the materials involved exist as microscopic particles with at least one dimension that is between 1 and 100 nanometers. To put this in perspective, consider that the typical nanosize particle of titanium dioxide in sunscreen is 20 nm in diameter. The particle is a clump of about a million molecules. A grain of pollen is about 1000 times the size of this titanium dioxide nanoparticle; bacterial cells are around 100 times as large, and the width of a human hair is about 4000 times as great.

A molecule of water, at 0.2 nm, is smaller than the nanoscale. But the deoxyribonucleic acid (DNA) molecule is 2 nm in diameter, and a particle of soot can be less than 100 nm. So, are DNA and soot examples of nanotechnology? No. By definition, nanotechnology does not include incidental by-products of human activities, such as soot, natural nanoparticles, such as those emitted by volcanoes, or unaltered nanoparticles from biological processes, such as proteins, cell fragments, viruses, or DNA. Nanotechnology refers to *manufactured* materials in the nanosize range, or to manufactured products containing these materials.

Some bulk substances behave differently from nanosize particles. For example, a coin made of gold is the color of gold, but nanoscale gold is red; bulk gold is inert, but nanogold can be a catalyst for chemical reactions. The fact that nanoparticles have intrinsic and unique properties is the driving force for nanoscale research and commerce.

The electronics industry is at the forefront of this revolution. For example, all hard-disk storage today is based on a magnetic effect that occurs at the nanoscale level, where ones and zeros are changes in the magnetic poles of the nanoparticles. In fact, you'll find the vast majority of nanomaterials in electronics—in computer memories, batteries, displays, solar cells, capacitors, fuel cells, filters, antistatic coatings, and flame retardants. In the future, nanowires may power medical implants or cellphones by generating tiny currents when subtle movements make them vibrate and displace ions. Carbon nanotubes, which conduct electricity much more efficiently than traditional wires, could form the basis of batteries that could be recharged thousands of times. Carbon nanotubes can also be used in flat screens that are more efficient than today's displays [see photo, "Tube Tangle"].

AS NANOTECHNOLOGY SPREADS across industries, concerns about its environmental and health effects are spreading as well. The concerns stem from the small size of nanoparticles as well as from the atoms that compose them. Consider the class of airborne pollutants known as particulates. The U.S. Environmental Protection Agency (EPA) and many U.S. states currently regulate "coarse" particulate matter, less than 10 000 nm in diameter. In air pollution terms, nanoparticles are considered ultrafine particles, less than 0.1 micrometer or 100 nm. Airborne particles are released, for example, from fuel combustion or brake linings. Coarse particles and smaller ones can trigger asthma, bronchitis, and other respiratory diseases, make cold symptoms worse, and decrease lung function. Children and the elderly are especially at risk.

As a general rule, the health effects of smaller particles are more worrisome than effects from larger ones. Nanoparticles can be smaller by factors of 100 to 10 000 than the air pollutants we are just now beginning to regulate, and they could be even more harmful. Günter Oberdörster, a professor of environmental medicine in the school of medicine and dentistry at the University of Rochester, New York, studying ultrafine particles in 1992, found a nonlinear relationship between toxicity and particle size: as nanoparticles get smaller, their toxicity increases disproportionately.

Coarse particulate air pollution can damage lungs, but such particles are simply too big to get past the lungs and enter other parts of the body. Nanoparticles, on the other hand, can be more invasive. Nancy Monteiro-Riviere, a professor of investigative dermatology and toxicology at North Carolina State University, in Raleigh, discovered last year that some nanoparticles can penetrate the skin and could enter the bloodstream. Similarly, when swallowed, nanoparticles may be able to pass through the wall of the stomach or lining of the intestines.

In 2003, Chiu-wing Lam of NASA's Johnson Space Center, in Houston, instilled carbon nanotubes into the lungs of mice and reported that they triggered granulomas, or areas of inflammation. In a similar experiment, David Warheit at Dupont's Haskell Laboratory for Toxicity and Industrial Medicine, in Newark, Del., found such inflammation in rats' lungs in the same year. Perhaps most troubling of all, nanoparticles can make their way into the brain by passing from the nose through the blood-brain barrier, a membrane that protects the brain from chemicals in the blood while allowing oxygen, carbon dioxide, sugars, and certain amino acids to pass through unaltered.

In 2004, experiments by Eva Oberdörster, a lecturer in biological sciences at Southern Methodist University, in Dallas, found that the buckyball, a nanostructure made of carbon atoms, can penetrate the brains of bass via the gills. There, the nanoparticles trigger a reaction in brain enzymes called oxidative stress, a change in brain chemistry that indicates harm. Eva Oberdörster (a daughter of Günter) also discovered that buckyballs are toxic to daphnia, tiny freshwater fleas used to test toxicity in aquatic systems [see photo, "Aquatic Mine Canaries"]. The buckyballs did not clump together and sink harmlessly to the bottom of the test sites as researchers had expected.

In 2005 Daniel Watts, of the New Jersey Institute of Technology, in Newark, reported that nanoparticles of aluminum oxide slowed plant growth; the same nanomaterials are used in some scratch-resistant coatings.

Researchers are also concerned about persistence. Because of their small size and light weight, nanoparticles can stay aloft in the upper atmosphere much longer than coarse particulate air pollutants, and current filter technologies for controlling particles have holes that are a thousand times too big to trap nanoparticles. Nanoparticles may also bioaccumulate. For example, bacteria can ingest them, so the particles could become part of our food chain. And we know that chemical pollutants, like some pesticides, can also accumulate in the chain. At the moment, though, we don't know what effect nanomaterials will have on the food supply.

These are just a few of the studies that are raising a yellow flag in the race to develop nanotechnology. And they suggest the need for much more study, so that agencies can formulate intelligent regulations to protect the public's health and the environment.

IT WON'T BE EASY. Because there is an infinite variety of nanomaterials, determining the specific risks of each one can be challenging. Researchers are studying them by grouping them not only by size—an obvious choice—but also by chemical composition, shape, structure, and their state of aggregation. Chemically, materials can consist of a single element like carbon or metals like silver and gold or be found as compounds like cadmium selenide or indium phosphide. Examples of structures and shapes include crystals, spheres, tubes, and wires. The aggregation state refers to how the material clumps—or doesn't clump.

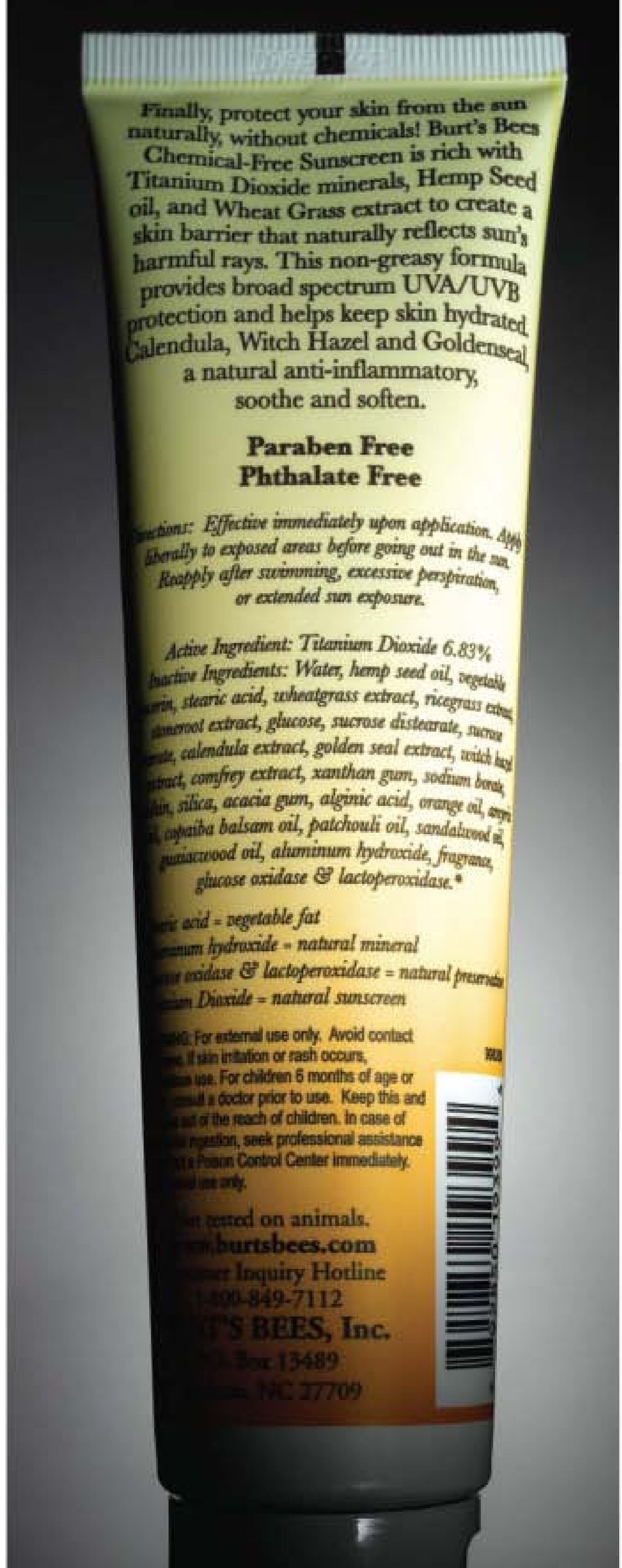
Some of these classification groups may prove to be more relevant than others to researchers looking for environmental or health effects. For example, the intrinsic toxicity of cadmium, the reactivity of nanogold, or the shape of nanowires could each make materials riskier to deal with.

Scientists have just begun trying to connect specific nanomaterials with the harm they might cause. Policy-makers are using the information to determine how best to protect the public from risks. Because nanoparticles generally do not exist outside of the laboratory or factory as free particles, regulators should be most concerned about the beginning and the end of a product's life. During manufacturing, emissions of nanoparticles can cause environmental or health problems, and at the end of the product's life, the disposal or deterioration of the item can also release particles.

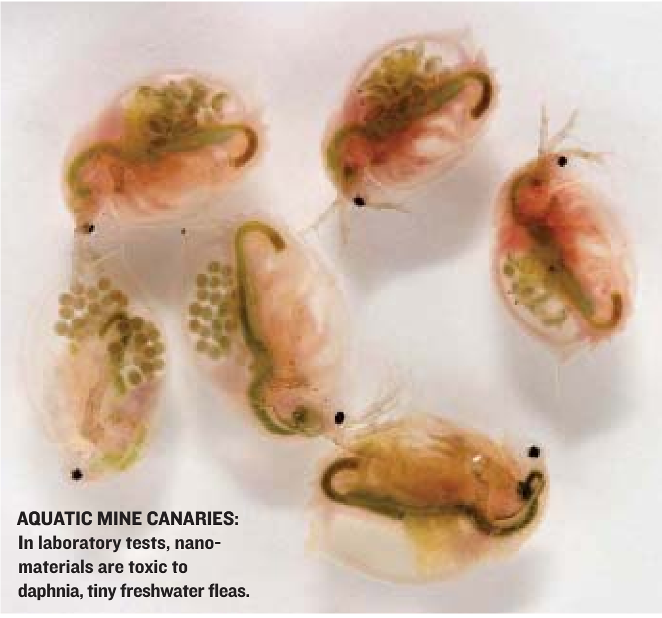
THE ELECTRONICS INDUSTRY, a key user of nanotechnology, can be a leader in investigating and preventing damage to the environment and health. It already has tools—used in designing products to be environmentally friendly—that look at all phases of a product's life cycle from manufacture to use and disposal. As it has in the past, the industry can encourage designers to make choices based on careful consideration of health and the environment rather than on cost or performance alone. For example, many consumer electronics companies eliminated lead-based solder from their products; the European Union banned it in products in 2006. And semiconductor companies have replaced toxic solvents in many processes with plain water.

One bright sign is that industry groups and government agencies are beginning to include concerns about nanotechnology in their long-term research planning. An encouraging new initiative is Green Nanotechnology, pioneered by the EPA and the Woodrow Wilson International Center for Scholars, in Washington, D.C. The two organizations are developing a framework and recommended practices that would help prevent manufacturers from releasing substances currently recognized as pollutants into the atmosphere, as well as prevent the manufacture of products containing nanomaterials that would knowingly harm the environment. The development of guidelines for Green Nanotechnology would let

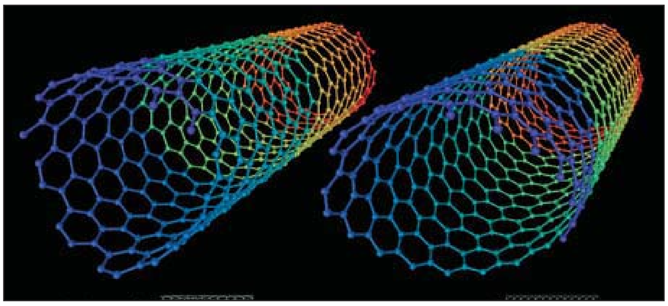
FAIR WARNING? Burt's Bees sunscreen touts itself as chemical-free. But the label doesn't mention that the active ingredient, titanium dioxide, is in the form of nanoparticles.



DAVID CLUGSTON



AQUATIC MINE CANARIES: In laboratory tests, nanomaterials are toxic to daphnia, tiny freshwater fleas.



TUBE TANGLE: Nanotubes could enable batteries to be recharged thousands of times instead of just hundreds, but they may damage the environment or threaten human health.

consumers or governments reward companies that are performing well, on the model of Energy Star, a joint program of the EPA and the Department of Energy. It sets guidelines for energy efficiency of consumer products and allows products that meet those guidelines to display Energy Star labels.

Recently, there was a small but significant victory: manufacturers of gold nanoparticles used for paint and, potentially, environmental cleanup and cancer treatment, developed a manufacturing method that eliminated the use of a toxic organic chemical and replaced it with water, reducing energy use at the same time.

GREEN NANO ALSO MEANS using nanotechnology itself to clean up production processes. The semiconductor industry can replace dangerous chemicals such as the perfluorooctane sulfonate polymers used in photo resists, antireflective coatings, and reagents with less toxic nano alternatives. Nanomembranes can filter out waste and pollutants in chemical processes. Nano-enabled sensors can improve process control and monitor emissions. Nanoproducts that improve energy efficiency, such as solar cells or better conducting materials, indirectly improve the environment through lower power-plant emissions.

The United States and other governments can help. In 1996, four U.S. agencies formed the Nanoscale Science, Engineering, and Technology (NSET) subcommittee of the National Science and Technology Council's Committee on Technology to coordinate federal funding of nanotechnology research and development. Today, 26 agencies work together on the NSET. Although there is no dedicated funding for nanotechnology in the federal budget, the subcommittee compiles a budget by annually aggregating the research in nanotechnology scattered across the R&D budgets of all its member agencies.

In 2005, nanotechnology research's budget totaled approximately $1.2 billion. But only about 3 percent of that went to research in environment, health, and safety issues, in spite of the fact that the group has declared that one of its main goals is to support responsible development of nanotechnology.

The EPA leads a partnership between the National Science Foundation, the Centers for Disease Control and Prevention, and the National Institute of Environmental Health Sciences to fund environmental health and safety research. It is the largest such research program, totaling some $21 million in more than 50 projects from 2003 through 2006. Research programs funded by this partnership are looking at the movement of different types of nanomaterials through the environment, the physical and chemical characteristics of nanomaterials that determine toxicity, and how nanomaterials enter the body.

The National Institute for Occupational Safety and Health laboratories are studying nanotech health issues related to the workplace, and the National Toxicology Program is testing individual nanomaterials for their effects.

Current programs to assess the risks of nanotechnologies are not enough, however, given the rapid advance of the technologies themselves.

NANOTECHNOLOGY IS ALREADY PART OF OUR LIVES. It will continue to roll out across industries and converge with advances in other rapidly developing fields including biotechnology, information technology, and cognitive science. It will enable amazing innovations.

And we don't have to sacrifice our lakes, rivers, air, and health to enjoy them. At today's still-early stage, we can develop nanotechnology correctly in the first place. It's an opportunity we should not miss. ■

ABOUT THE AUTHORS

BARBARA KARN is an environmental scientist in the U.S. Environmental Protection Agency's Office of Research and Development. She recently returned from a stint at the Project on Emerging Nanotechnologies at the Woodrow Wilson International Center for Scholars at the Smithsonian Institution, in Washington, D.C. The opinions expressed here are hers and should in no way be construed as EPA policy.

H. SCOTT MATTHEWS is an associate professor in the Departments of Civil and Environmental Engineering and Engineering and Public Policy and is research director of the Green Design Institute at Carnegie Mellon University, in Pittsburgh. He recently served as program and conference chair of the IEEE International Symposium on Electronics and the Environment (http://www.iseesummit.org).

TO PROBE FURTHER

More extensive information about what the U.S. government is doing in the field of nanotechnology is available at http://www.nano.gov.

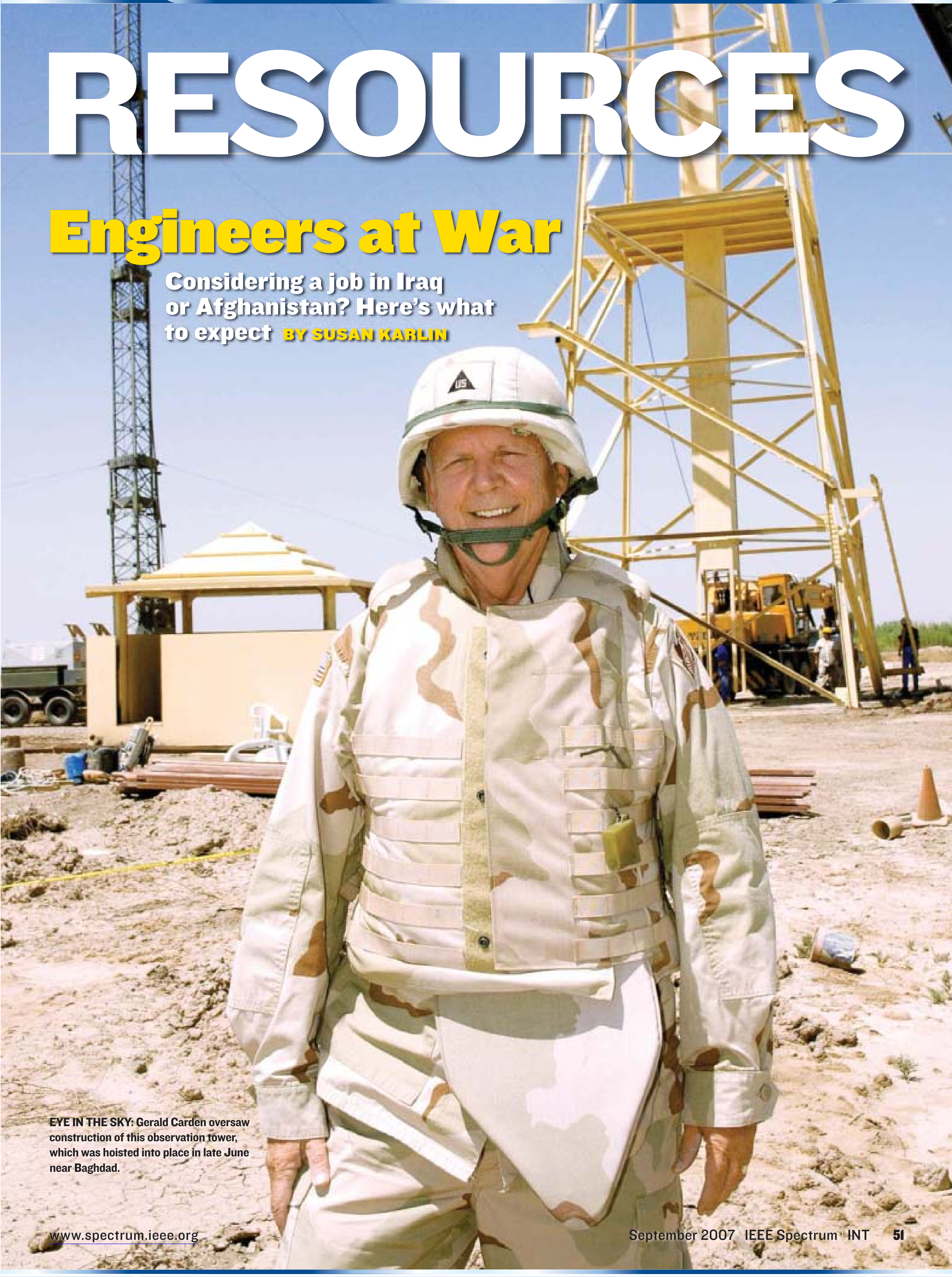
The Wilson Center's project on emerging nanotech provides webcasts, reports, and databases at http://www.nanotechproject.org.

EPA publications on nanotechnology, including the EPA's white paper on nanotechnology, are available at http://www.epa.gov/ncer/nano.

For the EPA Toxic Substances Control Act regulatory information, see http://www.epa.gov/oppt/nano. For the joint semiconductor/chemical industry road map for nanotechnology environmental and health issues see http://www.chemicalvision2020.org/techroadmaps.html.

LEFT: U.S. ENVIRONMENTAL PROTECTION AGENCY; RIGHT: MICHAEL STRÖCK

RESOURCES



Engineers at War

Considering a job in Iraq or Afghanistan? Here's what to expect BY SUSAN KARLIN

EYE IN THE SKY: Gerald Carden oversaw construction of this observation tower, which was hoisted into place in late June near Baghdad.

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RESOURCES

LAYING FOUNDATIONS: His Iraqi gig drew him "back to the nuts and bolts of engineering," Carden says.

CAREERS

So maybe it wasn't the safest route. But the road around Camp Anaconda, about 100 kilometers north of Baghdad, really was the quickest way to work. It was also a quick way to your karma. "I was told not to drive on it, first time," says Gerald Carden, a civilian project engineer with the U.S. Army Corps of Engineers. "When a mortar hit 200 yards behind me, that was the last time I drove on that shortcut."

In July, well into his second tour of duty, which ended last month, Carden was stationed at Camp Victory, adjoining Baghdad's international airport. "It's an unusual day if there are only two mortar attacks," he said then.

Like many of his colleagues, Carden was lured to the rebuilding efforts in Iraq and Afghanistan by a sense of purpose, the adventure, and a hefty paycheck. Combined with overtime and hazard pay, engineers can earn twice as much as for the same work stateside. Carden, with degrees in electrical and industrial engineering, was pulling in upward of US $220 000 a year for 12-hour days and six-and-a-half-day weeks overseeing work on hospital construction and power distribution.

The U.S. Department of Defense and the Army Corps of Engineers are still looking for a few good civilian engineers (go to http://www.cpol.army.mil). Although many of the contracts with private industry are winding down in Iraq, building in Afghanistan is ramping up.

Washington Group International, an engineering, construction, and management firm in Boise, Idaho, is exploring possible projects in Afghanistan. The company has cut its employment in Iraq to 75 expatriate and 1000 Iraqi engineers from a high of 200 expats and 5000 Iraqis. (At press time, the San Francisco engineering firm URS was poised to purchase WGI.)

An engineer's life in a war zone may be a little different from what you'd expect. First come a background check, a stringent physical exam, paperwork, safety training, and immunizations for diseases ranging from anthrax to tetanus. The process can take from two weeks to two months, depending on the employer. Then there's insurance. The Defense Base Act requires companies to pay death, disability, and medical benefits to workers on military bases outside the United States. But with DBA coverage maxing out at $4200 per month, employees—particularly those with dependents—tend to pay for supplemental life insurance, which can pay out six to eight times their annual salaries. They're also advised to draw up a will and set up a power of attorney.

Safety training and precautions vary by company and are the most important considerations when weighing job options. "The most common mistake people make is not realizing how truly dangerous the situation is there," says Paul Beat, director of project management for Control Risks, a risk assessment firm in London.

So before signing on, engineers should ask about their employer's crisis management plan, its security firm, the personal safety equipment it provides (such as helmets, gas masks, and Kevlar vests), the security of accommodations and in-country transport, and the training courses and briefings required before deployment. Such courses run from a day to a week and outline medical procedures and first aid, local customs and culture, how to survive an attack or kidnapping, how to cooperate with your personal security detail, and how to avoid land mines.

The screening and training processes winnow out about a fifth of the applicants, but even those who make the cut don't always get the hint. "We had a couple who wanted to go to the mosque as tourists and walked off the base in full violation of safety policies," says Debi Mitchell, WGI's human resources manager for the Middle East Construction Program. "They were okay, but we sent them home immediately. I guess they thought they were there to go sightseeing."

In fact, engineers rarely leave their bases. Since Americans on construction sites tend to attract insurgents, engineers mainly work from their computers on military bases, and they communicate by phone and e-mail. Off-campus travel requires a small convoy of armored vehicles and a personal security detail.

"Although my dominant consideration was salary, I had a different picture of getting out into the community, helping people, and being more hands-on," Carden says. "But in Baghdad, you don't have an option. You rarely visit the site you're doing the engineering for. Usually, the nationals come to the base for meetings."

He did have the chance to mentor some young Iraqi engineers working on the base and to sink his teeth into jobs converting a mishmash of foreign equipment to Iraqi frequencies. "There were problems you'd never see in the U.S.," he says. "It was getting back to the nuts and bolts of engineering."

Most of the engineers are male and married, though there are a handful of husband-wife teams, and more female engineers are joining than ever before. Spouses and kids remain in their home countries.

Vacation policies vary according to employer. The Corps of Engineers offers two weeks of R&R between the second and 10th months for those on a one-year tour. WGI allows a two-week vacation every 75 days. Engineers get a ticket home or the monetary equivalent toward a destination of their choice; most either go home or take vacations in Europe or Southeast Asia.

THIS PAGE AND PREVIOUS PAGE: NORRIS JONES/U.S. ARMY

In between breaks, military bases offer volleyball games, barbecues, and movies, as well as swimming pools and libraries, not to mention cable news and sports. "Golfers are just out of luck," Carden says. "There's plenty of sand trap and no course."

The best candidates for the jobs are flexible and low-key. In the words of one army major, "If a mortar exploding a hundred yards away will send them scurrying into a shelter sucking their thumb, then they should just probably stay home."

One civil engineer who worked with the Corps of Engineers at Camp Fallujah in 2005 and 2006 saw a contract for four police stations fall apart after insurgents killed the site superintendent. With more security came increased costs, and when the project finally did go ahead, it was for two stations for the price of the original four.

Due to the changing security situation, "you have to be flexible—there's a lot of hurry up and wait," says the engineer, who did not want to be identified. "If you like a certain routine and a latte before work, this is not the right job for you."

If the mortars don't get to you, the bureaucracy might.

"People who have never worked with the military are amazed by the amount of red tape and government paperwork," Carden says. "It's like trying to water-ski behind an aircraft carrier. Detail-oriented personalities and hotheads do not function well in this environment—there are too many projects to get done."

It can be taxing even for the most seasoned. After 19 months in Iraq, Carden was ready to call it quits in July. "This is the last tour," he said. "I'm 60 years old and getting past the point of wearing body armor. It's beginning to lose its appeal." ■

ABOUT THE AUTHOR

SUSAN KARLIN has contributed to *The New York Times*, *Forbes*, and *Discover*.

TO PROBE FURTHER

Organizations posting contracts in Iraq and Afghanistan include Washington Group International, in Boise, Idaho; Justengineers.net, of Morecambe, England; and the Iraqi Power Alliance, in Sydney, Australia, and London.

SHAYNE LYNN

KIDS, *DO* TRY THIS AT HOME

We built a backyard cannon, and you can, too

BY PAUL WALLICH

TOOLS & TOYS

Whoosh Boom Splat is a book for people who get along with the staff at the local hardware store. When I went to find parts for the T-shirt cannon on page 120, I got the new kid at the store. He was assigned the job of helping me as a way of learning the store's inventory. We spent the better part of an hour finding the right combination of reducers, couplers, valves, and PVC pipes to match the functional specs laid down by author William Gurstelle.

The book (published by Three Rivers Press, New York, in 2007) contains 10 projects for people who want to create interesting but potentially dangerous gadgets from PVC pipe and other readily available supplies. At the safer end of the spectrum are a blowgun for miniature marshmallows and a balloon-powered slingshot. For the more daring, there's a steam cannon that requires injecting water into a red-hot pipe fitting, a hair spray and Taser–powered potato shooter, and a pulse-jet demonstrator, which involves setting off several hundred controlled explosions inside a glass jar in the course of a few seconds. All 10 projects are reasonably safe as long as the reader observes the proper precautions.

I chose the cannon because it involved neither combustion nor uncomfortably high voltage. Instead, it simply requires a compressed-air reservoir and barrel, both made of PVC pipe, and a valve for delivering compressed air from the reservoir to the barrel quickly on command. Ancillary parts link those pieces, control the valve, and get compressed air into the reservoir in the first place.

The young clerk finally declared defeat when we reached the penultimate item on my list: a retaining nut for a 1/8-inch NPT air-tank valve (better known to most of us as the filler valve for an automobile or bicycle tire). One of the older hands took pity on both of us, picked up a different version of the valve, and walked right to another drawer, where he pulled out a slim metal torus that screwed onto the valve's tapered threads. "I knew I had some half-inch pipe-thread nuts around here," he said modestly.

The solenoid-operated sprinkler valve was the only fluid-flow item my hardware store couldn't supply. Nor could my local outlet of the home center that Gurstelle suggests, but an equivalent was readily available online. Then it was off to RadioShack for the electrical parts: a couple of switches and enough 9-volt batteries to feed a 24-V solenoid. I decided to forgo a ready-made project box in favor of a case from my junk shelf. For all I know, the Ethernet-to-AppleTalk adaptor it once housed still works perfectly, but no equipment anywhere in the civilized world needs that particular translation anymore.

A WHIFF OF GRAPESHOT (or of dirty laundry) should suffice to daunt any invaders of Paul Wallich's verdant Vermont domain.

RESOURCES

Assembling a project from *Whoosh Boom Splat* is mostly a matter of following an amalgam of instructions, but in every project there will be a moment or two of improvising very, very carefully whenever the instructions or your materials fall short. Along the way I found myself meditating on engineering practice. Pretty much all of the parts in the T-shirt cannon, like those in the book's other projects, are the wrong ones for the job, as far as conventional notions of design elegance go. PVC plumbing pipe was never meant as a compressed-air reservoir, diaphragm-style solenoid valves are horrendously unsuited to rapid airflow, and the less said about using 27-V dc to drive a solenoid whose manufacturer calls for 24-V ac, the better.

But it works. And the parts or their equivalents are all readily available throughout the industrialized world. The devices can be assembled by anyone willing to study the instructions. They're even corrosion-resistant. Talk about appropriate technology!

Implicit in Gurstelle's design—and explicit in his text—is an appropriate respect for devices that can potentially do serious damage to life, limb, and property. At the cannon's maximum design pressure of 5 atmospheres, the back-of-the-envelope range for a 1-kilogram projectile is on the order of 100 meters. So the two-switch firing design, for example (flip the cover off a toggle switch and turn it on to activate, push the momentary-contact switch mounted on the other side of the box to fire) is a healthy reminder that the cannon is serious as well as fun. The extensive derating of the pressure vessel similarly melds cautious forethought and sobering reminder. In more common use, the PVC pipe is designed to be twice as strong as it needs to be to contain a pressure of 8 atmospheres.

Actual assembly is simple but tedious: glue the PVC components together into subassemblies, wait for the glue to set, glue the subassemblies together. Apply Teflon sealing tape to everything that has threads, screw it all into the right places. The one finicky bit with my project was fitting the reservoir-filling valve; as its metal pipe threads tapped their way into the hole in the PVC end cap, I had to back the valve out every few turns to remove the swarf.

When the cannon was finished—I used only a few pieces of duct tape to hold the two barrels together and attach the control box to the rest—it was off to the closet for a test shirt. I chose my oldest, rattiest work shirt, rolled it up, stuffed it down the barrel, and then pressurized the tank to a mere 1.36 atmospheres with a bicycle pump. WHOOMP! Out came the shirt, fluttering to the ground on the other side of the front yard. At 2.72 atmospheres: WHOOMP! again.

I could have played with that toy all afternoon if my shirt hadn't gotten stuck 10 meters up in a tree. ■

ABOUT THE AUTHOR

PAUL WALLICH is a science writer who lives in Montpelier, Vt.

LOST IN SPACE

The Space Station's woes show what's wrong with NASA and hints at how to put it right

REVIEWED BY JAMES OBERG

BOOKS

You can learn a lot from this study of the International Space Station, a troubled attempt to coordinate NASA and its Soviet and later Russian counterpart. Above all, you learn how not to manage a major technological project.

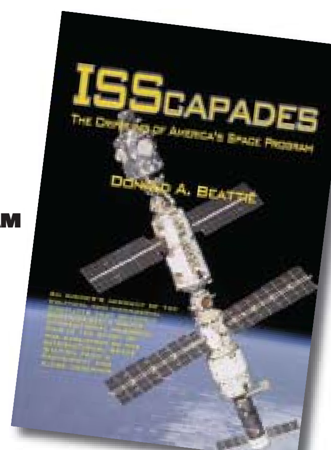
Donald A. Beattie, a retired senior manager at NASA, was in its inner sanctum during the crucial period, from 1982 to 1998, when the station was conceived and born. The reports, memos, transcripts, budgets, and memoirs that he gathers here, most of them never published before, chronicle the surges, droughts, and dams that characterized the funding of the project.

"In the final analysis," Beattie writes, "funding, or the lack thereof, shaped the program as much or more than any other events." The space station, he told me, was cursed from the start by the U.S. Office of Management and Budget.

His central theme is NASA's failure to learn from its history, much less that of other space programs. That, he says, is why it made so many errors of judgment.

Beattie also delves into the management of technological risk and crew safety. He details the 1997 report by NASA Inspector General Roberta Gross indicting the agency for ignoring the problems it had in working with the Russians and for yielding to political pressure. Workers who did not toe the line were forced out, even Gene Kranz, the heroic NASA flight director portrayed by Ed Harris in the movie *Apollo 13*. It came as no surprise—except to managers who had not wanted to know the risks—when Mir had a series of near-fatal disasters. NASA officials ignored even those red flags and adopted a culture of willful carelessness that led logically to the loss of the *Columbia* space shuttle with all its crew.

ISSCAPADES: THE CRIPPLING OF AMERICA'S SPACE PROGRAM
By Donald A. Beattie; Apogee Books, Burlington, Ont., Canada; 226 pp., US $23.95; ISBN-10: 1894959590



APOGEE BOOKS

Beattie provides plenty of insightful descriptions of leading managers, few of them complimentary. He calls Daniel Saul Goldin, the longest-serving NASA administrator in history, "a disaster" for bullying subordinates, fawning over politicians, subverting the technical review boards that he chaired by dictating off-the-cuff solutions to problems, and putting astronauts into top management slots for which they had no background or training. If Goldin hoped that their yearning for a future space assignment would make them totally compliant with his decisions, he was right. The astronauts did as they were told.

Hindsight, of course, is easy. Still, Beattie offers more than a mere catalog of woe—he offers a prescription for doing better. His recommendations have credibility, both from the many irrefutable details he provides and from the passion for space exploration that he evinces. He remains dedicated to the U.S. space program as a major national activity.

The book is a tough slog, though. Even the margins are too narrow for comfortable eyeballing. But space flight is not for wimps or lazy thinkers. Would-be space managers should have to read and digest this book to prove that they, like the astronauts, have the "right stuff." ■

ABOUT THE AUTHOR

JAMES OBERG worked for NASA for 22 years. He writes on space exploration from his home in Galveston County, Texas.

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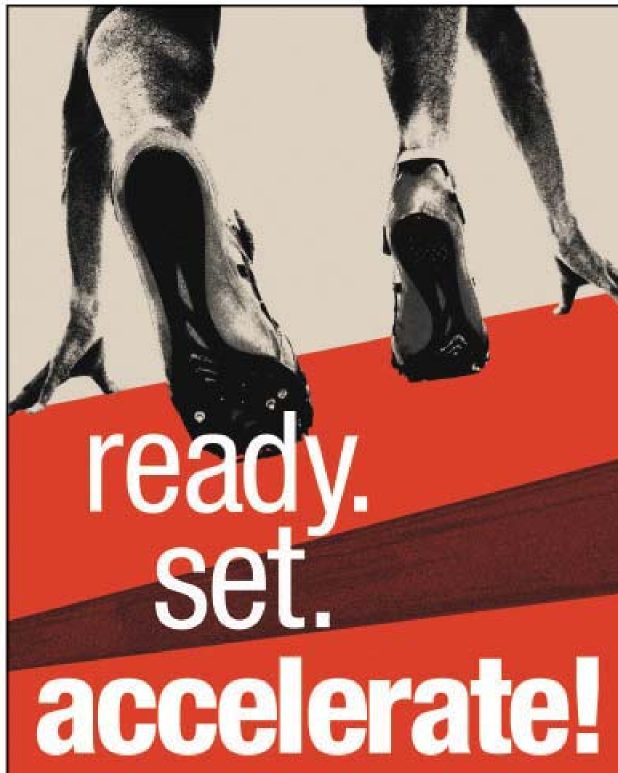

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REFLECTIONS

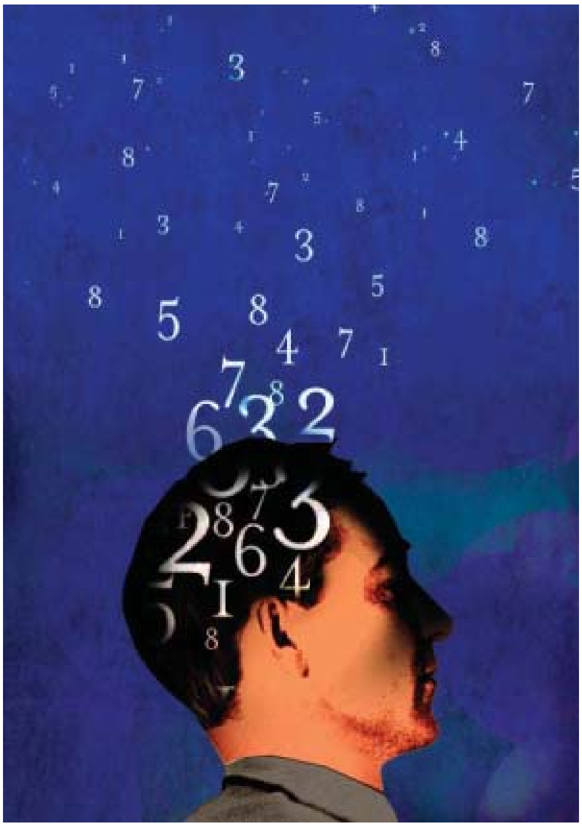
By Robert W. Lucky

Math Blues

I was browsing some of the features of a popular computer program for doing mathematics. Wow, I thought! What I would have given for this years ago!

But suddenly I was overcome with sadness. I don't need this anymore, I realized. In fact, it has been many years since I worked with "real" mathematics. I just never really thought about that loss before. It was as if my profession had slipped away when I wasn't looking.

I commiserated with several engineering friends. Two of them weren't concerned at all. That's what happens when you move along in your career, they said, and it doesn't make you any less of an engineer. The other, a researcher like me, shared my nostalgia and pain. It made him think of what he had been—and was no more.



I wonder how many engineers use advanced math in their jobs and whether fewer do so, now that computers have consumed so much of our work. Has mathematics disappeared behind the screens of our monitors, as have so many other subjects since engineering began to center increasingly on writing software?

Yet mathematics is a way of thought that binds us to our profession. Maxwell's equations are inscribed in the entrance foyer of the National Academy of Engineering as the very symbol of what we do. I look at them as the scripture of engineering—a concise and elegant description of the laws that govern electromagnetism. But I also wonder: How many engineers have actually used Maxwell's equations in their work? Alas, I've never had the pleasure myself.

Our journals are still full of mathematics. If you want to publish and have your work inscribed in stone for eternity, you must code your work in mathematical symbolism. If you want to parade among the elite of the profession, you must cloak yourself in mathematics. This is the way it has always been. Now, if math is disappearing from our practice, this would make me sad.

I remember well the day in high school algebra class when I was first introduced to imaginary numbers. The teacher said that because the square root of a negative number didn't actually exist, it was called imaginary. That bothered me a lot. I asked, If it didn't exist, why give it a name and study it? Unfortunately, the teacher had no answers for these questions.

As with much of the math that we've all studied, understanding comes only much later. We've all had the experience of learning mathematical principles before we had any idea what they were good for. If I could go back to that day in high school, how would I have explained matters?

I can think of two approaches, although somehow I doubt that my younger self would have been happy with either. The first is to say that mathematics is beautiful in itself, a study of consistent rules of logic that can be appreciated as an art form, quite apart from any application it may have to everyday problems. The second is to note that this square root of minus one is actually useful (in problems that my younger self didn't know about yet). It opens the door to two-dimensional thinking—a dimension that gets you off the line of real numbers. So whether or not this imaginary number exists in your world of arithmetic training, it's useful. In real world problems, it works.

I'm reminded of a famous saying in physics, variously attributed to Paul Dirac and Richard Feynman: "Shut up and calculate." It was a response to a class of problems in quantum mechanics in which the Shrödinger wave equation often contradicts common perception, yet it always provides the right answers. So don't worry about it: quit complaining and just calculate. Like using the square root of minus one, it works.

Since that first introduction to imaginary numbers, I've just about come full circle. I learned to appreciate math, and I found imaginary numbers useful. But now I'm thinking that, though the appreciation remains, the usefulness to me has faded.

The more I think about this as I write, the sadder I get. I'm going to go back and look at the features of that mathematics program again. ■

ROBERT W. LUCKY (IEEE Fellow), now retired, was vice president for applied research at Telcordia Technology in Red Bank, N.J. (rlucky@telcordia.com).