MICROSOFT'S QUIET QUEST TO PUT ROBOTS EVERYWHERE

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VOLUME 44 NUMBER 8 INTERNATIONAL EDITION

Tandy Trower serenades a coterie of robot friends at Microsoft Research in Redmond, Wash.

COVER: Photo: David Stuart; 3-D Illustration: Bryan Chrystie Design; Retouching: Smalldog Imageworks
THIS PAGE, LEFT: Brian Smale; RIGHT: Rainer Holz/zefa/Corbis

This month at SPECTRUM ONLINE
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THE SOUND OF MUSIC
Audio technology has evolved spectacularly during the past 25 years. We can now tweak singers' voices as they perform and pump up the volume on CDs. In a two-part report, *Spectrum's* Suhas Sreedhar explores the frontiers of music making.

WIRELESS HOSPITALS?
Even as Wi-Fi, ZigBee, and Bluetooth proliferate in hospitals, Joseph J. Morrissey of Motorola wonders if wireless transport will ever be as reliable or predictable as traditional wired schemes.

THE STATE OF GAMES
David Kushner reports on the hot trends emerging from this year's invitation-only E3 gaming trade show.

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IEEE SPECTRUM

AUGUST 2007

VOLUME 44 NUMBER 8 INTERNATIONAL EDITION

Russia and China plan to shoot for Phobos, one of Mars's moons. 11

LEFT: Nicholas Eveleigh
RIGHT: ESA/DLR/FU Berlin (G. Neukum)

NEWS

OPINION

RESOURCES

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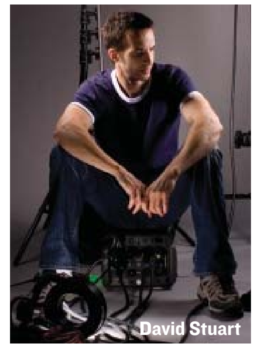
LEFT: MORGAN COOPER; RIGHT: DAVID STUART

THE BACK STORY


David Stuart


Scott Dorman

Making the Ghosts Live

Photographer David Stuart was on assignment for *IEEE Spectrum* in an atmospheric cemetery in Atlanta when he noticed an odd, bright apparition in the LCD panel of his digital SLR. "I got really excited for a second," he says, "but then I realized it was just a sun flare." So it was left to photo retoucher Scott Dorman of Smalldog Imageworks and illustrator Bryan Christie to get ghosts into the shot.

The three collaborated on the largest effort ever undertaken at *Spectrum* to bring an artistic concept to life, and you can see the results on the opening page of "Is It Live or Is It AR?" in this issue. (The three also worked on this month's cover image, showing a T. Rex head.) Senior Art Director Mark Montgomery came up with the idea and deployed the all-star team of past contributors to capture the emerging technology of augmented reality. "Many of the practical uses of augmented reality are for museums," says Montgomery. "So we wanted to show a person using AR as a virtual museum guide."

The image portrays the heartbreaking story of a woman, Sarah K. Dye, who carried her dead infant through Union lines during a Civil War siege to bury him in the cemetery. Dye's likeness has clearly been incorporated into an existing photo. It might be less obvious, however, that even the "existing" photo doesn't exist. The picture's elements—the tombstones, the man's face, his shirt, his hands, and the reflections on his glasses—were pieced together from about 2500 different shots. "You don't want it looking like you slapped it together out of 10 parts," says Dorman, which meant that the image needed to be "slapped together" out of hundreds of parts. ■

CITING ARTICLES IN IEEE SPECTRUM

IEEE Spectrum publishes two editions. The international edition is identified by the abbreviation INT at the foot of each page. The second edition goes only to North America; it is identified with the letters NA. Both editions have the same editorial content, but because of differences in advertising, page numbers may differ. If you cite an article, you should include the issue designation. For example, this note is in *IEEE Spectrum*, Vol. 44, no. 8 (INT), August 2007, p. 5, or in *IEEE Spectrum*, Vol. 44, no. 8 (NA), August 2007, p. 7.

FORUM


NEWS
NEWS BRIEFS
Delhi's Defense Spending Spree

"India is a victim of a colonial past that has put incompetent bureaucrats in charge of critical technical and military institutions"
—Nirode Mohanty

INDIA'S DEFENSE WOES

Seema Singh's item on "Delhi's Defense Spending Spree" [News, June] illuminates the dismal state of India's defense planning, policy, and procurement, despite the country's enormous scientific and technical manpower resources. Politics, corruption, indecision, and lack of vision have contributed to a situation in which there is no defense chief, no strategic planning, and no long-term investment. There is very little coordination among the three military branches and scientific organizations and only a haphazard shopping spree amid several weapons-purchase scandals. India is a victim of a colonial past that has put incompetent bureaucrats in charge of critical technical and military institutions.

Nirode Mohanty
IEEE Fellow
Huntington Beach, Calif.

MEGACOMMUTES TO MEGACITIES

I was concerned by the assumption that it's okay to commute 2 hours to work—each way! ["How To Keep 18 Million People Moving," June.] Why does modern society think that it's entitled to expend all that energy, in whatever form, merely to transport people to their jobs? No one mentions the toll that a 4-hour-per-day commute takes on relationships. And, by the way, the emerging world wants to emulate our folly.

What has always seemed more sensible to me is to live where you work. My commute is 10 minutes each way, on foot. And in my entire career as an engineer, the longest commute I've had was a half-hour drive. Even that seemed excessive to me.

Solution? Think about the whole system. For example, when designing new green buildings to house companies, add housing for those who will work there.

Peter Drexel
IEEE Senior Member
Plymouth, N.H.

The editor responds: We at *IEEE Spectrum* do not advocate 2-hour commutes. We regret any perception to the contrary.

URBAN INDIGESTION

I applaud Professor Rees's efforts to understand the way cities work and to measure their input and output ["How to Measure a City's Metabolism," June]. His conclusions sound an awful lot like communism, though. Professor Rees makes it sound as though the root problem that needs to be solved is prosperity. The United States, the United Kingdom, and most of the West are so prosperous because their people are free politically and relatively unencumbered economically. "Intervention in the economy," "densification," "appropriate planning," and using the tax code to control consumption are completely at odds with political and economic freedom.

For the better part of the last century, the leaders of the Soviet Union arrogantly employed the sort of centralized planning, economic intervention, and densification Professor Rees seems to be recommending. They failed, and their system crashed. I hope I have misunderstood Professor Rees.

Justin Clack
IEEE Member
Vancouver, Wash.

I ♥ LAGOS

As a Nigerian scholar, I thought the piece on Lagos ["How Not to Make a Megacity," June] was stereotypical, lacking in insight, and under-researched.

Lagos is improving. The Lagos business district wears a new look where multibillion-dollar businesses are leading a wave of capitalist revolution in Nigeria. A stock-market boom has led to the emergence of a new middle class, with planned communities like Lekki, in a Lagos suburb, springing up to accommodate it. New modern malls, cinemas, and shopping complexes welcome you to this urban wonderland off the coast of Lagos.

Maybe the next time the author actually gets around Lagos he will take off his "Afro-skeptic" hat and see the real Lagos. Then he can put the real story on view instead of hiding it in the mass of sensationalized pictures of filthy garbage.

Michael Oluwagbemi
IEEE Student Member
Houston

NEWTON, NOT BERNOULLI

"Fly Like a Bird" [May] promotes the ancient and popular myth that airplane wings provide lift as a result of Bernoulli's principle. Actually, almost all of the lift comes from forces resulting from the large mass of air deflected downward by the wing passing through the air at a positive angle of attack. In other words, it's more Newton than Bernoulli.

Using Bernoulli alone, you'd be hard-pressed to explain how most airplanes can fly upside down, rather than being forced downward by a double dose of gravity and Bernoulli. In fact, aerobatic airplanes, which spend a lot of time flying upside down, have virtually symmetrical top-to-bottom airfoil shapes.

Glenn Elliott
Albuquerque

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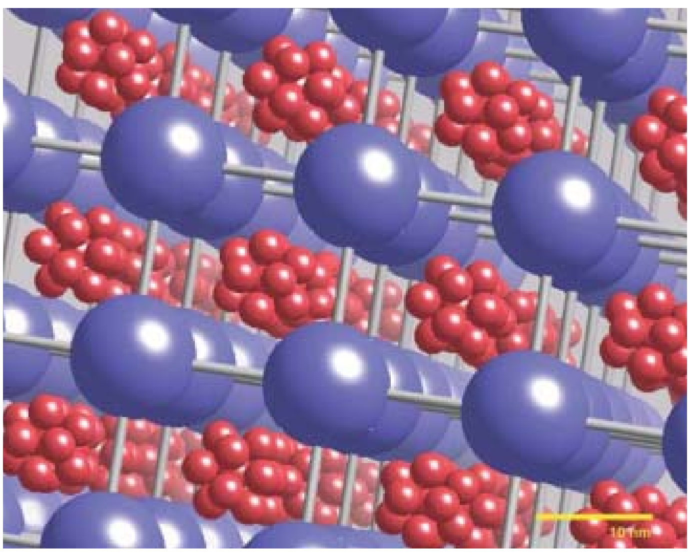
SPECTRAL LINES

Material By Design: Future Science or Science Fiction?

You don't hear much talk about it anymore, but one of the tacit promises held out by the field of nanotechnology has been "material by design." To solve a specific problem using this "bottom-up" approach—say, creating a material engineered for efficient hydrogen storage—you design and create structures, atom by atom or molecule by molecule, that provide the functionality needed for a particular application.



FRANZ REDL, KYUNG SANG CHO, CHRISTOPHER B. MURRAY, AND STEPHEN O'BRIEN, IBM T.J. WATSON RESEARCH CENTER AND COLUMBIA UNIVERSITY MATERIALS RESEARCH SCIENCE AND ENGINEERING CENTER

But despite government task forces and lots of fascinating nanoscale research (like the beautiful model of the first 3-D assembly of magnetic and semiconducting nanoparticles shown here), material by design isn't even on the horizon, certainly not for the production of bulk commercial materials. The goal of an ambitious business alliance launched in 1996, the Chemical Industry Vision2020 Technology Partnership, was to have designer materials in production by 2020. In fact, we are so far from that goal it's not clear whether we will ever be able to overcome all the obstacles.

Unfortunately, nanotechnology in the marketplace is still a "top-down" discipline that can only begin to approximate material by design. Novel nanomaterials and structures are discovered, their properties are determined, applications are sought out that may need those particular properties, and then it is finally determined whether there is any commercial need for applying the nanomaterial to an application. Chemical and material companies will produce what the market demands, in a way that promises the greatest profits. When talking about bulk chemicals and materials, it is nearly impossible to think about producing these atom by atom, because you can get to the same material by just following a hit-or-miss iterative process, and do so far more cheaply.

Some of the obstacles facing material by design would have been hard to appreciate in the nanoloving 1990s, when the Vision2020 group, all highly respected scientists from research institutes and the chemical industry, came together to develop a road map for their dream of creating custom nanomaterials.

One major roadblock is scientific. If we are ever to reach a point where we can take a certain requirement, and then be able to go to a computer and design the material that is ideal for this purpose, we are going to have to overcome some fundamental problems of material science. Currently, we don't even have a good grasp of how combining materials into particular compounds gives them certain properties, or how these properties give materials functional qualities.

A second major problem is computational. Not only do we not understand the basic physical principles we need to model, there are at the moment no computers powerful enough to predict how certain material structures yield particular properties. When it comes to solid matter, systems are so complex that current computer modeling tools quickly run out of steam. Granted, algorithms and processing power are always improving, but it would take orders-of-magnitude improvements for computers to reach the predictive power required to address these issues.

Any useful software modeling would need to be able to reveal how a material's structural alterations—for example, a change in a crystal's lattice structure—affect its properties and functions. Such a program would also need to be able to do that in a range of scales, because we also don't know whether we must look at the atomic or particle level to find out where effects are taking place.

The bottom line: material by design may elude us for centuries. Hit-or-miss approaches to large-scale commercial nanotechnology look more promising for now, but even here our ability to manipulate materials at the nanoscale for commercial applications may come down to serendipity rather than scientific method and design. ■

Guest editorial by Dexter Johnson, program director at Cientifica, a nanotechnology consulting firm, and blogger for IEEE Spectrum Online (http://www.spectrum.ieee.org).

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NEWS


PROTOTYPE SYSTEM: Nikon's beta EUV system, soon to be operational, will be suitable for experimentation but will not be able to make advanced chips.

NIKON CORP.

Plans for Next-Gen Chips Imperiled

Dim lights casting a shadow on extreme-ultraviolet lithography's debut date

Everyone in the chip industry knows that the giddy, exponential curve they've been riding for decades can't go on forever. Some day a "showstopper" will finally appear, signaling an end to the amazing pace at which microprocessors, memory, and other chips have become denser and faster without getting more expensive. Nobody ever expects that dreaded day to be right around the corner. But now, sobering revelations about a futuristic, multibillion-dollar chip-making initiative have thrown a shiver through the industry, raising concerns that the showstopper may be closer than anyone had thought.

As recently as March, researchers were still confident that a technique called extreme ultraviolet (EUV) photolithography would be ready in 2011 to start churning out cutting-edge logic chips. But at an advanced lithography symposium held that month by the photonics society SPIE, experts from IBM and its development partners AMD, Micron Technology, and Qimonda said they do not expect EUV to be ready for its intended debut. Others in the industry, though less blunt, say progress made in the coming year will make or break the deadline.

Historically, each generation of photolithography technology has remained useful for about six or seven years, spanning three size reductions, or nodes, in chip processing. Today's technology uses light with a wavelength of 193 nanometers to produce chips with key parts, or features, that measure just 65 nm. If the seven-year rule holds true, 193-nm lithography will need a replacement by 2012 or 2013.

Before anyone panics, it's important to note that the industry has been consistently wrong about when any particular production technology will hit its limits. But with six years to go, it's clearly crunch time for this technology. "The next year or so is going to be crucial," says Michael C. Mayberry, vice president of Intel's technology and manufacturing group.

Until recent years, semiconductor road maps anticipated challenges developing masks and photoresists capable of handling EUV, but not problems generating EUV light as such [see sidebar, "EUV: Expectations vs. Realities"]. Only in 2005 did the road map spell out the hurdles that would have to be surmounted for EUV lithography to work. Since then, contrary to expectations, obtaining an adequate light source has turned out to be the biggest stumbling block.

A chip's vast profusion of transistors is created by a process of depositing successive layers of metals, insulators, and other materials on a wafer of semiconductor, and then etching away the part of each layer not wanted. The process of defining what goes and what stays is known as photolithography. First the wafer is covered with a chemical called a photoresist. The circuit pattern to be projected on the wafer is drawn on a transparent photomask. The photolithography system shines UV light through the photomask, projecting a shadow of the circuit pattern on the wafer. The photoresist reacts to the light. The parts of the photoresist that react harden and protect the areas directly beneath, allowing everything else to be etched away.

The shorter the wavelength of the light used in the projection, the smaller you can make the transistors and wiring on a chip. EUV sources aim to operate at 13.5 nm—technically, past the ultraviolet part of the spectrum and into the low-energy end of the X-ray band. Transistor features on today's best chips are as small as 65 nm—less than 1 percent the width of the cotton fiber in your shirt. By the time EUV was supposed to come online, they were expected to be around 22 nm.

The EUV wavelength was chosen many years ago, not because there was a good source of 13.5-nm light at hand but because there were good reflectors and filters available. Chip makers expected that, over the years, all the other pieces of the technology would fall into place as they had for other new photolithography systems. But some of those pieces still don't fit. "The biggest challenge is the source," says Michael Lercel, lithography director at Sematech—an independent, nonprofit consortium with a charter to help develop new chip-manufacturing technologies. And the source is intrinsically tied to another problem: a light source has to be paired with new photoresists sensitive to it. But the development process for photoresists, too, has been more painful than predicted.

A commercial EUV lithography system will almost certainly need a source that can operate steadily and reliably at 150 to 200 watts. But in practice, developers of sources for photolithography systems—such as Cymer, Gigaphoton, Philips Extreme, Starfire Industries, and Xtreme Technologies—are still struggling to achieve 10 W on a consistent basis. At a Sematech workshop in late May, Gigaphoton reported an EUV source capable of a record 130 W, but only in short bursts, which suggests but does not prove that it could be made to provide 40 W of usable light. That's good for testing prototype systems, but it's still far too dim and intermittent for commercial use.

There are two ways to make sources specifically for lithography systems: a discharge-produced plasma (DPP) or a laser-produced plasma (LPP). "A year ago, DPP was in the lead," Intel's Mayberry says. "Today, it's a lot more of a horse race."

Traditional DPP sources use electrodes to conduct enormous pulses of current into tin vapor or xenon gas, turning it into a plasma that radiates EUV, among other wavelengths. But the proximity of the electrodes to the hot plasma and the tremendous current rushing through them cause the electrodes to overheat, melt, and evaporate. This erosion of the electrodes makes DPP systems unreliable and subject to frequent maintenance. Vapor from the electrodes also can gum up the expensive precision optics needed to collect and direct EUV light.

Although it provides less than 10 W of usable EUV light, the DPP source from one company, Energetiq, at least gets around the electrode problem. It does so using a method that CEO Paul Blackborow calls electrodeless Z-pinch. A large current pulse in a loop of wire outside the discharge chamber creates a magnetic field that induces loops of current within xenon gas inside the chamber, heating it to a glowing plasma. The geometry of the source is such that the external magnetic field "pinches"

NEWS BRIEFS

GALILEO'S TRIALS European transport ministers, meeting in early June, failed to breathe new life into the foundering public-private consortium set up to design, build, and operate Galileo, a global-navigation system meant to rival the U.S. GPS and Russian Glonass systems. Construction of Galileo is far behind schedule, and members of the multinational consortium of aerospace companies participating in it were unable to reach an agreement.

Pre-Katrina [above], you had a 1 in 100 risk of flooding to the indicated levels; today [below] your risk of flooding to indicated depths is 1 in 50.

U.S. ARMY CORPS OF ENGINEERS

VIRTUAL NEW ORLEANS The U.S. Army Corps of Engineers has issued a report showing interactively how much each neighborhood of New Orleans is at risk from flooding in 50-year and 100-year storm scenarios. Either by means of Google Earth or PDF overlays, maps show how vulnerable neighborhoods are now [see above], even with the enhanced storm protection system put in place since Hurricane Katrina [see "Protecting the Big Easy From the Next Big One," March]. The corps found that the heart of the hard-hit lower Ninth Ward can still expect to be under 1.2 to 1.8 meters of water once every 50 years and under 1.8 meters or more once in a hundred years. Its report, available at http://nolarisk.usace.army.mil, is a preliminary study of how to protect the city against all but a 100-year storm.

NEWS

the plasma loops, causing the xenon to emit EUV light while simultaneously keeping it clear of the chamber walls where it can damage the optics. "The plasma is decoupled from the walls it's in," Blackborow says. "It's clean, simple, long-lived." The source is suitable for use in developing the infrastructure for EUV technology, such as testing new photoresists and optics.

In LPP, the alternative to DPP, tin droplets are jetted through the source chamber tens of thousands of times per second. As they fall through the chamber they are hit by pulses from kilowatt-class lasers. The laser pulses turn the tin into an EUV-emitting plasma.

LPP developers, such as Cymer, Gigaphoton, and Xtreme, try to hit all the tin drops in just the right way, and with just the right amount of energy, according to Vivek Bakshi, a senior member of the technical staff in Sematech's lithography division. Too much or too little energy, and the tin plasma does not reach the particular energy state that generates the most 13.5-nm light, Bakshi says. Likewise, hit the droplet with a laser beam that's too broad, compared with the size of the droplet, and the tin will absorb too much energy, because it is still in the beam path even after it expands into a vapor. A beam that's too narrow, or one that's off center, will blast off droplets of debris that muck up the source's optics.

"No one has demonstrated the ability to hit [the tin] consistently," Blackborow says. So in practice the emitted EUV flickers too much to work in an industrial-scale setup.

The brighter the light, in general, the less time it takes to expose the photoresist and the faster the whole chip-making process runs. Chips today are produced by the hundreds on a 300-millimeter-diameter wafer. Commercial systems will have to process 100 of those wafers per hour. So whether the chip industry can settle for a mere 100 W or must wait for still brighter sources depends on how sensitive photoresists can be made. If the resist is so sensitive to 13.5-nm light that it needs to collect only a few thousandths of a joule of energy to set, a low-power source will provide those millijoules quickly enough for commercial throughput rates.

But so far, there has been little to cheer the chemists struggling with photoresist development. A few years ago, they thought it might be possible to develop a high-quality resist that would require only 1 or 2 millijoules of EUV energy per square centimeter to set. But they've had to scale back their expectations. Now the goal is a 5-mJ resist, which could be paired with a 115-W source to get an acceptable commercial throughput. A 15-mJ resist would probably need a 150-W source, and a 20-mJ resist would likely have to be paired with a source at 200 W or more. Sematech's Lercel says the very-high-resolution resists that some laboratories are using today are usually rated somewhere between 30 mJ and 50 mJ.

Christopher Sparkes, senior director of technology at Nikon Precision, a Japanese lithography systems manufacturer, says that a 15-mJ resist—which would require a 150-W source—might be the best that can be hoped for. But Intel's Mayberry says that's overly pessimistic.

There are, of course, other hurdles to getting EUV ready besides the source and resists, including new photomasks to carry the circuitry pattern and multilayer reflectors to steer the EUV beam. But these technologies have reached the point that major photolithography companies ASML, Canon, and Nikon are rolling out demonstration machines with weak light sources.

ASML has a test system it's calling an alpha tool—suitable for experimentation only. It has shipped two. Canon is also preparing an alpha machine.

Nikon already has at least one alpha model in operation in Japan, and plans to have a beta, dubbed the EUV1, ready by the end of 2007 [see photo, "Prototype System"]. The EUV1 also will be suitable only for experimentation, but Nikon is justifying the beta tag with the claim that the system can be upgraded for use in production with the addition of a powerful enough source, when available.

Provided that it does, in fact, become available.

Energetiq's Blackborow says the fact that ASML has shipped a system, unsuitable though it is for commercial use, is being taken as a very good sign. G. Dan Hutcheson, CEO of market analysis firm VLSI Research, agrees. But he points out that, judging from the path of earlier lithography innovations, it would take five or six years to thoroughly test a new production process and all the equipment in a new production line—and that's only if EUV were production-ready today.

Wisely, chip makers and their equipment suppliers are exploring alternatives, particularly those processes that will let them extend today's lithographic technology. One option is to replace the minuscule air gap between the lenses and the wafer with water or some other fluid, to alter the way the light bends and produce finer features, and then expose the wafer twice or more using different masks. The double patterning produces finer features, but it requires twice the number of photomasks, has slower exposure times, and frequently requires an extra etch step. That means higher costs and lower throughput, according to Sparkes. Nonetheless, ASML, Intel, Nikon, and others are developing the technology, in the increasingly likely case it is needed.

—BRIAN SANTO

EUV: Expectations vs. Realities

The 2001 and 2003 semiconductor road maps contain long tables detailing progress that will have to be made with masks and photoresists when extreme-ultraviolet radiation comes into play as the main lithography tool, but no discussion of EUV as such in their sections discussing "difficult challenges" in lithography.

Only in the 2005 road map does there appear a paragraph listing the main challenges of EUV. They include "developing mask blank fabrication processes with low defect density; developing EUV sources with high output power and sufficient lifetime for surrounding collector optics; controlling contamination of all mirrors in the illuminator and projection optics; fabrication of optics with figure and finish compatible with high-quality imaging at 13.5-nanometer wavelength; resist with sufficiently low line width roughness and low exposure dose; and protection of masks from defects without pellicles."

How is the industry doing? In brief—

- Development of optics: well enough.
- Photoresists: not quite as well as hoped in terms of matching resists to available light power.
- EUV light sources: far behind schedule.

MOCK-UP: The Phobos-Grunt spacecraft is evaluated at the Lavochkin Research and Production Association, near Moscow.

DESTINATION: A photograph of the Mars moon Phobos, as seen from NASA's Mars Global Surveyor spacecraft.

LEFT: MASHKOV YURI/ITAR-TASS/LANDOV; RIGHT: NASA

China Reaches For the Red Planet

Joint project with Russia anticipates retrieving soil from the Martian moon Phobos

China is getting ready to participate in its first interplanetary enterprise, teaming up with Russia, in a daring attempt to retrieve samples from the Martian moon Phobos. The Phobos-Grunt mission—*grunt* is the Russian word for soil—is scheduled to launch in October 2009, with the samples set to arrive on Earth in 2012 [see photo, "Mock-up"]. If Phobos turns out to have been formed from Mars, the mission will provide a shortcut to obtaining ancient Martian soil. In any case, Phobos-Grunt is Russia's only scheduled planetary mission for the next 10 years, and it is the first sample-return effort since Apollo, more than 30 years ago.

The China National Space Administration and the Russian Federal Space Agency (Roscosmos) signed a formal agreement in March that will allow China to send a small satellite called the CDP-1 to Martian orbit, piggybacking on the Phobos-Grunt orbiter. According to Alexander Zakharov of the Space Research Institute in Moscow, project scientist for the Phobos-Grunt mission, the CDP-1 would test a deep-space tracking system, measure the various constituents of the Martian atmosphere, and study the plasma field around Mars during a one-year period. The Chinese are also contributing a thermal differential analyzer for the gas-chromatograph system, to be used in analyzing the elements contained in soil samples taken from Phobos before they are brought back to Earth. The instrument is being built by the Hong Kong Polytechnic Institute.

The Lavochkin Space Association, in the Moscow area, is the manufacturer of the Phobos-Grunt spacecraft, which is to be launched on a Russian Soyuz-2b rocket and take eight to nine months to reach Mars. Once in orbit, the spacecraft will separate into three individual vehicles: the Chinese Mars satellite, the Russian Phobos orbiter, and the Phobos-Grunt lander [see photo, "Destination"].

Much of the Phobos-Grunt's work will focus on Mars and its atmosphere, but the moon itself has plenty to offer. Phobos and its fellow moon Deimos are named for the sons of Ares, the Greek counterpart of the Roman god Mars (*phobos* means fear; *deimos*, terror). Although the moons were discovered in 1877, Jonathan Swift already had a premonition of their existence, astonishingly, in his *Gulliver's Travels* (1726). Orbiting 5989 meters above Mars's surface, Phobos has a period of just 7 hours 39 minutes and is gradually being drawn into the planet—it will crash in about 50 million years.

Because Phobos orbits at roughly twice the rate of Mars's rotation, Phobos-Grunt will undergo a series of complex maneuvers to first enter Martian orbit, where it will stay and perform remote observations of the Martian atmosphere and surface. Then the orbiter will launch the lander to the surface of Phobos a month or two later. The lander will spend several months collecting samples with the aid of a robotic arm that can dig down to a depth of 1 meter.

Using a cache of scientific instruments, it will study the physical, chemical, and structural properties of Phobos's surface and inner structure and send the data back to Earth. After that has been accomplished, a sample-return canister mounted on top of a small rocket (called an Earth-return vehicle) located on the Phobos lander will be filled with 1 kilogram of soil, dust, and rock. "Because Phobos has no atmosphere or large gravity field to contend with, launching a small rocket should be relatively simple," Zakharov says.

If all works according to plan, the return vehicle will blast off from Phobos and head toward Earth, taking from seven to 18 months to arrive. The sample container could either be picked up in Earth orbit by a Russian spacecraft or enter Earth's atmosphere to land at some location in Siberia and be retrieved by helicopter.

The origins of the Martian moons are a mystery that Phobos-Grunt intends to illuminate. There are two contending theories: that Phobos was formed from Mars and hurled into orbit by a collision with a large asteroid or comet millions of years ago; or that Phobos is a captured asteroid from the asteroid belt, which is located between Mars and Jupiter.

If Phobos was once part of Mars, it may contain ancient subsurface water ice or even ancient microfossils from a time when Mars was warmer and wetter.

Thomas C. Duxbury, NASA's Stardust

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NEWS

project manager and a coinvestigator on the Soviet Phobos-2 mission in 1988 that ended prematurely because of a computer glitch, says he believes Phobos and Deimos were blasted off the surface of Mars by an impact event. If that turns out to be the case, "then we have a much simpler Mars sample-return mission," he points out.

Alternatively, if Phobos was an asteroid, then its soil can provide planetary scientists with a sample of the raw material from which the planets were formed. In January 2006, NASA's Stardust space vehicle was the first to successfully bring back samples of a comet to Earth. They are believed to contain material that existed before the solar system came about. Material in the asteroid belt, on the other hand, is thought to be the debris left over from the formation of the planets.

Given that NASA has now put its own Mars Sample Return project on hold until 2020 or later, could Phobos-Grunt also be a dress rehearsal for an eventual Mars sample-return mission? Mikhail Marov of the Keldysh Institute of Applied Mathematics in Moscow, principal investigator on the Phobos-Grunt mission, explains: "The experience gained from Phobos-Grunt will be extremely valuable for the follow-up Mars missions that are now in the Russian Science Academy's [planetary exploration] blueprint."

—BARRY E. DIGREGORIO

Low Power to the People

A South Carolina city is the latest battleground for low-watt community radio

On Sunday evening, 10 June, WMXP-LP/95.5 FM, in Greenville, S.C., signed on the air for the first time. The event marked the end of a seven-year battle to provide an alternative to the city's large commercial stations for the African-American community, which makes up one-third of greater Greenville's 300 000 population. WMXP is a community radio station owned and operated by the local chapter of the Malcolm X Grassroots Movement for Self-Determination, situated in the heart of a long-depressed but rebounding black community that abuts Greenville Downtown Airport [see photo, "Against All Odds"]. The fight to get WMXP on the air exemplifies a growing movement that has pitted community activists, public interest lawyers, and electrical engineers against the National Association of Broadcasters, the lobbying organization in Washington, D.C., that represents commercial radio stations in the United States. NAB members fear that their listenership—and their advertising revenues—would suffer from the presence of alternative programming.

AGAINST ALL ODDS: Seven years after applying for a low-power FM license, Efia Nwangaza, director of Greenville's Malcolm X Grassroots Movement, stands outside the home that hosts WMXP's broadcast tower.

The Greenville radio station is a new beachhead in a conflict over whether political, ethnic, and religious groups, as well as neighborhoods and school authorities, may operate low-power FM (LPFM) radio stations, which—by dint of their small broadcast ranges—are necessarily focused on local interests. Starting in the late 1980s, activists and advocates created pirate LPFM stations and went to court, challenging radio rules. The aim was to change regulations that effectively shut out community organizations from the broadcast spectrum in favor of corporate media. The result was the Federal Communications Commission's 2000 decision to create LPFM licenses for community radio stations.

Currently there are approximately 600 LPFM stations in the United States that, like WMXP, broadcast at 10 to 100 watts. But organizations such as the Prometheus Radio Project, a Philadelphia-based activist group, say they won't be satisfied until they have helped knock down legal and administrative barriers that are preventing hundreds more from going on the air. Six hundred low-power stations may seem like a lot, but there are roughly 6000 full-power FM stations, many of which are capable of transmitting signals at up to 100 000 W, says Timothy L. Warner, an IEEE member in Asheville, N.C. Warner, an audio, acoustic, and communications systems designer, helped build the Greenville radio station.

The LPFM framework, as originally set up by the FCC, promised to make stations like WMXP and others that Prometheus has helped build—in places as diverse as Tennessee, Oregon, Tanzania, Nepal, and Guatemala—available in most cities. But commercial broadcasters lobbied the U.S. Congress intensely, claiming that low-power stations cause interference that prevents radio receivers from tuning in to the full-power stations' broadcasts.

In response, Congress inserted restrictions into the LPFM rules regarding usable frequencies and minimum distances between transmission towers; these hold low-power stations to more stringent standards than commercial stations. For example, high-powered repeaters that extend the signals from full-power stations hundreds of kilometers beyond the boundaries of their stated broadcast range can operate on the second-adjacent channel from a local station (meaning that the frequency at which its signal is broadcast has to be on average 400 kHz above or below the protected station's) as long as other conditions are met. Low-power stations, however, have

WILLIE D. JONES (4)

to be at least 800 kHz away from local stations' towers and stations' repeaters, dramatically reducing the available frequencies. For example, if there had been stations in Greenville using frequencies anywhere between 94.9 MHz and 96.1 MHz, WMXP would not have been able to broadcast at 95.5 MHz.

An engineering study ordered by the FCC found the commercial broadcasters' contention regarding interference laughable. Nevertheless, Congress voted down proposed amendments to the LPFM restrictions introduced in 2005 and 2006 that would have liberalized the restrictions in favor of low-power radio. But groups such as Prometheus haven't given up. Senators John McCain, R-Ariz., Maria Cantwell, D-Wash., and Patrick Leahy, D-Vt., introduced a bill this summer containing amendments striking down the restrictions—which community radio advocates hope will become law.

Controversy over interference threatened to shut down the Greenville project before the station ever powered up. The original construction plan, submitted to the FCC in 2000, immediately after LPFM licenses first became available in South Carolina, called for the transmission tower to be located on the Malcolm X Center's premises. But that plan was scuttled, along with the entire low-power FM application, when the owner of a high-power commercial station located a few hundred kilometers away filed a motion asserting that erecting a tower there would inhibit the expansion of its broadcast area. "The preeminence of commercial stations over low-power FM stations resulted in our initial construction permit being withdrawn," says Efia Nwangaza, the Malcolm X Center's founder and director.

With the assistance of a team of attorneys and engineers who volunteered their time or offered it at greatly reduced rates, Nwangaza, an attorney and longtime human rights activist, filed an amended application, and eventually the center received the broadcast license. (Nwangaza gained a measure of fame when, as a Green Party candidate for the U.S. Senate in 2004, she was one of two women barred from debates sponsored by the League of Women Voters.) The revamped plan required the transmission tower to be located in one of two sites, both of which were in residential areas. As fate would have it, one of the spots was in the backyard of another longtime community activist, who readily agreed to host the tower.

Once the station's advocates had overcome that hurdle, the Prometheus Radio Project organized a three-day event, a "barn raising," to help build the station. Prometheus is a standard-bearer in an ongoing fight, in the words of Pete Tridish, one of the organization's cofounders, to "help demystify technology and put it in the hands of communities." Volunteers from across the globe gathered in Greenville to lend their engineering, construction, programming, news gathering, community organizing, and fund-raising expertise (or just additional pairs of willing hands) to build the station from scratch and prepare locals to run it.

EACH ONE TEACH ONE: A retired radio engineer [top] uses skills honed during a career in the U.S. Army to ready a used sound board. A veteran of low-power radio projects in Central America [center] leads a workshop focusing on technical know-how—including ways antennas and receivers work. As an activist from Amman, Jordan, recounts the experience of building a community radio station there [bottom, left], the budding radio reporter in the middle gathers audio with guidance from the seasoned journalist to his left.

An important part of the task was creating a wireless Ethernet bridge connecting a 6-meter mast on the center's roof to the 10-story freestanding transmission tower that had already been built in the community activist's yard 3 km away. An IEEE 802.11a link carries the encoded digital signal from the station to the tower, where it is decoded, amplified, and routed to the broadcast antenna.

Although the accelerated construction timetable required almost an around-the-clock effort, sawing and soldering were only one part of the goings-on. Workshops each day offered bare-bones explanations of the physics of sound and radio transmission, as well as tips on applying for a radio license. Volunteers gave short courses on how to conduct interviews and elicit stories of interest to the local community [see photos, "Each One Teach One"].

When the participants weren't working or learning, they gathered at Greenville's Phillis Wheatley Community Center, which served as home base. From Friday afternoon through Sunday evening it resembled a commune, with some participants bunking and showering there, and most of the workers eating meals prepared by other volunteers. By the time the switch was flipped on Sunday evening, old friendships had been renewed, new acquaintances made, a radio station completed, and a battle for the expansion of community radio won.

"It's been an interesting experience," Nwangaza says. "I have to give great credit to Prometheus in their commitment to the issue of community radio and their willingness to work with community people. I am certainly an example of that commitment and will be ever indebted to them—and so will Greenville." —WILLIE D. JONES

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NEWS


EARLY WARNING: This NOAA buoy in the Pacific Ocean is part of the oceanographic agency's Deep Ocean Assessment and Reporting of Tsunamis system.

A Global Search Engine For Geospatial Data

Scientists inch toward a standardized, universal system

If you're a scientist or engineer cobbling together a geospatial project—say you're trying to figure out how many people would be threatened by a tsunami in the Indian Ocean—a truism holds that you spend 80 percent of the time hunting down usable data [see photo, "Early Warning"]. The data, when they exist at all, often are archived in incompatible formats, have varying degrees of accuracy and precision, and sometimes require a good deal of political savvy to find.

Yuri Gorokhovich is an assistant professor at the State University of New York at Purchase who has been investigating tsunami damage in Southeast Asia. Getting what he needed meant negotiating with the Indonesian government, agreeing to pay US $4500 for the required data, and identifying the one and only person who could authorize the transfer. Even then, in order to develop a model identifying how many people lived in the areas directly hit by the December 2004 tsunami, Gorokhovich had to secretly get classified government data smuggled over by foreign colleagues.

Making such work as simple as a Web search is the central objective of the Global Earth Observation System of Systems (GEOSS), an endeavor taking its first baby steps this summer. The system's architects are compiling what is essentially a search engine for environmental data, including not just data from Earth-observing satellites but also terrestrial sensor data, population figures, and regional health and ecosystem information. Formatting and indexing the data, designing a portal, and creating a standards repository are the fundamental, if humdrum, components upon which hinge the lofty goals of GEOSS: to improve environmental models and forecasting.

"The seismic community, the solid earth guys, the weather folks, the climate folks—they all speak different languages," says Jay Pearlman, a chief engineer at Boeing, in Seattle, and chair of the IEEE Committee on Earth Observations. Finding ways to enable those disparate communities to use the same data has been a mammoth task since GEOSS was conceived in 2003. According to Pearlman, a GEOSS portal and data clearinghouse are expected to launch by November, just ahead of a ministerial summit that month in Cape Town, which will bring together high-level delegates from all 70 contributing countries.

The implications are not just humanitarian and scientific, but commercial as well. Right now, a Google Earth mash-up can locate, say, all ice cream carts in Moscow; with GEOSS online, it may soon be possible to identify the places where the best golfing conditions will prevail five days from now. "This really is a quantum difference, not a matter of degree," says George Percivall, the chief architect for the Open Geospatial Consortium, in Wayland, Mass.

Still, the main thrust of GEOSS is human-oriented science. Geospatial coordinates alone can vary tremendously depending on how scientists in disparate disciplines record the locations of observations—sometimes to the point of rendering the data unusable. "Around the world there's hundreds, if not thousands, of ways people use to specify location," says Siri Jodha Singh Khalsa, the IEEE Committee on Earth Observations' vice chairman for standards. Location coordinates are made relative to a particular model of the Earth, for example, and different scientific communities use different models.

Although the more standardized observations from satellites help, taking data from space introduces other problems. The geographical coordinates for observations made on a moving platform are inherently less precise. Add to that the fact that many measurements are inferred from other properties—for instance, temperature data come from infrared readings—and it's easy to see why space data are considered less reliable until they have been validated by overlapping observations made on Earth.

In the case of the Indonesian tsunami estimates, Gorokhovich had developed a model from satellite observations of how far inland damage had gone, but he needed to verify it. Eventually, he says, he "got lucky" and met someone who had mapped the locations of displaced refugees while traveling through the country.

Data from ground-based sensors, for their part, are less likely to be well indexed or to use standardized representations such as those based on XML, the mark-up language commonly used on the Internet. That makes it harder for researchers to locate and use the data.

If all relevant sources of Earth-based information could be logically connected and recorded in well-documented formats, life would be a lot easier for modelers.

Another goal of GEOSS's architects is to persuade national governments to make more data freely available. Some countries restrict access to their space data more tightly than others, and the availability of any one measurement can vary from country to country. NASA has made elevation data for the United States available at 30-meter resolution, but data for the rest of the world, generated by the same satellite mission, is released only at 90-meter resolution.

In Europe, despite all the talk in Brussels of transparency, satellite data are even less freely available. According to Khalsa, the European Space Agency in Paris is very guarded with its satellite records, which it generally releases only to approved European Union researchers. "You have to go through special approval processes to get their data," he says.

—SANDRA UPSON

U.S. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

THE BIG PICTURE

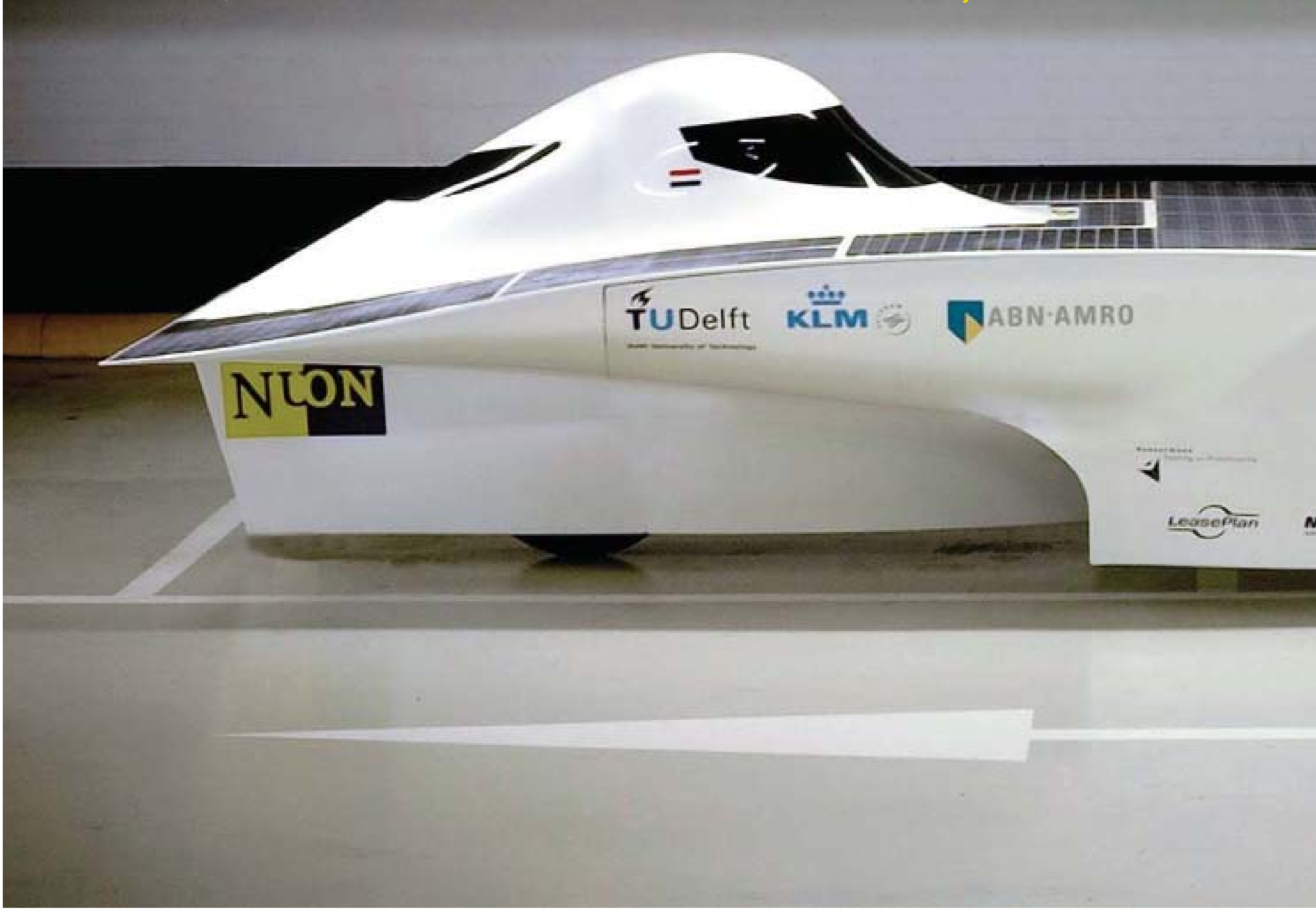
Stellar Performer

If past performance is any indication of future results, you are looking at the winner of the 2007 World Solar Challenge, to be held this coming 21 October. The 3000-kilometer race is run every two years, slicing north to south through the dusty red heart of Australia. Like all the racers, this slick number, called Nuna4, is powered entirely by the sun's rays. It is the latest eco-speedster from the Nuon Solar Team, which is based at the Delft University of Technology in the Netherlands. The Nuon team has won all of the three contests held since 2001.

Nuna3, which won in 2005 with an average speed of 103 kilometers per hour, did so well that it scared race officials into changing the rules. It briefly and unofficially hit 145 km/h (90 miles per hour)—"freakishly fast," notes Oliver van der Meer, a member of the Nuon team. The speed limit on many Australian highways is 110 km/h. So for this year's race, drivers have to wear crash helmets and sit upright under a protective roll cage—which explains the relatively tall rear cockpit bulge of Nuna4 as compared with its flatter predecessors. Solar panels have also been limited to 6 square meters per vehicle. "It's really an engineering competition now," van der Meer says.

For more on the Nuon Solar Team and the 2007 race, see http://spectrum.ieee.org/jun07/5273.

Photo by Hans-Peter van Velthoven




NUON
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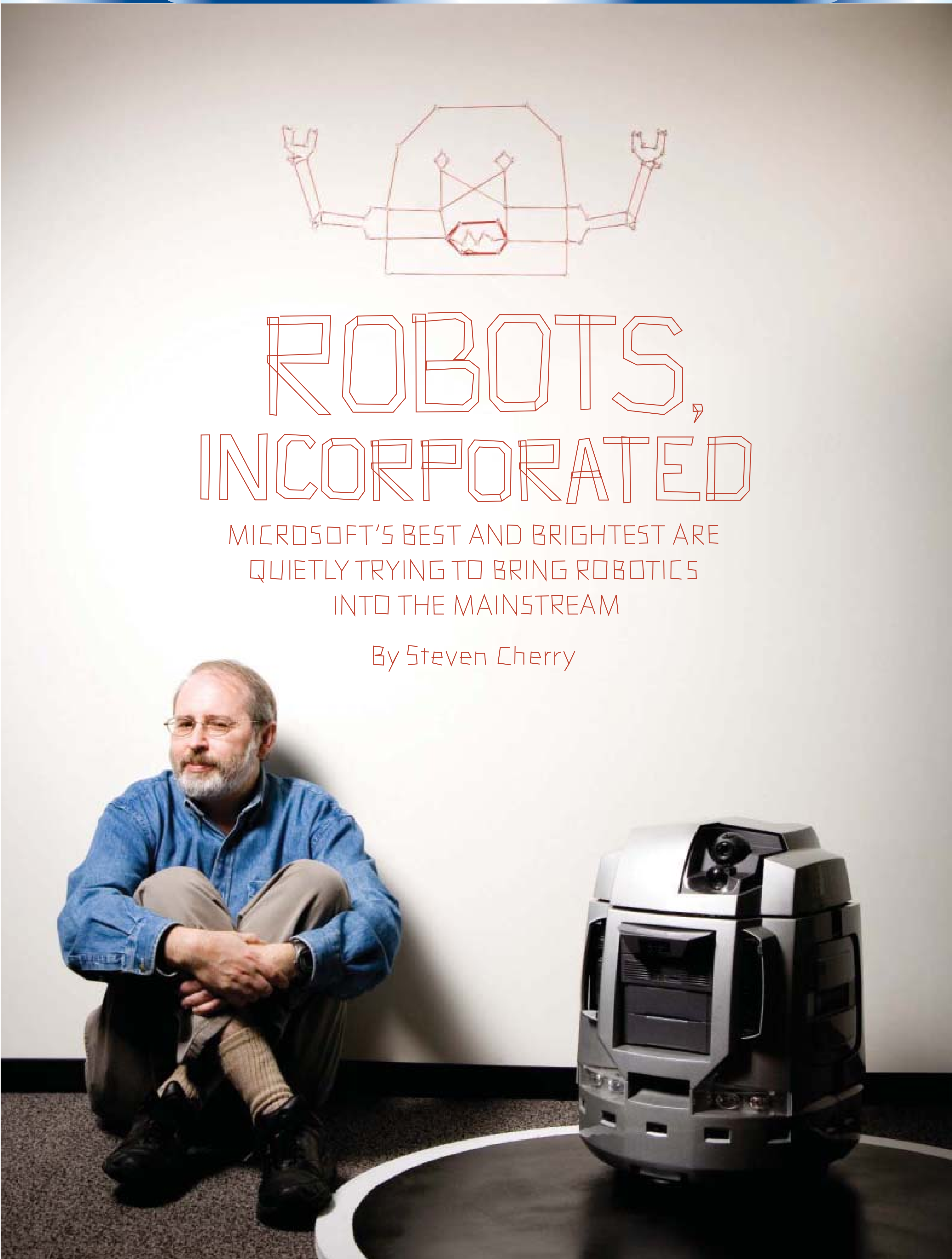
NUON
sikkens
FAG
TENCATE

ROBOTS, INCORPORATED

MICROSOFT'S BEST AND BRIGHTEST ARE QUIETLY TRYING TO BRING ROBOTICS INTO THE MAINSTREAM

By Steven Cherry



Software pundits and tech analysts can be forgiven for overlooking Microsoft's new robotics group. Compared with the company's billion-dollar businesses—Windows, MSN, Xbox, and more—robotics is nonexistent. Microsoft is giving the group's software away for free for noncommercial use. In other ways, robotics is merely minuscule. And indeed, the company is hardly betting the farm on it, having devoted only 11 of its 76 000 employees to creating Robotics Studio 1.0.

Yet this tiny group of elite software engineers, housed in a small set of open offices known as the "Broom Closet," handpicked by a 26-year company veteran who has the ear of Bill Gates, and tucked into a tiny corner of the company's research budget, has put together a set of tools that may bring robot manufacturers under one roof, the way Windows did for most PC makers. Indeed, future versions may someday find their way into more machines than Windows did—and be just as lucrative. Microsoft's eventual plan is to charge users US $399 to license up to 200 copies of the software components that go into a commercial robot.

Right now, the robotics world is rife with devices that don't easily work together or with standard programming tools. Take the Create, a generalized, programmable version of the popular Roomba vacuum-cleaning robot. The Roomba's maker, iRobot Corp. of Burlington, Mass., stripped out the vacuuming-specific parts and put in a cargo bay, a serial cable, 32 different sensors, and a 25-pin expansion port. At $130, it's a budding roboticist's dream. But to program it, you have to write in C or C++. If you want to add a webcam or a robotic arm from another manufacturer, you have to write more code—first for the accessory and then for integrating it into the robot. If you later swap out the new unit for a better one from a different vendor, you have to invent that wheel all over again.

Good robotics programming is far harder than writing a typical application for personal computers. Each component is expected to act autonomously and react to complicated events in the world of a kind that a printer or mouse never has to deal with.

Robotics Studio, released in December, aims to handle much of that complexity for robot programmers. It isn't an operating system. But manufacturers will use

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it to write software for their robotic components much as a maker of a device that hooks up to a PC does, whether it's a printer, an LCD display, or a data-acquisition sensor. Once such a service is written—telling, for example, a robotic arm to move up or down, grip or release, rotate *n* degrees, and so on—the action can be done with a single instruction. And when you substitute a new arm, the same commands work in the same way, so a minimum of reprogramming is needed. Microsoft's software, in other words, will do what MS-DOS and then Windows did: nurture an ecosystem in which new devices spawn new programs for more and more end users who in turn inspire yet more innovation—the same virtuous cycle that brought explosive growth to the cottage PC industry 25 years ago.

Whether that cycle will develop remains to be seen, but there are signs it may have already begun. The tool kit has been downloaded more than 100 000 times since its December release. An enhanced version, previewed in April, will be used this fall in computer-science and engineering classes at Georgia Tech, Carnegie Mellon, and other schools. And it's already being tested by a variety of manufacturers, from makers of the tiny iRobot units to Kuka Robot Group, in Augsburg, Germany, which in May released the first robot able to lift 1000 kilograms. Even though the software is free for many, managers at Microsoft say they're confident that once it's in millions of machines, money-making businesses will emerge. The company's free media player, for example, was the seed from which its Internet-based television software—with customers such as AT&T and Verizon Communications—sprouted.

Today's $11 billion robot sector—mostly industrial robots—will double by 2010, according to estimates by the Japan Robot Association, and it should exceed $66 billion by 2025. Most of the growth will be in nonindustrial applications—especially, analysts say, in areas such as toys, transportation, and health and senior care. Imagine a robot helping a recovering heart-attack patient get some exercise by walking her down a hospital corridor, carrying her intravenous medicine bag, monitoring her heartbeat and other vital signs, and supporting her weight if she weakens.

The International Federation of Robotics predicts that 5.6 million robots for domestic, entertainment, and leisure applications will be sold from 2006 to 2009, and right now the field is wide open. Microsoft's competitors include Player, an open-source project partially funded by the U.S. National Science Foundation, DARPA, and various artificial intelligence labs; Gostai, in Paris, a small maker of open-source robotics software; and Evolution Robotics, based in Pasadena, Calif., and Tokyo. None has anything near the vast resources of a Microsoft. It's no wonder the 10 people who wrote Robotics Studio 1.0 say they believe they're the pioneers of the next big thing, not just for their company, but for the world.

At Microsoft, even the lowliest new programmers have their own offices, and buildings on the company's sprawling Redmond, Wash., campus consist largely of corridor after corridor of individual offices, each with a large window equipped with blinds for privacy. Except, that is, for one particular corner of the third floor in Building 113. There you'll find a large open space—the Broom Closet—with a couch, easy chairs, a coffee table, a giant LCD television, and more robots, robot accessories, and robotic toys than you thought existed.

There are iRobot's Roomba and Create robots, of course. Attached to another robot are a radio and antenna, small stereo speakers, and some kind of sensor attachment that looks for all the world like a small coffeemaker. There's also the Traxster, a robot made by Summerour Robotics Corp. of Atlanta, which has wheels that run in tracks, as on a tank, and optionally includes vision sensors connected to an articulated neck. There are joysticks, keyboards, and remotes of various kinds; a low, circular, wheeled robot that looks like a cross between the Roomba and a blue ladybug; several Lego Mindstorms robots; a black-and-white spaceman robot that looks handmade; and a green-and-purple stuffed dinosaur. When I ask whether the dinosaur is a robot, Ioana Butoi, a 26-year-old Romanian software engineer on whose desk it sits, answers shyly, "No. But it could be."

Setting up shop in what was assumed to be a utility closet was the idea of Tandy Trower, manager of the group and its sole office dweller. "I wanted a small group that spent time together," he says. "Good things happen in small groups of people who talk to one another a lot."

In late 2005, Trower cherry-picked its members from every area, including two engineers from the first team to work on the Xbox, another project in which Microsoft tried to do something completely different. Today, the Xbox is the heart of the company's $4 billion entertainment division.

TEAM MEMBER	AGE	BIRTHPLACE
Tandy Trower (SEATED IN FRONT)	N/A	Germany
Steve Sklepowich	43	Canada
Paul Roberts	34	United Kingdom
Pavel Khijniak	24	Russia
Henrik Frystyk Nielsen	37	Denmark
George Chrysanthakopoulos	32	Greece
Kyle Johns	42	United States
Ioana Butoi	25	Romania
Andreas Ulbrich	31	German Democratic Republic
David Lee	41	United States
Joseph Fernando	41	Sri Lanka

CAME FROM	LISTED AS THEY APPEAR, FROM LEFT
Engineering Excellence Group, Office of the Chief Software Architect	
Digital Media Division	
Windows Security Team	
Windows Core OS Division; Incubation Group "Big Top"	
World Wide Web Consortium, Cambridge, Mass.	
Advanced strategies, R&D; Xbox	
Xbox	
Windows Live OneCare	
Technische Universität, Berlin	
Visual C++	
Digital Media Division	

The idea for the robotics group came from several different sources. The first was Craig Mundie, the company's chief research and strategy officer. Back in 2000, he took a broad look at trends in computing and the Internet. What he foresaw was a "sea-change of increasing complexity. There would be processors everywhere," he says. Computation would be distributed across different processors in a single chip, a single device, or across a network, local or otherwise. Processors would be loosely coupled; that is, they would come and go at will. And computing was moving to a services-based model, meaning that software would increasingly be written for a network cloud—a company's network or the Internet itself—instead of individual computers.

That's just the opposite of what happens on a PC, where a single processor is in charge; peripherals ask to be connected and disconnected and in between have to request some of the processor's valuable attention. We're all familiar with a print job or a Web browser timing out because the printer or a remote Web site doesn't respond quickly enough. Now imagine the timing and attention problems a robot will have—the feet want more information from the eyes before deciding where to step, while the eyes can provide that information only when the next step is taken. Or there might arise two unrelated but equally critical tasks, such as walking beside a hospital patient and simultaneously regulating the flow of her intravenous medications.

In programmer-speak, each of those tasks is a thread. A conventional program can run only a single thread to completion or put it on hold while another thread runs. In a computer with multiple processors, or a single processor with multiple cores, more than one thread can run simultaneously, each taking in a stream of data from a set of sensors and responding to the data in some way. But there's still the problem of coordinating the two threads and the responses. A thread managing the hospital patient's heart rate might tell the thread managing the IV drip to stop one of the medications from flowing.

To work on such problems, Mundie put together a team of researchers, known as the Advanced Technology Incubation Group. They came up with something called a concurrency and coordination runtime (CCR). The CCR hides the complexity of managing multiple threads simultaneously by letting programmers create a software object called a dispatcher, which can manage multiple threads (typically one for every processor in the computer) and assign scheduling priorities for each one. The CCR even lets a programmer create multiple dispatchers, which are managed through a class of objects called arbiters. Other tools in the CCR let threads share data or claim it exclusively, pass data from one thread to another, and let one thread command another to do something.

In Mundie's picture of computing's future, processing and information aren't just distributed among the components of a system; they're strewn throughout its environment. Consider the Roomba, iRobot's lowly $119 vacuum-cleaning robot. Today, it employs several strategies to navigate a room in ever-widening circles as it cleans. But most things in the room haven't moved since it vacuumed yesterday, and some things—such as the walls—don't move at all. In the distributed, services-oriented model, some other computer in the household could be a repository of information about the location of walls and furniture and electrical outlets. Any robot moving about the room could draw from that data and update it when, say, a chair gets shifted from one place to another. Access to information about the layout of a house is a service that would be available to every robot. Access to electricity is another.

A small army of Roombas, communicating with one another directly or through a household server, could quickly vacuum an entire house. Eventually, the tables and chairs themselves would be smart enough to report their new locations when they get moved. And new robots coming into the household would quickly acquire whatever information they need, just as servants do when one royal family visits another. In Robotics Studio, such services, whether they reside in another component within the same robot, in a local computer, or across the Internet, show up whenever they're available. Microsoft calls this DSS, for decentralized software services.

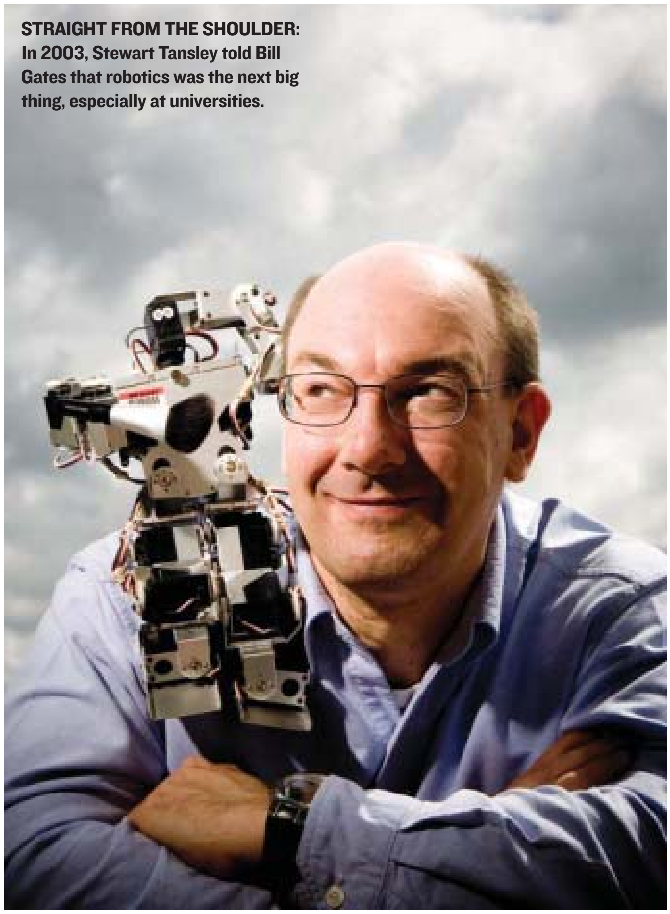
CCR and DSS are the two key technologies developed by the Advanced Technology Incubation Group to have ended up in Robotics Studio. Although the main burden of making sure that a robot doesn't get bogged down doing one thing, to the exclusion of other vital tasks, belongs to the operating system, and so-called real-time operating systems (RTOSs) have been around for decades now, CCR and DSS ensure that the benefits of an RTOS don't get lost at higher levels of programming.

The Studio software hides complexity from programmers

THIS PAGE AND OPENING PAGE: BRIAN SMALE

in some other ways as well. Services in a program can be displayed as simple block icons, and by connecting them with arrows, programmers create relations between them—such as sending data from one to another. When Trower demonstrates this process on the big television screen, it seems almost too easy. (Programming something that could guide a heart patient down a hospital corridor would be considerably more complicated.) The software tool kit also contains tutorials, sample programs, and generic robotics code, as well as a simulation tool that lets you test your program without having to risk sending an expensive robot down a flight of stairs headfirst.

Robotics Studio is written for Windows, but it doesn't follow that the robot itself is using any form of that operating system. Of course Microsoft would like robot makers to use Windows. But many of the robots in the Broom Closet don't even use a formal operating system.



STRAIGHT FROM THE SHOULDER: In 2003, Stewart Tansley told Bill Gates that robotics was the next big thing, especially at universities.

BRIAN SMALE

of computer-science students as interns, funds faculty and graduate student research, and brings several hundred professors from around the world to Redmond every summer for a Faculty Summit, honoring five as New Faculty Fellows, and giving them $200 000 each to spend on their research. Through these various relations, Stewart Tansley, program manager in ER&P, got a clear message from computer-science professors: we want to use robots in our classrooms, but it's too hard. [See photo, "Straight From the Shoulder."]

"The idea of robots, of giving machines the powers of humans, is very powerful in our culture," Tansley says, "going all the way back to the Greeks. We kept hearing that robotics research was popular but challenging. Students wanted to program robots, but they were spending all their time on fundamental engineering. There was a lot of reinvention of the wheel."

Microsoft, Tansley says, is the software equivalent of a plumbing company. "The notion of doing the fundamental plumbing for robotics seemed like a good idea." So in December 2003, he set about using a uniquely Microsoft invention to get the company focused on robotics. With a colleague, he started to write a paper on the topic for Think Week, Gates's semiannual retreat during which he reads a hundred or more papers from employees at every level of the company. "While writing it," Tansley recalls, "we came across Tandy Trower." Trower decided to write his own Think Week paper about robotics.

That winter, Gates would hear about robotics directly. A few months after reading Trower's and Tansley's Think Week papers, he visited six schools on a university tour, another of his semiregular brainstorming exercises. By his account, at every stop students and faculty were excited to show him at least one robotics project.

When Mundie's group wrote a base of code for multiprocessor programming, they didn't have robotics, or anything else, specifically in mind. Mundie simply had assigned several architects to write some general software for concurrent, distributed computing. So he needed someone to figure out what applications could take advantage of the new software. Trower was given that job. He looked for tasks that were highly distributed, requiring a great deal of local autonomy, and used lots of computation in real time. He would eventually find the field of robotics, but not right away.

He first considered biologically inspired technologies, such as neural networks and genetic algorithms, "because they're inherently built on the idea of distributed processing and concurrency," he says. Mundie's ideas were applicable to it, he says, but biotech was "too immature" for anything that Microsoft could add value to.

After an entire year of searching, Trower was reassigned to Bill Gates's staff. "I went to work for Bill as an extra set of strategic eyes and ears," he says. "I kind of stumbled upon people from the robotics community who were knocking on our door." For example, at a meeting with Microsoft CEO Steve Ballmer, the head of Lego, maker of the robot toy Mindstorms, told Ballmer, "We ought to do something together." There was also a visit to the Microsoft campus by Red Whittaker, whose Carnegie Mellon team would soon do better than any other in the first DARPA Grand Challenge, a competition for robotic vehicles that required them to undertake an arduous trek through the desert.

Unknown to Trower, Whittaker was far from the only university professor telling Microsoft about the importance of robotics. The company has an entire group, now known as ER&P, for external research and programs, that, among other things, hires hundreds

The message to Gates was clear: go anywhere in the world, from Germany to Korea, and there's an excitement, an anticipation that something is happening with robots. They're a powerful attractor for students and everyone else. And concurrent, distributed programming on multicore multiprocessors was the new, disruptive technology that was going to take robots out of their largely industrial settings and put them everywhere.

Once Gates decided to involve Microsoft in robotics, the next step was to figure out how. Should Microsoft write an operating system specifically for robots? What other resources existed within the company that could help? Even in late 2003, Microsoft had a set of programming tools for Web services, called .Net; a small, efficient version of Windows, called Windows CE, which today can be found embedded in everything from ATMs and cellphones to gas pumps; language products designed for

Web-style programming, such as C#; and Mundie's codebase, including CCR and DSS. Gates sent Trower on an open-ended mission to figure out just what Microsoft should do, and who within the company should do it. After a five-month study covering everything from Lego's Mindstorms to the latest industrial robots, Trower reported back to Gates: "I told him I thought there was a business here for Microsoft and that I might want to run it myself."

Trower's modest title—general manager, Microsoft Robotics Group—accurately reflects the genial 26-year veteran's self-effacing ways but hides both his influence at Microsoft and a résumé tailor-made for running such a venture. He arrived in 1981 to manage the company's BASIC language products, already its biggest business and one that would develop into a division that sold compilers for C, Fortran, and Pascal, as well as BASIC. Next, he managed the first two releases of Windows and, even before that, developed programs for it, including Microsoft's famous flight simulator. He founded the company's first usability lab. Eventually, Trower became a minister-without-portfolio reporting directly to Gates.

Besides giving the robotics group its manager, Gates can be credited with finding an ideal niche within Microsoft for it. He told Trower to form a regular business unit with a staff, a budget, and its own quarters—the Broom Closet—in a building that also housed other research groups. Version 1.0 of Robotics Studio would have a release date, just like any commercial product, and was to be updated and maintained like any other release. But Gates also located the group organizationally within Microsoft's research division, freeing Trower from the need to produce revenue. There would be no product managers telling him who his customers were or what features they needed. In place of market research, Trower was to rely on his five-month study, his years at Microsoft, and his knowledge of what programmers need and users want.

By maneuvering the new group into a gray space between Microsoft's business and research wings, Gates created a start-up right in the middle of the vast Redmond campus, a skunkworks that had the boss's blessing. Soon after, Mundie gave Trower the fruits of the Advanced Technology Incubation Group's research, CCR and DSS, as well as the two programmers who were their principal architects, George Chrysanthakopoulos and Henrik Frystyk Nielsen. By then, Trower had chosen several of the group's eight other software engineers.

The resulting team is as eclectic as the special-forces crew in the World War II movie *The Dirty Dozen*. Just as Lee Marvin's Major Reisman had a mix of sharpshooters, demolition experts, and so on, Trower needed specialists for everything from operating-system-level programming to user interfaces. [See photo, "Microsoft's Dirty Dozen (Minus One)." Since the photo was taken, a Korean software engineer, Young Joon Kim, has joined the group, making it an even dozen after all.] No three members were born in the same country or were from the same part of the company.

Chrysanthakopoulos, a wiry, entertaining Athens-born electrical engineer who doesn't stop talking until someone tells him to (a task other team members don't shy away from, to everyone's merriment), wrote much of the CCR and became the robotics team's technical lead. Prior to joining Mundie's group, he wrote software for the Xbox, as did another denizen of the Broom Closet, Kyle Johns. Nielsen, a Dane, became the group's program manager. Along with DSS, he wrote an associated Web-specific protocol, DSSP. Nielsen is an old hand at such things: for his master's thesis in electrical engineering, he had helped World Wide Web inventor Tim Berners-Lee write the Web's fundamental protocol, HTTP.

The two youngest team members, Pavel Khijniak, a Russian-born 24-year-old who works on user interfaces, and Butoi, the shy Romanian, came from the Windows group. Two other members were managers elsewhere in the company before joining the robotics team. Joseph Fernando was a development manager in the digital media division. A gentle accent is the only sign of his Sri Lankan origins. Johns, one of the two U.S.-born members, was a lead programmer working on graphics performance tools for the Xbox. "They came here as individual contributors," Trower says, "because they were very excited and passionate about working in this particular area."

Indeed, if there's anything that unifies this motley crew, it's a love of robots. For example, even before the robotics group was formed, David Lee, who grew up in Utah, worked on an entry for the second DARPA Grand Challenge with his brother and a friend, both of whom are electrical engineers. He was able to write all their vehicle's software with Microsoft's .Net programming package, much to his surprise. (He says their entry failed to make the second-round cut, largely because of the vehicle's poor turning radius.)

When I visited the team in March, several members were working on a sample entrant for a robot competition that the group was sponsoring at an upcoming conference on embedded systems. A strip of duct tape ran down the middle of a sheet of plywood, taking up much of the Broom Closet's limited floor space. The idea was to test the ability of infrared sensors to read surfaces of various textures and degrees of reflectivity. All the contestants were to use an iRobot Create chassis; an embedded computer made by ICOP Technology of El Monte, Calif.; and, of course, Microsoft Robotics Studio 1.5.

To look at the team in this robotics playground, it seems to be all fun and games. But there's also an air of seriousness. Trower's recruits know this is a unique opportunity to help Microsoft change direction, a task often compared to turning an aircraft carrier.

Team members seem to be unaware of how much attention the company's top management is paying to the Broom Closet. Several mentioned that at their previous positions at Microsoft, they were 10 or 11 rungs below "Bill," without knowing that they are now only one hop away—via Trower—from Gates, who, though he is no longer CEO or chief strategist, can still make or break a project with a single word.

Are ubiquitous robots, dreamed of for millennia, in our immediate future, or are they still a number of years over the horizon? At least the world Mundie imagined seven years ago is here, with data centers filled with multiprocessor servers and desktops everywhere sporting multicore personal computers for less than $2000. We're about to see whether the other half of his and Trower's and Gates's vision is correct. Will the new processors lead us away from PCs and toward a future filled with robots—robots running Microsoft's software? ■

TO PROBE FURTHER

At http://channel9.msdn.com/wiki/default.aspx/Channel9.MSRoboticsStudio, Microsoft has technical information and a community forum for Robotics Studio developers, as well as a link to the software's home page.

The Player Project software is available at SourceForge: http://playerstage.sourceforge.net. Gostai, another provider of a universal programming tool for robotics, is at http://www.gostai.com/urbi.html. Evolution Robotics is at http://www.evolution.com.

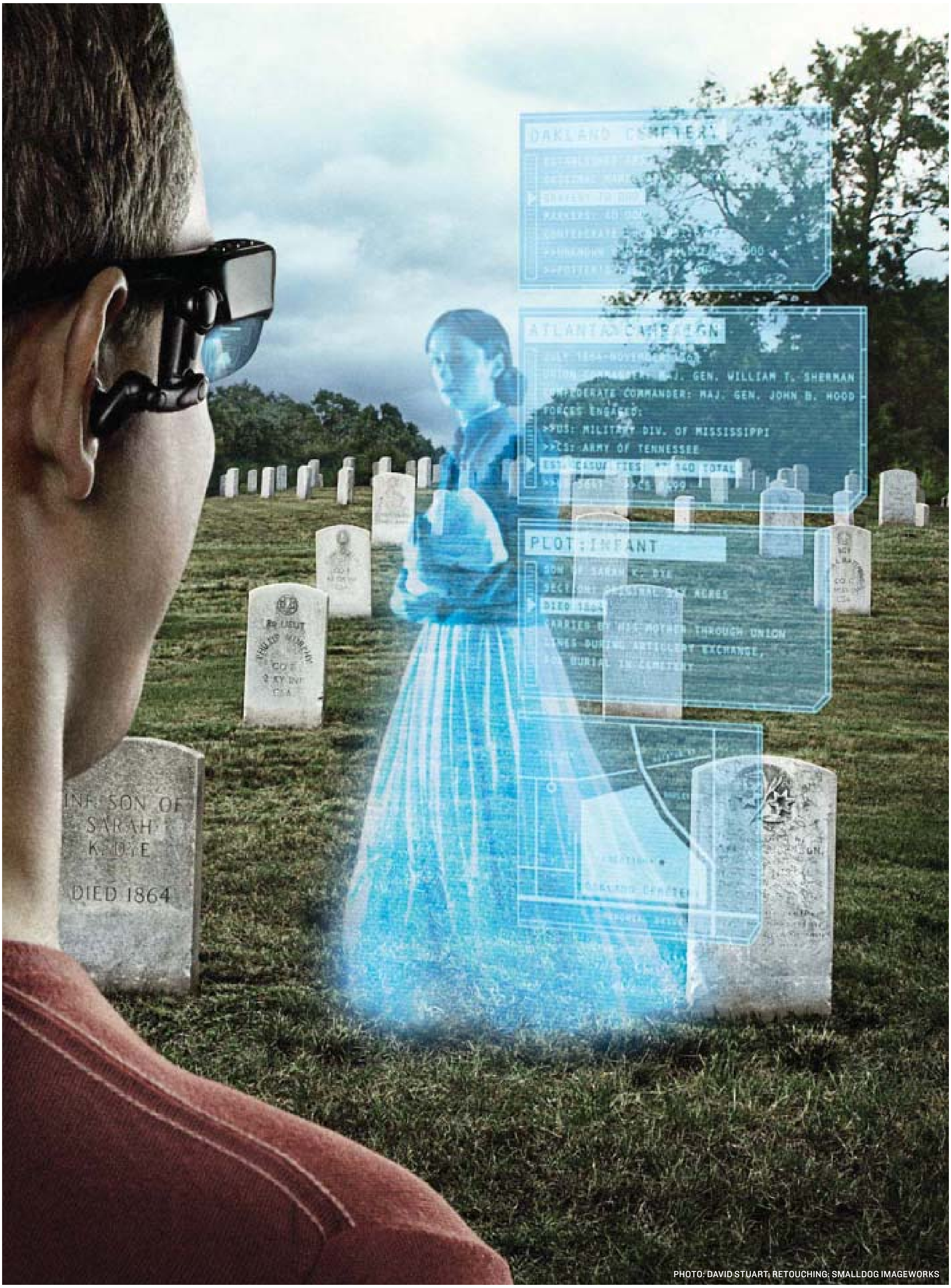


PHOTO: DAVID STUART; RETOUCHING: SMALLDOG IMAGEWORKS

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MULTIMEDIA

IS IT LIVE OR IS IT AR?

By blending digital creations with our view of the world, augmented reality is set to transform the way we entertain and educate ourselves

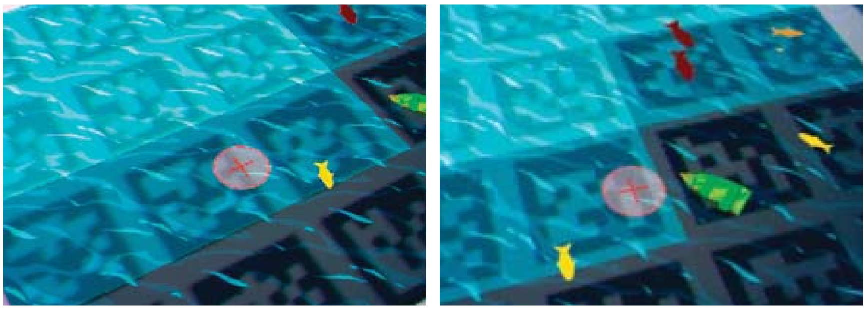
BY JAY DAVID BOLTER & BLAIR MACINTYRE

There are two ways to tell the tale of one Sarah K. Dye, who lived through the Union Army's siege of Atlanta in the summer of 1864. One is to set up a plaque that narrates how she lost her infant son to disease and carried his body through Union lines during an artillery exchange, to reach Oakland Cemetery and bury him there.

The other is to show her doing it.

You'd be in the cemetery, just as it is today, but it would be overlaid with the sounds and sights of long ago. A headset as comfortable and fashionable as sunglasses would use tiny lasers to paint high-definition images on your retina—virtual images that would blend seamlessly with those from your surroundings. If you timed things perfectly by coming at twilight, you'd see flashes from the Union artillery on the horizon and a moment later hear shells flying overhead. Dye's shadowy figure would steal across the cemetery in perfect alignment with the ground, because the headset's differential GPS, combined with inertial and optical systems, would determine your position to within millimeters and the angle of your view to within arc seconds.

That absorbing way of telling a story is called augmented reality, or AR. It promises to transform the way we perceive our world, much as hyperlinks and browsers have already begun to change the way we read. Today we can click on hyperlinks in text to open new vistas of print, audio, and video media. A decade from now—if the technical problems can be solved—we will be able to use marked objects in our physical environ-



BRAGGING RIGHTS: In *Bragfish*, a game created by the authors' students, players peer into handheld game consoles to see their own boats and those of other players overlaid on the game board. But they can see and try to catch only those fish [inset panels, right] that are near enough for their own, hard-won powers to detect.

PARIS, ENHANCED: Nokia's prototype mobile AR system couples a camera, a cell-phone, GPS, accelerometers, and a compass to follow the user through a city and point out all the sights.

TOP: SAMI DEEN/GEORGIA INSTITUTE OF TECHNOLOGY (3); BOTTOM: NOKIA ment to guide us through rich, vivid, and gripping worlds of historical information and experience.

The technology is not yet able to show Dye in action. Even so, there is quite a lot we can do with the tools at our disposal. As with any new medium, there are ways not only of covering weaknesses but even of turning them into strengths—motion pictures can break free of linear narration with flashbacks; radio can use background noises, such as the sound of the whistling wind, to rivet the listener's attention.

Along with our students, we are now trying to pull off such tricks in our project at the Oakland Cemetery in Atlanta. For the past six years, we have held classes in AR design at the Georgia Institute of Technology, and for the past three we have asked our students to explore the history and drama of the site. We have distilled many ideas generated in our classes to create a prototype called the Voices of Oakland, an audio-only tour in which the visitor walks among the graves and meets three figures in Atlanta's history. By using professional actors to play the ghosts and by integrating some dramatic sound effects (gunshots and explosions during the Civil War vignettes), we made the tour engaging while keeping the visitors' attention focused on the surrounding physical space.

We hope to be able to enhance the tour, not only by adding visual effects but also by extending its range to neighboring sites, indoors and out. After you've relived scenes of departed characters in the cemetery, you might stroll along Auburn Avenue and enter the former site of the Ebenezer Baptist Church. Inside, embedded GPS transceivers would allow the GPS to continue tracking you, even as you viewed a virtual Reverend Martin Luther King Jr. delivering a sermon to a virtual congregation, re-creating what actually happened on that spot in the 1960s. Whole chapters of the history of Atlanta, from the Civil War to the civil rights era, could be presented that way, as interactive tours and virtual dramas. Even the most fidgety student probably would not get bored.

By telling the story in situ, AR can build on the aura of the cemetery—its importance as a place and its role in the Civil War. The technology could be used to stage dramatic experiences in historic sites and homes in cities throughout the world. Tourists could visit the beaches at Normandy and watch the Allies invade France. One might even observe Alexander Graham Bell spilling battery acid and making the world's first telephone call: "Mr. Watson, come here."

The first, relatively rudimentary forms of AR technology are already being used in a few prosaic but important practical applications. Airline and auto mechanics have tested prototypes that give visual guidance as they assemble complex wiring or make engine repairs, and doctors have used it to perform surgery on patients in other cities.

But those applications are just the beginning. AR will soon combine with various mobile devices to redefine how we approach the vast and growing repository of digital information now buzzing through the Internet. The shift is coming about in part because of the development of technologies that free us from our desks and allow us to interact with digital information without a keyboard. But it is also the result of a change in attitude, broadening the sense of what computers are and what they can do.

We are already seeing how computers integrate artificially manipulated data into a variety of workaday activities, splicing the human sensory system into abstract representations of such specialized and time-critical tasks as air traffic control. We have also seen computers become a medium for art and entertainment. Now we will use them to knit together Web art, entertainment, work, and daily life.

Think of digitally modified reality as a piece of a continuum that begins on one end with the naked perception of the world around us. From there it extends through two stages of "mixed reality" (MR). In the first one, the physical world is like the main course and the virtual world the condiment—as in our AR enhancement of the Oakland Cemetery. In the other stage of MR, the virtual imagery takes the spotlight. Finally, at the far end of the continuum lies nothing but digitally produced images and sounds, the world of virtual reality.

Any AR system must meld physical reality with computer-modeled sights and sounds, a display system, and a method for determining the user's viewpoint. Each of the three components presents problems. Here we will consider only the visual elements, as they are by far the most challenging to coordinate with real objects.

The ability to model graphics objects rapidly in three dimensions continues to improve because the consumer market for games—a US $30-billion-a-year industry worldwide—demands it. The challenge that remains is to deliver the graphics to the user's eyes in perfect harmony with images of the real world. It's no mean feat.

The best-known solution uses a laser to draw images on the user's retina. There is increasing evidence that such a virtual retinal display can be done safely [see "In the Eye of the Beholder," *IEEE Spectrum*, May 2004]. However, the technology is not yet capable of delivering the realistically merged imagery described here. In the meantime, other kinds of visual systems are being developed and refined.

Most AR systems use head-worn displays that allow the wearer to look around and see the augmentations everywhere. In one approach, the graphics are projected onto a small transparent screen through which the viewer sees the physical world. This technology is called an optical see-through display. In another approach, the system integrates digital graphics with real-world images from a video camera, then presents the composite image to the user's eyes; it's known as a video-mixed display. The latter approach is basically the same one used to augment live television broadcasts—for example, to point out the first-down line on the field during a football game [see "All in the Game," *Spectrum*, November 2003].

This comparison with augmented-live television highlights the problems that must still be solved. TV broadcasters can fix their cameras in precisely known positions and track their orientation with high-quality built-in encoders. And they can delay the video signal by a few dozen frames to gain time to clean things up. Because millions of people are watching, it makes economic sense for the television broadcaster to employ a team of technicians to monitor and adjust the system. Whoever wishes to bring AR to museums and historic landmarks—let alone less-traveled paths—will have to find less expensive ways around such problems.

The biggest technological challenge is to track position and orientation. Just how good the tracking must be depends, of course, on what you want to do with it. In the Oakland Cemetery example, it would be acceptable to place the ghosts within, say, 10 centimeters of their graves. However, a mechanic depending on AR to replace tiny components in a jet engine would need greater precision. The system might indicate the tiny components by highlighting them in a color; if they are just a few millimeters wide, clearly the system must have millimeter-level accuracy. Distance is just as important—the farther away you look, the more an error in the angle of the line of vision will become obvious.

For the display to have a chance of appearing perfectly aligned, the orientation error must be less than the visual angle of one

CATCH ME IF YOU CAN: A world-spanning game by Britain's Blast Theory is played out simultaneously by runners in the streets of Sheffield, England [left and above] and in a virtual representation of the city that allows online participation. To help designers visualize the melding of real and virtual objects, the authors' laboratory at Georgia Tech has developed DART, a tool kit that allows commonly used programs, sensors, and networks to coordinate three-dimensional objects [below].

TOP: BLAST THEORY (2); BOTTOM: GEORGIA INSTITUTE OF TECHNOLOGY

pixel on the display. A typical display today might have a field of view of 24 degrees and a horizontal resolution of 800 pixels, meaning that an orientation error greater than 0.03 degree would result in perceptible misalignment between the virtual and physical objects.

To track things outdoors over a wide area, orientation sensors typically use magnetometers, inclinometers, and inertial sensors. The magnetic components can, however, be thrown off by the presence of magnetic fields, iron, or other ferric material. In smaller areas that can be surveyed or fitted with an infrastructure—fixed antennas, printed markers, and the like—the absolute accuracy of the sensors can be excellent.

A major research goal is to dispense with such an embedded infrastructure by devising automatic ways to find and track "natural features"—say, an uncataloged tree or boulder. That way, the system could handle whatever comes up, without any prior knowledge of the territory. Particularly promising are technologies that combine wearable cameras with inertial sensors.

It is just as important to develop easy-to-use tools for AR. Without them, designers are not likely to enter the field. For our work on the Oakland Cemetery project, we used a programming system, created in the Augmented Environments Lab at Georgia Tech, called DART (Designer's Augmented Reality Toolkit). DART was built to facilitate rapid prototyping, so that designers can quickly visualize and test their ideas. We believe that DART can help contribute to the development of AR as a medium for art and creative design.

DART provides extensions to the Adobe Director multimedia-authoring system that allow it to coordinate three-dimensional objects, video, sound, and tracking information—the entire AR experience. It can track marked objects in a live video feed and react to real-time data streaming in from sensors, a wide variety of which can be made to work together seamlessly through the Virtual Reality Peripheral Network, an open-source system developed at the University of North Carolina, Chapel Hill. The VRPN also makes it easy to integrate DART programs with programs written in other languages.

DART has palettes of behaviors—that is, the actions of a computerized system as it responds to stimuli, as when a video camera follows a person's movements. It is not our intention to provide a collection of behaviors so complete that it would satisfy the needs of all AR application designers; such an effort would be doomed to failure. Rather, we have designed the behaviors to provide a modular and extensible framework that designers can easily appropriate for their own needs. Anyone developing a new AR application can edit the DART behaviors.

We are by no means the first to promote this combination of techniques as a new medium of expression. Designers and artists have been experimenting with precursors of the idea for years, although without using fully developed tracking technologies or head-worn displays. Since its founding in 1979, the Ars Electronica festival, in Linz, Austria, has featured digital artists

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such as Myron Krueger, whose work has involved embedding computer monitors in art installations or projecting images on large screens or the surfaces of rooms or buildings, often in real time. The Canadian installation artist Janet Cardiff has created a series of audio tours in which the user wears headphones and walks along a predetermined path as Cardiff's voice fashions an audio landscape.

In addition, curators and designers have been moving toward mixed and augmented reality as they seek to enhance the visitor's experience in museums, historic sites, and theme parks. One famous example is the audio tour of Alcatraz prison in San Francisco Bay, in which the user wears headphones and embarks on an evocative walk through the empty cells and hallways, accompanied by a reconstruction of the sounds and voices of 50 years ago. However, the tour is a linear experience: the user must follow the path dictated on the CD; there is no tracking of the user's location.

Some of the most compelling work uses mobile phones to combine Internet-based applications with the physical and social spaces of cities. Many such projects exploit the phone's GPS capabilities to let the device act as a navigational beacon. The positional information might let the phone's holder be tracked in cyberspace, or it might be used to let the person see, on the phone's little screen, imagery relevant to the location.

Blast Theory, an experimental art and technology group in Brighton, England, has been one of the leaders in such enterprises. Its participatory game event *Can You See Me Now?*—designed in collaboration with the Mixed Reality Lab at the University of Nottingham—pitted online participants against runners in the streets of a real city. In one installation, in the center of Sheffield, the runners carried handheld computers that showed them the same map that the online participants had in front of them; the computers also bore GPS receivers that let the online people follow along. The runners tried to reach points in Sheffield that corresponded to the virtual positions of as many online participants as possible, thereby "catching" them. An open-mike audio channel connected the runners to the online players, giving the online players a sense of being in a shared physical space, no matter how far from Sheffield—or even England—they really were.

Meanwhile, new phones are coming along with processors and graphics chips as powerful as those in the personal computers that created the first AR prototypes a decade ago. Such phones will be able to blend images from their cameras with sophisticated 3-D graphics and display them on their small screens at rates approaching 30 frames per second. That's good enough to offer a portal into a world overlaid with media. A visitor to the Oakland Cemetery could point the phone's video camera at a grave (affixed with a marker, called a fiducial) and, on the phone's screen, see a ghost standing at the appropriate position next to the grave.

Video and computer games have been the leading digital entertainment technology for many years. Until recently, however, the games were entirely screen-based. Now they, too, are climbing through mobile devices and into the physical environment around us, as in an AR fishing game called *Bragfish*, which our students have created in the past year. Players peer into the handheld screens of game devices and work the controls, steering their boats and casting their lines to catch virtual fish that appear to float just above the tabletop. They see a shared pond, and each other's boats, but they see only the fish that are near enough to their own boats for their characters to detect.

We can imagine all sorts of casual games for children and even for adults in which virtual figures and objects interact with surfaces and spaces of our physical environment. Such games will leave no lasting marks on the places they are played. But people will be able to use AR technology to record and recall moments of social and personal engagement. Just as they now go to Google Maps to mark the positions of their homes, their offices, their vacations, and other important places in their lives, people will one day be able to annotate their AR experience at the Oakland Cemetery and then post the files on something akin to Flickr and other social-networking sites. One can imagine how people will produce AR home movies based on visits to historic sites.

Ever more sophisticated games, historic tours, and AR social experiences will come as the technology advances. We represent the possibilities in the form of a pyramid, with the simplest mobile systems at its base and fully immersive AR on top. Each successive level of technology enables more ambitious designs, but with a smaller potential population of users. In the future, however, advanced mobile phones will become increasingly widespread, the pyramid will flatten out, and more users will have access to richer augmented experiences.

Fully immersive AR, the goal with which we began, may one day be an expected feature of visits to historic sites, museums, and theme parks, just as human-guided tours are today. AR glasses and tracking devices will one day be rugged enough and inexpensive enough to be lent to visitors, as CD players are today. But it seems unlikely that the majority of visitors will buy AR glasses for general use as they buy cellphones today; fully immersive AR will long remain a niche technology.

On the other hand, increasingly ubiquitous mobile technology will usher in an era of mixed reality in which people look at an augmented version of the world through a handheld screen. You may well pull information off the Web while walking through the Oakland Cemetery or along Auburn Avenue, sharing your thoughts as well as the ambient sounds and views with friends anywhere in the world.

At the beginning of the 20th century, when Kodak first sold personal cameras in the tens of thousands, the idea was to build a sort of mixed reality that blended the personal with the historic ("Here I am at the Eiffel Tower") or to record personal history ("Here's the bride cutting the cake"). AR will put us in a kind of alternative history in which we can live through a historic moment—the Battle of Gettysburg, say, or the "I have a dream" speech—in a sense making it part of our personal histories.

Mobile mixed reality will call forth new media forms that skillfully combine the present and the past, historical fact and its interpretation, entertainment and learning. AR and mobile technology have the potential to make the world into a stage on which we can be the actors, participating in history as drama or simply playing a game in the space before us. ■

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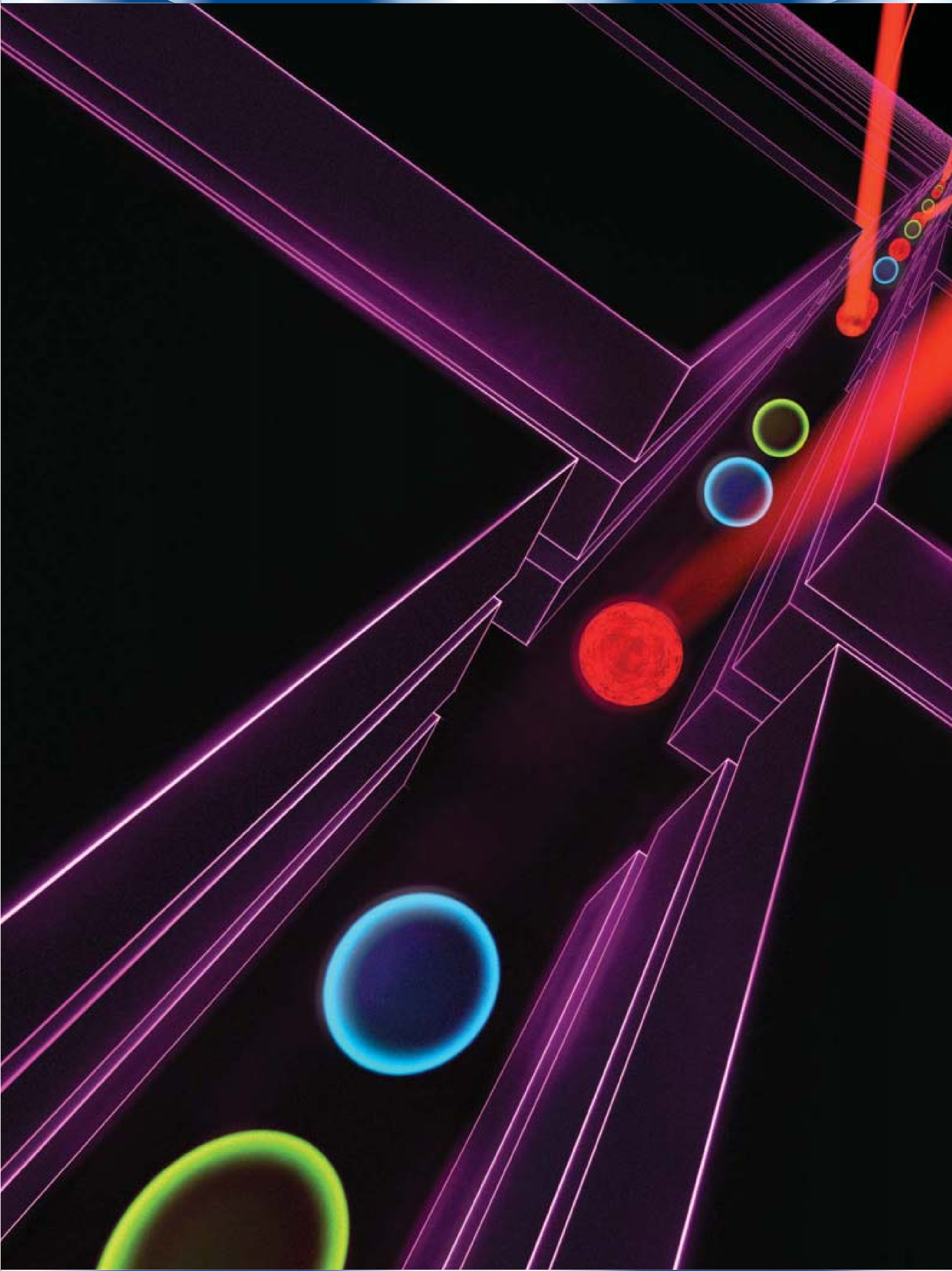

FIRST IN A 2-PART SERIES ON QUANTUM COMPUTING

THE TRAP TECHNIQUE

TOWARD A CHIP-BASED QUANTUM COMPUTER

BY DANIEL STICK, JONATHAN D. STERK & CHRISTOPHER MONROE

COMPUTERS TODAY are fast approaching some fundamental limitations. Perhaps their biggest problem is that they exploit the classical physics that governs the hurly-burly rush of countless billions of electrons through nearly as many transistors. And the chips at the heart of today's computers are running out of room for classical physics to work.

To make those chips' transistors switch faster, we've primarily relied on making the devices smaller. But when they begin to approach 10 nanometers or so—and it is the goal of the semiconductor industry to get there in the next decade—very odd things will happen. Formerly well-behaved electrons will start revealing their quantum nature—darting across the transistor on the dictates of probability, regardless of whether the device is switched on or off. When transistors reach those infinitesimal dimensions and electrons start showing their true colors, computer makers will have two choices: try to fend off the quantum weirdness with radically new types of semiconductors and transistors, or embrace the weirdness.

We say: surrender to the weirdness. Working with the quantum nature of things instead of against it will open up vast new frontiers for computing. And achievements during the past couple of years at university and government laboratories around the world have made it clear that a large-scale, practical quantum computer could be built, probably in the next 25 to 30 years. These achievements have demonstrated that the semiconductor manufacturing technologies underpinning modern computing, which were developed over nearly half a century, need not be abandoned. On the contrary, they will be instrumental in making quantum computers a practical reality.

These machines will take computing where it's never been before. Most notably, there are classes of problems for which a conventional computer can do little more than try out all the possible solutions one at a time until it stumbles on the answer. Say, you have a phone number and want

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to look up the name it's paired with in a phone book that has 1 million entries. There's not much you can do but go page by page looking for the match. On average, your classical computer must examine half a million entries before finding a match. Sure, at gigahertz microprocessor speeds even that won't take long, but there are plenty of much larger needle-in-a-haystack problems scientists face all the time, some of which would take your laptop 100 years to complete.

If you had a computer based on the principles of quantum mechanics, however, you could, in effect, examine all the entries in the telephone book practically at the same time. Such a quantum computer would need just 1000 steps—one five-hundredth of what a classical computer needs—to find the right name in the million-entry phone book. The theoretical ability of quantum computers to perform parallel processes seemed like an odd parlor trick when they were dreamed up in the 1980s, first by Richard Feynman and more concretely by David Deutsch. But in 1994 something happened that put quantum computing squarely in the crosshairs of governments, armed forces, and everyone else with digital secrets to keep.

Peter Shor, a theoretical matematician then at Bell Labs, discovered an algorithm for a quantum computer that could far more efficiently determine the prime factors of a large integer. Factoring is one of those problems that tie conventional computers in knots. Computers are so bad at it, in fact, that most encryption systems today rely on the products of enormous prime numbers, figuring it would take a computer decades to factor the number. Shor's algorithm changed all that, and the idea that so much information could become so vulnerable has sparked a worldwide race to build a machine powerful enough to crack codes.

IT WAS TIME TO SHOW THAT ION-TRAP QUANTUM COMPUTERS COULD BE SCALED UP. AND THAT MEANT SHRINKING THEM DOWN

The first step in building a quantum computer is to find something to act as a quantum bit, or qubit, something whose quantum state can be read and manipulated. The trouble is that a quantum state is an exceedingly delicate thing, mainly because it can be changed by the most evanescent interactions—a fluctuation in a magnetic field, a wayward photon, and so on. Just a year after Shor's breakthrough, two physicists then at Austria's University of Innsbruck, Juan Ignacio Cirac and Peter Zoller, theorized that a string of ions held fast in a vacuum by an electromagnetic field and cooled to within a few thousandths of a degree above absolute zero could act as stable qubits and form the basis of a quantum computer. Scientists at the U.S. National Institute of Standards and Technology (NIST), the nation's timekeeper, already had plenty of experience trapping and cooling ions from their work with atomic clocks, and they wasted no time in putting the scheme into practice. That same year, David Wineland of NIST and one of us (Monroe) used a trapped beryllium ion as a qubit to perform logic operations that are key to running a quantum computer.

Since then, physicists have come up with at least half a dozen potential ways to do quantum computation—including using the atomic nuclei in dissolved organic compounds as qubits and manipulating electrons within superconducting loops. With few exceptions, though, these schemes will never lead to a quantum computer that can solve a useful problem, because they simply can't handle more than a dozen or so qubits, and what's needed are hundreds—if not thousands.

We can't construct a full-scale ion trap big enough to house that many qubits. So the only way we can see to build a practical quantum computer is to borrow a page from the electronics industry and build the equivalent of quantum integrated circuits. The analogy here is to transistors—traps work pretty much the same way if you shrink them down enough and put many of them on the same piece of semiconductor. That was demonstrated just last year when our research group at the University of Michigan and Wineland's group at NIST independently produced the first ion-trap microchips built with the same techniques that microprocessor and MEMS makers employ. These chips are far from being useful computers themselves, but they are the first step in a path that could take us beyond the limits of computing as we know it.

THE HEART OF ANY QUANTUM COMPUTER, whether it's built on a sliver of semiconductor or not, is the qubit. A word about the qubit: it's odd.

In an ordinary computer, information is stored as bits, usually a minuscule reservoir of charge or the charge's absence in a memory cell's capacitor. At any given instant, an ordinary binary digit can be in one and only one of two different states. But the value of a qubit is determined by the quantum states of individual particles. So, like those quantum states, a qubit can have the value 1, or 0, or it can be—in the paradoxical world of the quantum—both values at the same time. This versatility is central to the power of quantum computers. In an ordinary computer you can represent a number between 0 and 31 using five binary digits. But using the same number of qubits you could represent all 32 numbers *at once* and perform the same calculation on them *simultaneously*. And that's not even the end of the weirdness: two or more qubits can be linked together in ways no two transistors could ever be, influencing each other instantaneously—even if they are separated by a distance of light-years.

The specific quantum state of a particle that is generally exploited to determine a qubit's value is called spin. In an ion-trap computer as well as several other schemes, the value of a qubit is determined by the direction of a particle's spin state.

Spin is a measure of a particle's angular momentum. Angular momentum is easy to understand for large spinning objects like a basketball, but photons, electrons, and other fundamental particles that make good qubits are as close as you can get to being dimensionless points in space. The question is, How can they spin?

They don't. Like many aspects of quantum mechanics, spin makes no intuitive sense—even to physicists. But it's real, and it's something measurable. For a particle, spin is an intrinsic property like charge, not something that comes about because of physical rotation.

Spin has direction—up or down, in quantum computing's shorthand—and it's the direction we use to represent the value of the qubit. The qubits used in ion-trap quantum computers rely on the spin state of an ion's outermost electron and that of its nucleus. If the electron's spin is aligned with that of the nucleus it orbits, we say the qubit is in the 1 state. If the two quantum states are pointing in opposite directions, we say the qubit is in the 0 state. And the qubit ion can be put in a combination of 1 and 0 if the electron's spin is itself a combination of up and down.

This ability of a qubit to have two values simultaneously is called the principle of superposition, and it allows a register of qubits to hold exponentially more information than the register

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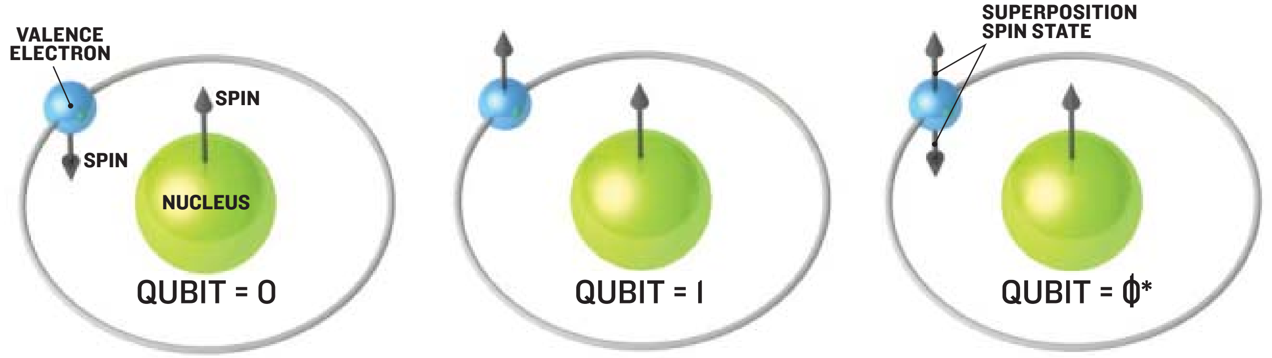
Qubit Basics

JUST AS A BIT is a basic unit of information in the digital world, a **qubit** (pronounced "cue bit") is a unit of information in the quantum world. A digital bit can be either a 0 or a 1, but a qubit can be both 0 and 1 at the same time—a property called superposition.

In many quantum computing schemes, the qubit is represented by the spin state of a particle. Spin, a quantum property of particles only loosely analogous to angular momentum, is typically in one of two directions, up or down. But it can be put into a superposition state so it is up and down at the same time.

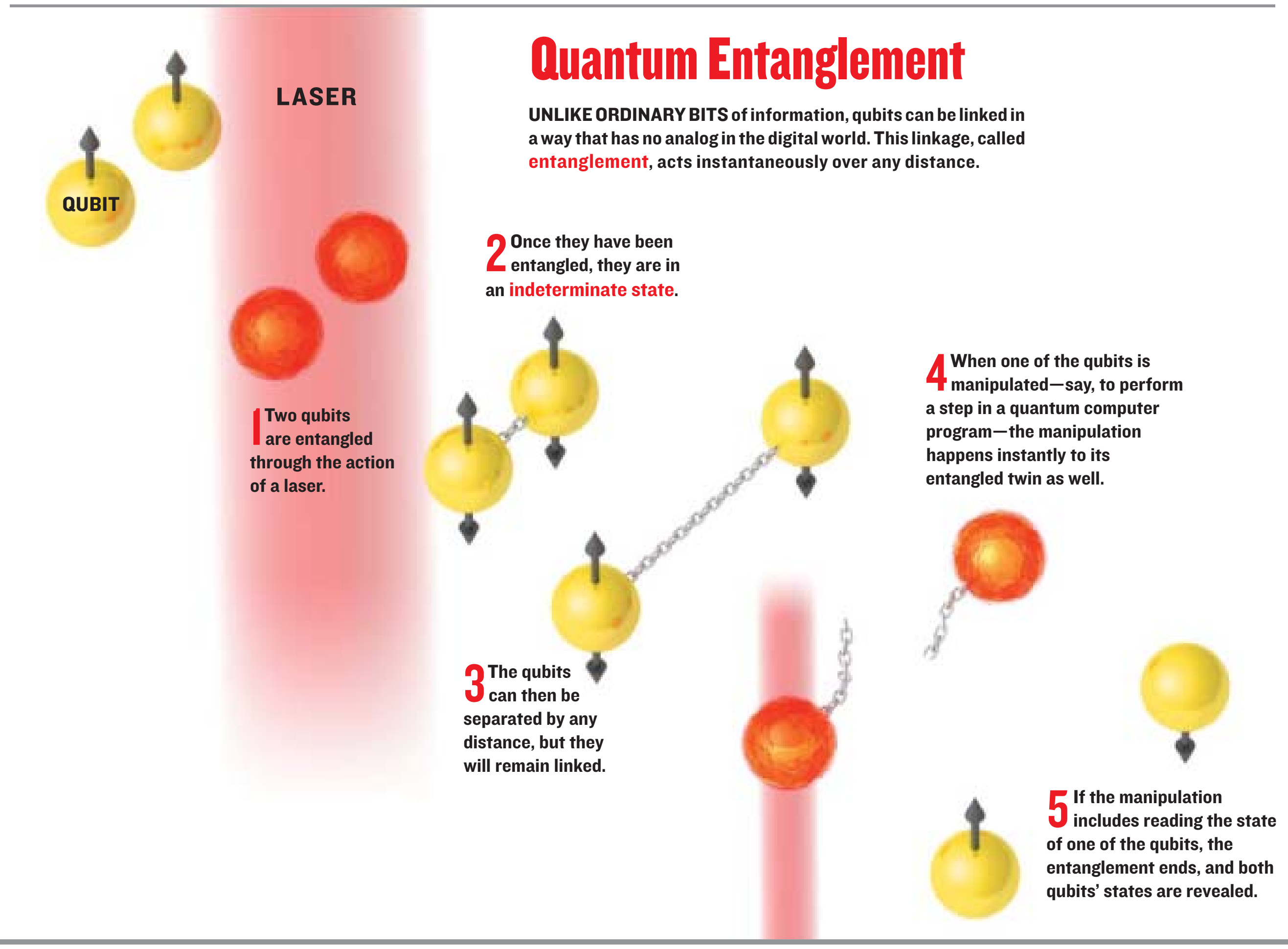
In an ion-trap computer, the qubit stems from the spin states of an ion's nucleus and its outermost, or valence, electron. When their spins are opposing, the qubit is a 0. When they are in the same direction, it is a 1.



*Superposition of 1 and 0

Quantum Entanglement

UNLIKE ORDINARY BITS of information, qubits can be linked in a way that has no analog in the digital world. This linkage, called **entanglement**, acts instantaneously over any distance.



with the same number of classical bits. For two ordinary bits, for example, the possible combinations are 00, 01, 10, or 11. But for qubits in a state of superposition, their values could be all four of those numbers at the same time.

Best of all, you can perform a calculation on all four at once, whereas in a classical computer it would have to be done one at a time. Although that would give you only a fourfold improvement for the 2-qubit example, the gain grows quickly as the number of bits increases. In theory, with n qubits you could be calculating with 2^n numbers at once. With just 300 qubits, you could simultaneously perform a calculation on more numbers than there are atoms in the universe.

But quantum information is very delicate. Interactions with the environment—a random fluctuation in an electric field, say—can turn a superposed qubit into just another 1 or 0, or flip a 0 to a 1, or vice versa. Such an occurrence is called decoherence,

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and it can immediately render all the computation up to that point worthless.

The length of time that a qubit remains in the state or superposition of states that you put it in is called the coherence time. A quantum computer is limited in the number of operations it can perform by the time it takes for decoherence errors to overwhelm the computation. Ion traps are designed to be extremely quiet environments, in which qubits have been known to last 10 seconds or more—long enough to carry out several complex calculations.

Another trick is that qubits can be linked together in a way that has no counterpart in the macroworld we experience. This linkage, called entanglement, was one of the main arguments against quantum mechanics when it was introduced in the early 20th century. According to the theory, two particles can be linked so that if you perturb or measure one, the quantum state of the other changes instantly. For instance, you could entangle two ions so that their spin states will always be opposite to each other. If you measure the state of the first as a 1, the second will instantly become a 0. Entanglement is key to executing many quantum computer programs, because it allows operations performed on one qubit to simultaneously be performed on all the others it is entangled with. Rainer Blatt's group at the University of Innsbruck set the record for most entangled ions, at eight.

TO UNDERSTAND EXACTLY how entanglement and other quantum elements work in an ion-trap computer, you have to understand how an ion trap operates. A linear Paul trap, the Nobel Prize–winning invention of Wolfgang Paul, is a vacuum chamber that houses four long electrodes arranged so that they form the long edges of a rectangular box. On two of the electrodes, diagonally across from each other, is a voltage that oscillates at a radio frequency. On the other two is a dc voltage. The combination of the electric fields emanating from the electrodes tends to force ions toward the centerline equidistant from all four electrodes.

Here's why. Consider, for a moment, only the RF electrodes. At any one instant, the forces on an ion between them are like the force of gravity on a ball sitting on a saddle-shaped surface.

5 Things Every Quantum Computer Needs

EVEN IN A BRAND-NEW AREA of technology like quantum computing, some standards are necessary. IBM quantum computing expert David DiVincenzo came up with a set of requirements that any system would need if it were used as a quantum computer. Over the years physicists have proven the first four are true for ion traps, and the development of ion-trap microchips implies that the fifth is true as well. Stated plainly they are:

1. **You must be able to set all the qubits to 0 at the start of a calculation.**
2. **You must be able to read the answer when the calculation is done.**
3. **The qubits must last long enough to run a program of a decent size.**
4. **The computer must be able to carry out the two fundamental operations that are necessary to perform every quantum computer program.**
5. **The system's basic architecture must be able to handle large numbers of qubits.**

The first of DiVincenzo's requirements is achieved using lasers. In this case, the laser has been tuned to deliver photons with exactly enough energy to knock the ion's outermost electron from the 1 state—where the spin is pointing in the same direction as the ion's nucleus's spin—into a particular excited state. The excited state is unstable, and the electron won't remain there for long but will fall back toward either the 0 or the 1 state, with a certain probability associated for each outcome. If the qubit falls back to 1, another photon will kick it right back up into the excited state again. But if it falls into the 0 state, it stays there, because the laser beam isn't at the right frequency to promote the electron from 0 to the excited state. So, ions in the path of the laser will bounce between being excited and the 1 state until, by chance, they fall into the 0 state, where they get stuck. This first process usually takes less than 1 microsecond.

Data—quantum or classical—aren't much use if you can't read them. You have to know the value of the ionic qubits, and that's done by lasers as well. This laser is resonant between a particular qubit state, 1, say, and an excited state; so that the ion can fall back only into the 1 state. When the electron falls back, it emits a photon. Photons are collected and counted, and their presence or absence tells you the ion's qubit value. This method of measuring is actually one of the ion-trap technique's strong points; it's better than 99 percent accurate—quite good compared with other technologies.

Qubits last quite a long time in an ion trap, but decoherence errors are bound to happen, and flipping a qubit can ruin a calculation. Error-correcting codes make digital computers relatively immune to the effects of a flipped bit. Some of these codes rely on redundant bits to transmit data that let a receiver detect and correct the error. Initially, it seemed impossible to develop an error-correcting scheme for quantum computers. Error detection and correction implies knowing the values of the bits that need correcting. But reading out a qubit's value before the calculation is complete is no different in its effect on a quantum calculation than a decoherence event, in that it can render the prior steps in the calculation worthless.

Former Bell Labs scientist Peter Shor and University of Oxford physicist Andrew Steane independently came up with quantum algorithms that spread the value of one qubit over several physical qubits—the quantum equivalent of the redundancy used in classical error correction. Amazingly, these error-correction schemes can both tell an error has occurred and what the error was without knowing the value of the qubit that experienced the error.

Almost 10 years after Shor's and Steane's work, David Wineland's group at the U.S. National Institute of Standards and Technology (NIST) performed the first quantum-error correction in an ion trap. Unfortunately, quantum-error correction requires additional qubits—lots of them. For

The saddle traps in one dimension—the ball will not roll in either uphill direction. And it antitraps in the other—if moved, the ball will tend to roll down and off the saddle. But because the electric field from the RF electrodes is always oscillating, it's as if the saddle were rotating beneath the ball. An ion slightly off the centerline would find itself on the uphill slope being pushed back in line for half of the cycle and on the downhill slope falling outward for the other half. However, the RF signal is designed so that the outward force is weaker than the inward force when the ion is close to the center, so on the average the force an ion feels is toward the centerline. The trap's other electrodes, the ones with the dc voltage, keep the ion from wandering along the centerline by pushing on it from both sides.

The result of the trapping is a string of ions along the centerline of the trap, and because they all have the same charge, they repel each other. Imagine the ions as balls suspended on strings and attached to each other by springs. The ions can be frozen in place by catching them at the intersection of three lasers, or they can slide back and forth along the line or vibrate against each other. The ion's collective motion is called the vibrational state, which acts like a data bus. Starting from a standstill using a sequence of specially tuned lasers, one qubit's data can be mapped onto the shared vibrational state, and then the vibrational state can alter a second qubit. That mapping technique is key to carrying out the operations that make up quantum algorithms.

BY 2003 ion traps had proven that they could do all the basic functions needed for quantum computing, but could they handle enough qubits to do anything useful? [See sidebar, "5 Things Every Quantum Computer Needs."] It was time to prove that ion-trap computers could be scaled up. And that meant shrinking them down.

The natural step was to turn to photolithography and other methods for making microchips. But we knew it wouldn't be easy. Traps have pretty exotic requirements compared with your garden-variety logic chip. For example, the RF voltages, which oscillate at anywhere from 15 to 200 megahertz, are typically about 50 to 300 volts. Compare that with the 1.5-V signals inside

an ion-trap computer to do useful calculation, it might need to encode a single qubit with 50 or more extra ions to handle the errors.

The fourth criterion has to do with an ion-trap computer's ability to carry out logic operations. Classical computers use arrangements of just two types of logic gates—NAND and NOR—to produce all the others they might need. Quantum computers are the same. The only two gates you really need are single qubit rotations and the two-qubit controlled-NOT (CNOT) gate.

Qubit rotation, accomplished using a particular polarization and wavelength of laser, is like a richer version of a NOT gate in an ordinary logic circuit. NOT turns a 1 to a 0 or a 0 to a 1. By tipping over the ion's valence electron's spin, the laser in an ion-trap quantum computer can turn a qubit 1 into a 0 or a 0 into a 1, but it can also turn either value into a superposition of 1 and 0—using, for example, an operation called square-root of NOT.

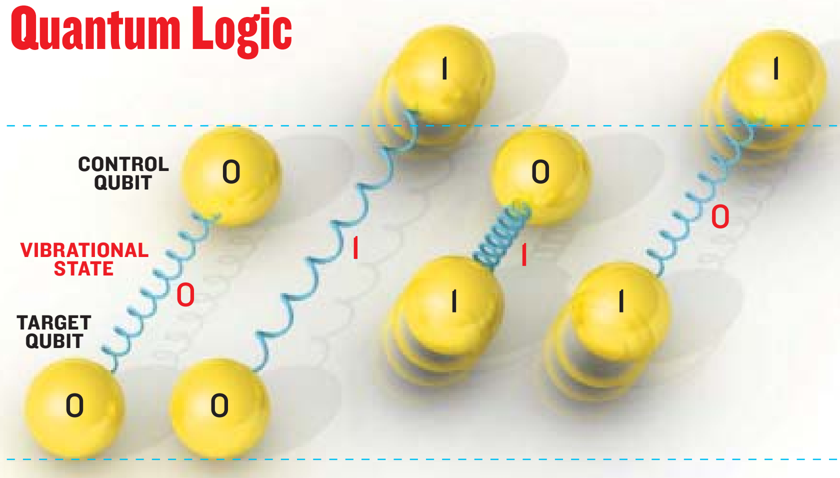
In the other needed gate, the two-qubit CNOT gate, a qubit called the target changes value depending upon the state of another qubit, called the control. In CNOT, the target will flip from a 1 to a 0 or a 0 to a 1 only if the control qubit is 1. If the control qubit is 0, nothing happens to the target qubit. (The resulting truth table looks like an exclusive-OR: If this is true or that is true then the output is true, unless both this and that are true.)

There are various CNOT gate schemes that act on trapped ions. Imagine, for example, a trap containing two ions [see illustration, "Quantum Logic"]. It turns out that a laser that is appropriately tuned can impart a force on the ions that depends upon whether their qubit state is a 1 or a 0. So the laser might push ions to the right only if they are in the 1 state. If both qubits are 0, the laser has no effect. If they are both 1, then both ions move to the right in unison. In either case, the relative motion—the way the ions vibrate against each other—gains no energy.

Now imagine if the left (target) ion is a 0 and the right (control) ion is a 1. The laser would then push the right ion farther to the right, stretching the imaginary spring between them. If their values are switched, so the target ion is a 1 on the left and the control ion is a 0 on the right, the control ion pushes into the target, squashing the spring. In both cases, the ions would vibrate against each other once the laser had stopped tugging at them. (Because particles with like charges repel, it is slightly easier to move the ions apart—stretching the spring—than push them together—squashing it. Hence the change in energy, which goes into the vibrational state of the two qubits for these cases, is not the same.)

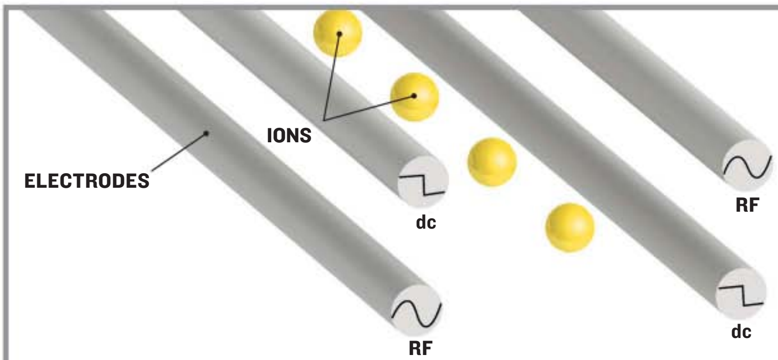
The result of the laser pulse is to perform the CNOT logic operation, but instead of imposing the result—what the target qubit should be at the end of the operation—on the target qubit itself, the result is mapped onto the vibrational state of the two-qubit system. That is, if the qubits are vibrating, the target qubit should be a 1. If they are not, it should be a 0. A further sequence of single-qubit operations, again done with lasers, uses the vibrational state to flip the target qubit as needed. *—D.S., J.S. & C.M.*

Quantum Logic



A pair of qubits in an ion trap repel each other in a way that makes them act as if they were two balls connected by a spring. The motion of the balls and spring, the vibrational state of the system, contains measurable information that can be used in quantum computations.

A particular color and polarization of laser has the effect of forcing a qubit ion to move in a particular direction, but only if the qubit's value is 1. This trick is key to implementing the controlled not (CNOT) gate, a necessary logic operation for any quantum computer. The operation maps the result of the CNOT gate onto the vibrational state. Further laser manipulations impose the vibrational state onto the target qubit.



How an Ion Trap Works

IN A TYPICAL TRAP, ions are suspended in a line by the electromagnetic fields generated by four electrodes.

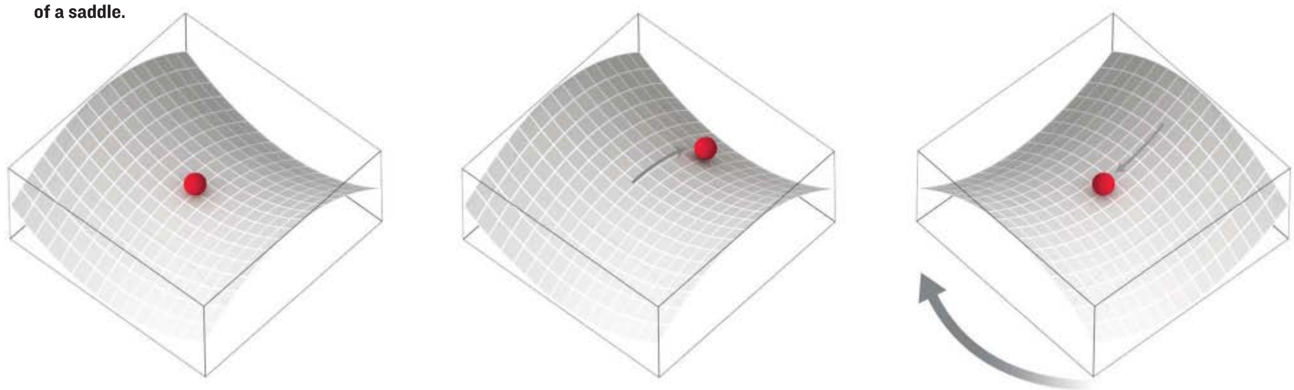
Two of the electrodes produce a steady dc electric field that pushes on the ions and keeps them from moving too far along the line between the four electrodes.

The other two electrodes generate an RF field that keeps them from moving away from the center line.

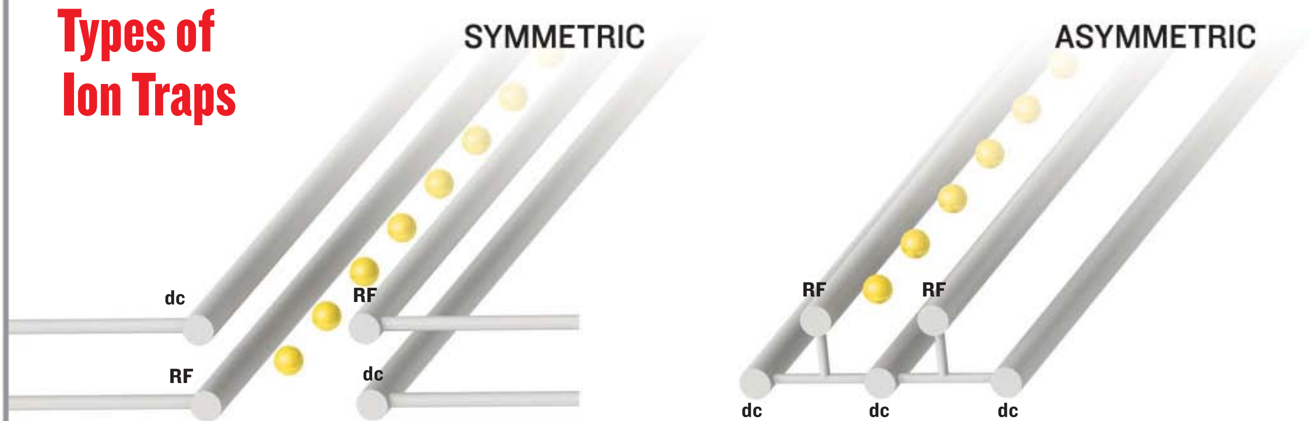
1 At an instant in time, the RF electrodes exert a force on an ion akin to the force of gravity on a ball at the flat point in the middle of a saddle.

2 The ball will not naturally roll uphill (into a repulsive electric field), but it can roll in either downhill direction.

3 However, as the RF field varies in time, it's as if the saddle were rotating beneath the ball. So a ball rolling downhill will suddenly be pushed back toward the stable midpoint of the saddle.



Types of Ion Traps



MICROCHIP VERSIONS of ion-trap quantum computers come in two varieties.

Symmetric traps hold the ions in a line at the midpoint between two pairs of dc and RF electrodes. They require that a notch be carved all the way through the microchip.

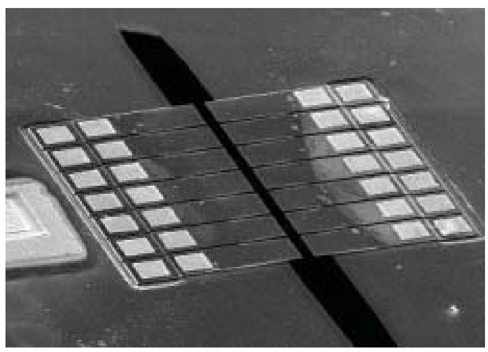
Asymmetric traps suspend ions above the microchip. Their manufacture is potentially simpler than that of symmetric traps, but the electromagnetic fields needed to hold the ions are more complex because of the ion's off-center position.

a modern microprocessor. Making chips with insulators strong enough to survive such large potential differences is difficult, as is dissipating the heat the RF electrodes generate. We fried our share of chips giving it our best shot.

Trap designs fall into two general categories: symmetric and asymmetric. For symmetric traps, dc and RF electrodes are arranged so the sum of the dc electric field is 0 at the midpoint between the RF electrodes. Our chip is symmetric, and it's carved from a wafer of gallium arsenide. Using photolithography and several types of standard etching techniques, we built a segmented trap where the ions line up in a narrow rectangular hole about 60 micrometers across and more than 1 millimeter long that goes all the way through to the back of the chip. Each of the trap's four segments has four electrodes that look like microscopic diving boards, two on each side, arranged one on top of the other, to form the familiar four electrodes of a Paul trap. The segments allow us to push ions from one side of the trap to the other or even push them out of the trap simply by manipulating the dc voltage—applying a negative voltage to draw in a positive ion from a neighboring segment, for instance. Groups at other labs such as Sandia National Laboratories, in Albuquerque, have built microfabricated symmetric traps working on the same principles.

Because symmetric traps are made on thin slivers of already thin semiconductor wafers, the thickness of the insulator between electrodes is limited, which limits the voltage you can apply to them. This restriction may not be fundamental, however; a European ion-trap fabrication effort has a plan for a semiconductor trap with thick insulating layers.

The other type of ion-trap geometry is the asymmetric trap, in which the RF node is not symmetrically located with respect to the electrodes. The ions float above the surface of the chip, out of the plane of the semiconductor, obviating a symmetric trap's hole and cantilever electrodes. Wineland's group at NIST has already built such a trap using gold electrodes patterned on the surface of a sapphire substrate, and one constructed at Alcatel-Lucent's Bell Labs uses aluminum for the conducting electrodes and silicon oxide as the insulator. Figuring out the voltages that will keep the ions still and suspended above the chip is complex compared with what's needed in symmetric traps. Getting the lasers on the ions is also a bit more difficult. They either have to be shot across the surface of the chip or through holes etched in particular areas of the trap. Bringing a laser beam across the surface can scatter its light—which makes reading the state of the ions more difficult. But without a bunch of trenches cut all the way through the chip, as with symmetric traps, it's easier to lay out an interconnected array of traps. Asymmetric traps are also attractive because their construction requires less three-dimensional carving, making the process more like traditional chip fabrication, which is largely two-dimensional.



TINY TRAP: Ions get trapped and manipulated in a 60-micrometer-wide gap between the seven sets of electrodes in this chip-based ion trap.

LABORATORY FOR PHYSICAL SCIENCES

Regardless of the trap type, making them chip scale means controlling the motion of the ions, critical to many calculations, is even harder. Anomalous electric fields appear on the electrodes that make the ions vibrate and heat up—wreaking havoc with our calculations. Noise that overlaps the vibrational frequency of an ion in the trap—about 1 MHz—is the prime culprit. But ions in chip traps experience more noise than we would have expected. The source of this noise, called "patch-potential noise" for the patches of voltage that seem to move around the electrodes, remains a mystery. Researchers are trying to identify its cause and hope to eliminate it. As an example, patch-potential noise can be suppressed greatly by decreasing the temperature of the electrodes. In one experiment, halving the temperature from room temperature to 150 K cut the noise at the ion by an order of magnitude. Other experiments have shown that the farther from the electrodes the ions are, the less noise they experience, so making bigger traps may help keep things cool. Researchers also would like to identify materials and surface preparation techniques that limit noise or—better yet—don't create any at all.

IN SOME WAYS, a full-scale quantum computer would work like the standard desktop computer, in that it would have a place to store data, a place where a program manipulates the data, and interconnections to move the data from one to the other. In the computer you are using now, bits of data—stored as quantity of charge or its absence—are transferred from memory to a processor in the form of levels of voltage. At the processor the computer's program determines which logic operations the bits will be subjected to. Once the logic operations are completed, the bits are converted to amounts of charge and stored in memory again.

Similarly, in an ion-trap computer, stored qubits would be called from a storage trap to a logic trap, the kind we've been building so far. The two traps would be connected by a long trap that acts like an interconnect or a data bus. In truth, there's little structural difference between the memory, logic, and interconnect regions; so by building one, we've pretty much built them all.

Qubits leaving the storage trap would be moved along the centerline of the interconnect trap by varying the strength of the dc electric field holding the ion in place—strengthening the field ahead of the ion and weakening the field behind it, thereby pulling it along. Once the qubits are in the logic trap, the program—the series of laser pulses that rotate, entangle, and otherwise manipulate the qubits—goes to work. The answer to a calculation could be read out then, or the qubits could be sent down another interconnect and later brought back to the logic region to continue the calculation with other qubits. Because ions cannot pass each other on the interconnect, there would also have to be junctions—points where three trap lines converge—so that ions could move to other interaction regions or storage areas or simply get out of the way of other ions coming down the interconnect.

It sounds simple, but such a structure would have to be repeated and connected many dozens of times on the same chip to handle the number of ions we'd need. Assume that we require 100 qubits to perform a particular algorithm and that each qubit is encoded with 50 extra ions for error correction. This 5000-ion array would need on the order of 50 000 individually controlled dc electrodes and their attendant wires. Therefore, a quantum computer equivalent of very-large-scale integration would be required to handle the control circuitry just to move the ions around.

Five thousand ions would need many dozens of lasers for cooling, detection, and gate operations. They'd all have to be precisely controlled in coordination with the ions' motion in the trap—which is in turn determined by the 50 000 dc electrodes. The lasers would have to be aligned on the ion and maintain that alignment over the entire course of the computation, a straightforward task for a small experiment but nearly impossible for an array of 5000 ions without feedback-controlled motorized mirrors.

Such considerations lead to a great irony: you'd need a great deal of infrastructure, including a powerful classical computer, to run a useful quantum computer. But there is hope. The small-scale quantum algorithms that scientists are running today and plan to run in the near future will almost certainly lead to insights that could make full-scale quantum computing, if not easy, at least more tractable. ■

ABOUT THE AUTHORS

CHRISTOPHER MONROE leads the trapped-ion quantum computing group at the University of Maryland, College Park, and was involved in many of the field's milestones, including the first demonstration of a quantum logic gate in an ion trap. **JONATHAN D. STERK** is a doctoral student in Monroe's lab, and **DANIEL STICK** is a former student of Monroe's now doing postdoctoral research at Sandia National Labs, in Albuquerque.

TO PROBE FURTHER

The authors described one of the first ion-trap chips in "Ion Trap in a Semiconductor Chip," by Daniel Stick et al., *Nature Physics*, January 2006, pp. 36–39.

PRIVACY

DOUBLE HELIX JEOPARDY

DNA DATABASES HELP SOLVE CRIMES BUT AID AND ABET RACIAL DISCRIMINATION

By Simon A. Cole

ON 4 JANUARY 1998, POLICE IN LONDON arrested a man, whom court records call "B," on suspicion of burglary. The police swabbed the inside of the suspect's cheek to collect a sample of his DNA.

In August, B was acquitted and released. But in September, B's DNA profile was—accidentally and illegally—entered into the United Kingdom's national DNA database. The system automatically compares newly loaded DNA profiles against unidentified samples obtained from crime scenes. The system found a match—a sample recovered from a 1997 rape and assault case. The police arrested B, and the government successfully prosecuted him for those crimes.

Is there anything wrong with such a turn of events? Privacy advocates say there is, as do people worried about racial discrimination. Among these are lawyers working with the American Civil Liberties Union (ACLU) and the Council for Responsible Genetics, in the United States, and with GeneWatch and Privacy International, in the United Kingdom. Law-enforcement officials and forensic scientists, on the other hand, say the use of such a tool is invaluable for solving crimes, not only to match evidence from a recent crime to an individual in the database but also to link some unsolved cases, showing that they share an as-yet-unknown perpetrator.

Since that 1998 incident, governments have been rapidly expanding the collection of DNA for databases, and changes in database-searching technology that target near matches are raising new concerns. As a result, civil libertarians and privacy advocates are lobbying for restrictions, while some scholars are pushing in the opposite direction, arguing that the only fair way of building a DNA database is to create a universal one—that is, to record the genetic profile of each citizen.

The information loaded into such databases reflects a feature of DNA known as short tandem repeats (STRs). DNA contains a sequence of paired bases, or nucleotides, of which there are four types. The human genome contains about 3 billion such base pairs, arranged into 23 pairs of chromosomes. A small subset of the long sequence creates the 20 000 or so human genes, most of which code for the proteins that determine a person's biochemical makeup and physical characteristics. The rest—about 98 percent—is noncoding DNA. Although scientists are discovering that a surprisingly high fraction of these seemingly useless sequences may affect the body's functions, some of them seem clearly to be meaningless artifacts of evolution.

In certain sections of the human genome, the noncoding DNA contains repeated patterns of two to five nucleotides, the number of repeats in each sequence varying by person. For forensic typing, scientists consider repeats at several loci, or positions on the genome. The number of repeats at each locus is known as an allele. People have two alleles at each locus, one from each parent, that vary in length depending on the number of repeats.

In the United States, the Combined DNA Index System (CODIS),

ILLUSTRATIONS: DAVID PLUNKERT

established by the FBI in 1990 to link existing local, state, and federal systems, is based on STRs at 13 loci. In London, the Home Office currently relies on STRs at 10 loci. Although the estimated rarity is different for each DNA profile, the estimated rarities of complete profiles can be smaller than one in a trillion.

To gather DNA for forensic databases, a law-enforcement official typically swabs inside the cheek of a suspect or criminal to obtain a sample of cells. Although scientists can extract DNA from hair, semen, or blood, a cheek swab is the most efficient and least invasive way to collect a large sample of DNA. The swab goes to a laboratory, where a technician or a robotic instrument isolates the DNA from the other cellular components.

The extracted DNA goes through a second process: polymerase chain reaction, or PCR, a standard method of creating many additional copies of a selected segment of DNA. In this case, the PCR step targets all the relevant sites (10 in the UK, 13 in the United States). A genetic analyzer then separates the resulting 10 or 13 DNA fragments and measures the number of repeats in each. The numbers, one or two for each sequence, typically range from five to 20. There is just one number in some cases because a person can inherit the same number of repeats from both parents.

The DNA databases store those numbers, along with the sex of the individual. In the United States, the federal database alone contains more than 4.6 million such records. The UK's, which started in 1995 as the world's first national DNA database, has about the same number, drawn from a population one-fifth the size.

In the British rape and assault case, B demanded that the court exclude the DNA evidence from his trial because the police had added it into the database illegally. The trial judge agreed. The government appealed, but the Court of Appeal backed the trial judge, noting that Parliament, in establishing the national database, had created rules restricting the database to those convicted of certain crimes. Had Parliament wished to do otherwise, the appeals court argued, it could have done so. Parliament took the ruling as a call to action and in 2001 passed the Criminal Justice and Police Act, allowing law-enforcement agencies to retain DNA samples of individuals charged with a crime but not subsequently convicted.

The United States is now following the UK example. Today, FBI agents cannot legally store data from suspects who were not convicted or from individuals who volunteer their DNA samples for an investigation but are not suspects. But state officials can. Today, four states—Louisiana, Minnesota, Texas, and Virginia—mandate arrestee sampling. California voters in 2004 passed a ballot proposition that will establish by 2009 what should be the largest such database in the United States. New York Governor Eliot Spitzer has proposed including in the state database those convicted of all felonies and misdemeanors. In addition, a bill being considered in South Carolina would mandate the most aggressive arrestee-sampling program in the nation, demanding samples from those arrested for even the pettiest misdemeanors, such as shoplifting.

Some states, including California, Florida, Illinois, Missouri, and New York, though they don't mandate arrestee sampling, already retain data that may not be added to CODIS, such as samples voluntarily given by someone to eliminate himself as a suspect. The legality of such state databases is "a cloudy area," according to law professor David Kaye of Arizona State University in Tempe. Stephen Saloom, policy director of the Innocence Project, an organization in New York City that assists prisoners who could be exonerated through DNA testing, has called them "rogue databases."

Meanwhile, Virginia is experiencing an echo of the B case. Members of the state crime laboratory early this year reported that they had matched a crime-scene DNA sample to stored profiles of DNA from individuals who were arrested but not convicted. Because Virginia mandates that the DNA records be expunged if the suspect is not convicted, the samples were in the database illegally. The state legislature is now considering a bill that would facilitate that record clearing but also allow matches to illegally retained samples to be used in court if they were kept in "good faith."

> "AN 'ARREST-ONLY' DATABASE WOULD HAVE THE LOOK AND FEEL OF A UNIVERSAL DNA DATABASE FOR BLACK MALES"

The UK case and subsequent passage of legislation in other countries illustrate the central paradox of DNA databases: inclusiveness. The more samples in a database, the more useful it potentially is at solving and preventing crimes. If the law requires a criminal conviction to allow officials to record a DNA profile, then crimes such as the rape that B carried out in 1997 go unsolved, and B perhaps goes on to commit other rapes.

The problem with inclusiveness is that there is no obvious end to it. Because people arrested for one offense have a higher-than-average probability of having committed other crimes, the inclusion of samples from all those arrested but not convicted has a crime-fighting utility. But then again, so does the inclusion of a sample of the victim, who could also be the perpetrator of another crime. And, for that matter, why wait until B acquires a burglary arrest to include his DNA sample? If it were loaded into a database at birth, he would have immediately been identified as having committed the 1997 rape.

There is no limit to the theoretical utility of adding anyone's DNA profile to a database. Presumably, though, at some point the utility of inclusion no longer outweighs a free society's interest in privacy. But where is that point?

When law-enforcement agencies first developed DNA databases, most country and state statutes that dealt with DNA testing mandated it for specified categories of crimes, typically murder and rape. DNA is particularly useful in solving sexual assaults, because investigators often recover semen as evidence.

As public awareness of DNA databases grew, so did the scope of the databases. Politicians could appear tough on crime by extending DNA sampling to an ever-growing array of offenses. Many such moves, however, were merely statutory; politicians did not allocate funding to enable police to do the sampling and analysis. Law-enforcement agencies, sensibly, continued to focus on the most violent offenders and did not take DNA samples from pickpockets even when the law allowed it.

Recently, however, the inexorable expansion of DNA databases has gone beyond individuals convicted of petty crimes and reached people arrested but never convicted. Meanwhile, the U.S. Justice Department is now authorized to take DNA samples from anyone detained by federal agents—which means, principally, those suspected of immigration violations.

Unlike the laws expanding the reach of DNA databases to those convicted of petty crimes, the new laws extending inclusion to arrestees not only allow such sampling, they mandate it. In California at least, that means maintenance of the arrestee

DNA database may divert resources from other important tasks. In particular, many law-enforcement agencies still have backlogs of semen samples recovered from rape victims that have not been subjected to DNA testing.

A 2005 U.S. Bureau of Justice Statistics report estimated that it would take 1900 additional workers and US $70 million to reduce the forensic evidence backlog to a manageable size. And in a February 2007 interview with *The New York Times*, Robert Fram, chief of the FBI Scientific Analysis Section, decried the mandating of new populations to sample without any increase in resources and noted that the FBI has a backlog of 150 000 samples.

Arrestee sampling can't possibly be a better use of resources than clearing that backlog. Most likely, such wholesale sampling would also divert money from other pressing needs, such as crime prevention and drug treatment.

Privacy advocates have other reasons for fighting against the inclusion of arrestees in DNA databases. Tania Simoncelli and Barry Steinhardt, both of the ACLU, have been particularly vocal on the subject. In the *Journal of Law, Medicine, and Ethics*, Simoncelli argued that "the very existence of DNA databases turns the presumption of innocence on its head," because those included in the database are treated as potential suspects every time a new crime is investigated.

Of course, governments have long maintained databases containing the fingerprints of convicts, arrestees, and various individuals who are not criminals, including teachers and immigrants. The law considers such databases acceptable intrusions into personal liberty. But civil libertarians say that DNA samples, unlike fingerprints, include personally sensitive information to which the state should not have access: people's ancestry, disease propensity, and perhaps even behavioral characteristics. They argue that such information could be abused by the state, by employers, or by insurance companies.

Scientists can identify weak correlations between fingerprint-pattern types and ethnicity. But people are generally more anxious about disclosing their genetic information than their fingerprints—a concern that typically generates a strong emotional response against broadly inclusive DNA databases.

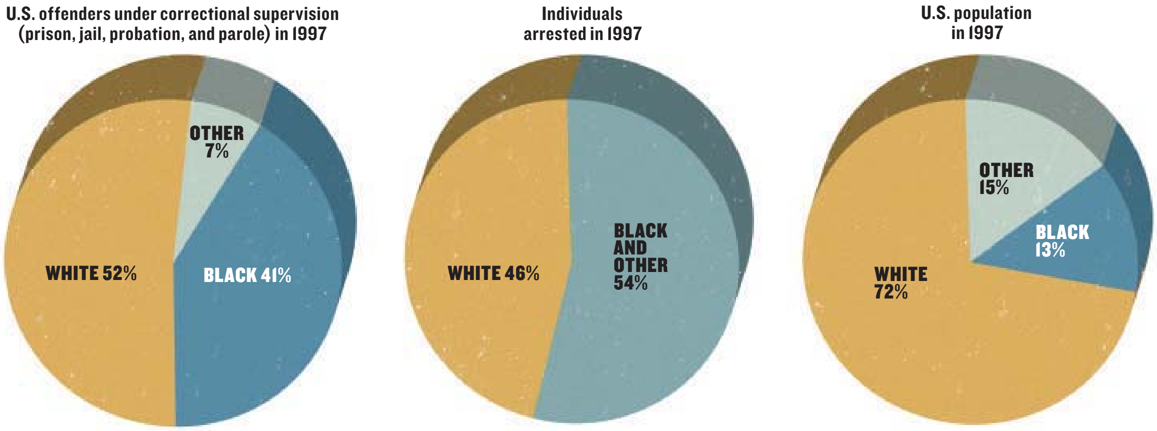
Sociologist Amitai Etzioni and others who tend to value the interests of the community over those of the individual argue that broad inclusion might be a good thing. "Collecting the DNA of convicted, nonviolent felons," Etzioni says, "may still be justified, because they have significantly lowered rights." In his contribution to the essay collection *DNA and the Criminal Justice System*, Etzioni went further and argued that even "suspects have diminished rights, including much lower rights to privacy," and therefore he sees "no obvious reason why suspects should not be tested and their DNA included in databases."

Advocates for DNA databases also contend that because the DNA used for standard forensic profiling is noncoding DNA, the concern about genetic privacy is not an issue. But noncoding DNA may correlate with disease propensity, even if it does not cause disease, potentially allowing "tracking" of genetic diseases. But however useful such information might be, what an insurer would really want would be not just a profile, but a complete biological sample—the original cheek swab.

And there's the rub. In all U.S. jurisdictions except Wisconsin, law-enforcement officials typically retain the samples themselves. Therefore, all the genetic information of those who are being tracked in the DNA database remains accessible to the state. There are a number of state statutes forbidding such uses of genetic information, but such laws will not necessarily remain in place.

The government could destroy the sample and record only the numeric values of its DNA profile. And that procedure could become the compromise struck between the desire for privacy and the need for crime control. But as yet, data-banking proponents are holding out against it, because such a compromise assumes that the DNA-database technology is mature. If forensic scientists develop a new scheme for DNA matching, they'll need original samples to re-encode the existing database population. To be sure, the current systems are powerful, robust, and widely accepted, and the existence of today's large databases is a powerful deterrent to changing the protocols. Nonetheless, the technology has advanced so rapidly during the past two decades that it would be naive to think that the existing systems represent an eternal standard.

Discrimination is another powerful argument against arrestee databases. Even convict-only databases risk being discriminatory. In the United States, courts convict some racial minorities at much higher rates than their proportion of the overall population. Criminologists are divided as to what extent the overrepresentation arises from discrimination in policing and in the courts, as opposed to a higher rate of offending, at least in the case of violent crimes. But when it comes to drug crimes, which consti-



SOURCES: U.S. Bureau of Justice Statistics, "Demographic Trends in Correctional Populations"; Federal Bureau of Investigation, "Age-Specific Arrest Rates and Race-Specific Arrest Rates for Selected Offenses 1993–2001"; U.S. Bureau of the Census, "Selected Social Characteristics of the Population, by Sex, Region and Race: March 1997."

Color Wheels

THESE THREE CHARTS give a rough idea of the effect that different criteria for inclusion in a DNA database have on its racial mix. Constructed using data from 1997, the most recent year for which comparable data from multiple sources are available, these hypothetical databases are only rough models. While these models provide snapshots of the custodial and arrestee populations in a single year, convict and arrestee databases would be assembled cumulatively, eventually including all individuals who had arrests or convictions in their lifetimes. Notice in particular that the arrestee database incorporates the largest number of racial minorities and the smallest number of whites.

tute a large portion of the criminal caseload in the United States, discrimination is undisputed. And one wouldn't want the injustice to extend to inclusion in a convict DNA database (although the harm seems far less than the damage that is done in the first place by discrimination in the criminal convictions).

When it comes to arrestee databases, however, the issue becomes more salient. Criminologists agree that racial discrimination is greater at the level of arrest than it is at the level of conviction, because arrest depends so heavily on police discretion. Arrest discrimination is not based merely on race but also on class and geography. For example, you can use, or even sell, narcotics with a far lower risk of arrest if you are rich, white, and live in the suburbs than if you are poor, black, and live in the inner city. Some demographic sectors of American society, such as poor, black, inner-city males, have shockingly low probabilities of getting through adolescence without having at least one run-in with the police. If such encounters trigger inclusion in a DNA database, the database becomes discriminatory.

To glimpse the likely outcome in the United States, look at the United Kingdom, where the database covers a much larger portion of the overall population than in the U.S. There, 37 percent of black men, 13 percent of Asian men, and 9 percent of white men have had their DNA profiles included in the national database. The figures are even starker if one considers only younger males. Approximately 77 percent of black males between 15 and 34 are in the national database, compared with 22 percent of white males in that age bracket.

Such an arrestee database tends to include the maximum number of racial minorities and the smallest number of whites [see charts, "Color Wheels"].

As Kaye and the University of Wisconsin's Michael Smith put it starkly in their contribution to *DNA and the Criminal Justice System*, "Such an 'arrest-only' database would have the look and feel of a universal DNA database for black males, whose already jaundiced view of law enforcement's legitimacy is itself a threat to public safety."

When law-enforcement officials enter new genetic records from unidentified samples recovered at crime scenes into a DNA database, the system compares them with existing profiles. Some legal scholars say that this procedure amounts to daily searches of each person in the database—no different from stopping drivers for pat-downs without warrants. Other experts maintain that because the individuals aren't aware of the searches, no harm is done.

The risks might seem remote now, but even so, perhaps they should be borne by all citizens equally.

One risk, the possibility of false incrimination, either through DNA planting or laboratory error, is less remote. There simply isn't good current data on the false-positive error rate for DNA profiling. But although forensic DNA-profiling technology is robust, reports of recent errors abound. And it's not just the laboratories generally considered poor (like the police crime lab in Houston) but also those regarded as among the nation's finest (such as the FBI's and the Virginia State Department of Forensic Sciences) that are making mistakes. The errors, documented by Professor William Thompson, of the University of California, Irvine, and others, have led to wrongful convictions.

Planting DNA is possible as well, and it is likely to become increasingly easy and cheap to do, allowing more people to learn how. Of course, the planting of evidence is not new. But because DNA evidence commands such enormous trust and is conceived as scientific, the potential hazards of evidence tampering would be particularly pernicious. Again, perhaps the risks of such mistakes or malfeasance should be borne equally.

The newest trend in DNA-database searching exacerbates the discrimination problem. In the past, when a crime-scene sample failed to match any record in a database, investigators were stymied. Recently, however, they have begun exploring an alternative in such cases: search the DNA database again, looking for close matches. A near-match profile will not be that of the perpetrator, but it may belong to a close relative. The authorities can then investigate other family members. Crime investigators have used so-called low stringency or familial searches successfully in the UK, Canada, and the United States.

The legal issues surrounding familial searching are tricky, especially when combined with the practice of surreptitious seizure of "abandoned" DNA samples from cigarette butts, soda cans, and other discarded objects. In the notorious Bind, Torture, Kill serial-murder case in Wichita, Kan., investigators obtained DNA from a tissue sample gathered for medical purposes from the daughter of the suspect, to avoid alerting him that he was under investigation. No significant constitutional barriers to such actions exist.

But familial searching also raises policy issues. A slight brush with the law that does not result in a criminal conviction puts not only the arrested individual but also effectively the person's entire family into the database. The individual's diminished privacy ripples through the family.

Today, DNA-database systems routinely search newly recovered crime-scene samples against the entire existing database. So the legal system subjects individuals and their families daily to suspicionless searches. In a society in which young black males in some neighborhoods have a one-in-three probability of ending up in state custody at some time in their lives (and an even higher chance of getting an arrest record), the racial overtones of such a practice are dramatic.

Experts debate whether familial searching is reasonable. At a 2006 symposium in Boston on forensic DNA, sponsored by the American Society of Law, Medicine, and Ethics, Harvard scholars Frederick Bieber and David Lazer said that after having initially been skeptical of familial searching, they concluded from their research that the potential benefit to society in crime control outweighs privacy concerns. But an interdisciplinary team from Stanford led by law Professor Henry Greely concluded that familial searching is ethically questionable, stating that "the way that familial forensic DNA puts African-Americans under much greater investigative scrutiny may not be unconstitutional, but seems unfair and quite possibly unwise."

With experts voicing such concerns, why have so many jurisdictions opted for arrestee databases? The answer seems both obvious and troubling: the databases are popular with voters who see them as tracking people other than themselves.

Essentially voters are willing to legislate away the privacy rights of others—especially those they stereotype as potentially dangerous, such as racial minorities, the poor, and residents of economically disadvantaged neighborhoods—but are much more protective of what they perceive to be their own constitutional guarantees. This dichotomy is reflected in the U.S. government's 1940s decisions to reject universal fingerprint databases but allow law-enforcement agencies to maintain fingerprint records in arrestee databases.

Some scholars have decided that there is no longer any alternative than to propose what many would have previously considered unthinkable: a universal DNA database. Alec Jeffreys himself, the University of Leicester, England, geneticist who developed the earliest method of DNA profiling, has now declared that the existing UK database is racially discriminatory, and he has espoused an all-inclusive database as a solution. Jeffreys also proposed that the judicial system use DNA matches for investigative purposes only. That is, DNA would provide leads that would have to be corroborated by other evidence, and courts would never use DNA as evidence. Several American legal scholars, including Kaye, Smith, and Akhil Reed Amar, a Yale law professor, have also advocated for a universal database as the antidote to the discriminatory nature of existing arrangements. And in 2005, Portugal announced its intention to become the first country to include its entire population in its database of DNA profiles.

A universal database, on the surface, has a certain egalitarian appeal. Rather than those stigmatized by an arrest record being disproportionately burdened, all members of society who benefit from the database would bear the associated risks, including the release of sensitive personal information and repercussions from laboratory errors.

Another attractive aspect of the universal-database proposal is that it would engender a more honest appraisal of the risks of government genetic databases. Consideration of a universal database shifts the debate from being about whether other people's privacy rights are worth protecting to being about whether everyone's are. If voters and legislators aren't worried about the misuse of genetic information in a state-run database, let them be the first to offer their samples to it. Such voluntary contributions are rare, although in 1999, British Prime Minister Tony Blair provided his own DNA for the UK's database.

The egalitarianism of the universal database, however, may be a mirage. The facts that have led some scholars to embrace a universal database in the first place—such as discriminatory arrest practices—would not change with the advent of a universal database. In *DNA and the Criminal Justice System*, sociology professor Troy Duster of New York University writes, "If the lens of the criminal justice system is focused almost entirely on one part of the population for a certain kind of activity (drug-related, street crime), and ignores a parallel kind of crime (fraternity cocaine sales a few miles away), then even if the fraternity members' DNA are in the data bank, they will not be subject to the same level of matching. That is, if the police are not stopping to arrest the fraternity members, it does not matter whether their DNA is in a national database, because they are not criminalized by the selective aim of the artillery of the criminal justice system."

The police would still target racial minorities, the poor, and residents of disadvantaged neighborhoods differently, Duster argues, only the still-discriminatory police would have more powerful tools in hand.

Although the DNA-database debate will probably occupy judges, legal scholars, and legislators for some time, the most likely outcome is the least equitable—including only arrestees.

Indeed, if policy-makers were purposefully trying to find the most discriminatory system possible, an arrestee database would be the ideal choice. If an arrestee database is the least equitable solution, we are left with only two reasonable alternatives: a convict database or a universal database. The decision between those two alternatives depends on how much people trust their governments. But the merit of such a debate would be that it would not be about "other people's" DNA but about our own. ■

ABOUT THE AUTHOR

SIMON A. COLE is an associate professor of criminology, law, and society at the University of California, Irvine.

TO PROBE FURTHER

A special issue of the *Journal of Law, Medicine & Ethics*—Vol. 34, Issue 2, 2006—explores DNA and civil liberties in depth.

Simon A. Cole addresses this topic with coauthors Michael Lynch, Ruth McNally, and Kathleen Jordan in a forthcoming book, *The Contentious History of DNA Fingerprinting* (University of Chicago Press). Other works on the subject include *DNA and the Criminal Justice System*, edited by David Lazer (MIT Press, 2004); *Forensic Identification and Criminal Justice*, by Carole McCartney (Willan, 2006); and *DNA Profiling, Science, Law, and Controversy in the American Criminal Justice System*, by Jay D. Aronson (Rutgers University Press, 2007).

The American Society of Law, Medicine, and Ethics has a project on DNA fingerprinting and civil liberties and an extensive Web resource at http://www.aslme.org/dna_04.

Excellent background material on this issue in the UK is in a Wellcome Trust report by Robin Williams, Paul Johnson, and Paul Martin, *Genetic Information & Crime Investigation* (2004), available at http://www.dur.ac.uk/resources/sass/sociology.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RESOURCES

The Trading Test

A big-time financial firm is recruiting tech talent by offering prizes to the college kids whose software chooses the best investments

BY ERICO GUIZZO

YOU'RE HIRED! Steven J. Sanders of Interactive Brokers stands between new hires Stan Li [left] and Bharath Govindarajan, who ranked in the top five in a trading contest.

RESOURCES

Brian Eckerly, an electrical engineering student at Ohio State University, booted up his Dell laptop one morning in January and loaded a little program he'd finished coding the night before. Numbers flashed on the screen, and Eckerly scanned them for a minute. Then he went to class.

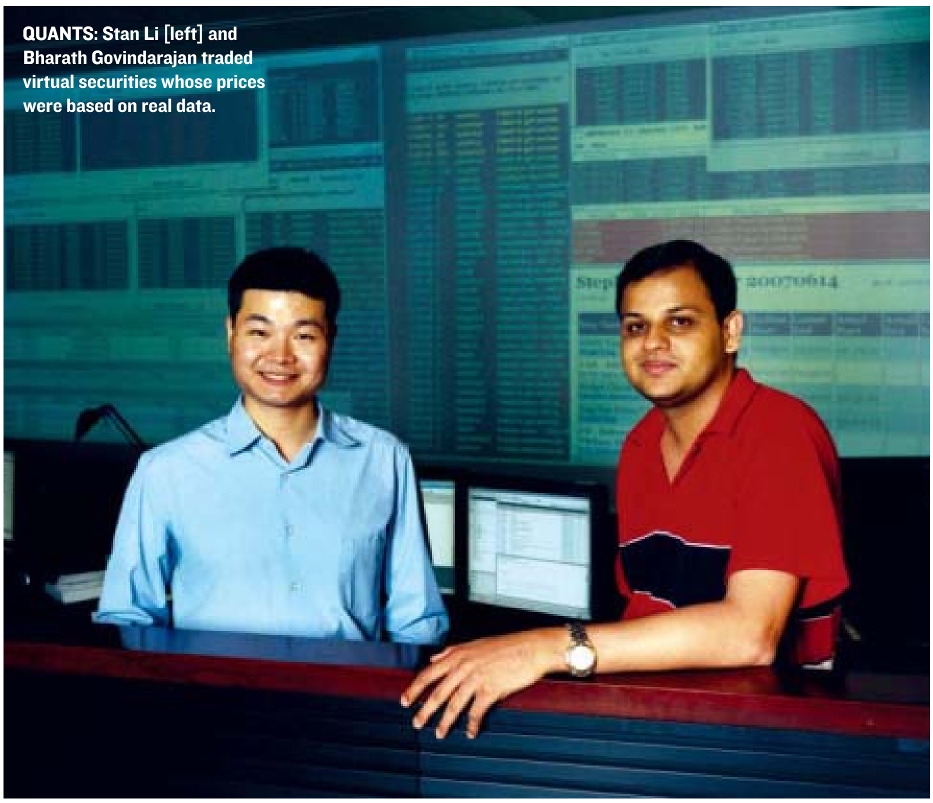
CONTEST

That day, and in the following weeks, the laptop sat undisturbed at Eckerly's off-campus apartment in Columbus, carrying out his program's instructions. It connected to an online brokerage firm, gathered stock data, crunched some statistics, determined whether certain conditions had been met and, if so, executed trades. Eckerly began with a handsome sum—US $100 000—and in seven weeks his program increased it to $394 190.

If only it were real money!

It was all for a trading contest organized by Interactive Brokers Group, a $2.8 billion securities firm in Greenwich, Conn., that wanted to find tech-savvy engineers and scientists willing to work in the financial industry.

"The old trading world required big, aggressive, street-smart folks—now it's technology skills that count," says Steven J. Sanders, a senior vice president with Interactive. "We just don't ever get enough good technologists."



QUANTS: Stan Li [left] and Bharath Govindarajan traded virtual securities whose prices were based on real data.

The contest, which was open to students from the United States, Canada, and Mexico, required participants to elaborate a trading strategy and write software to execute it. Each contestant took a starting stake in virtual money and used it to trade stocks, bonds, options, futures, and currencies during an eight-week period. Although all trades were virtual, taking place on a simulation system created by Interactive, the buying and selling prices were based on real market data.

Real, too, were the cash prizes. Eckerly, who finished first, took home $100 000. Two runners-up each got $50 000, and several other participants got prizes of $10 000 or $1000.

THE FINANCIAL INDUSTRY has long been known to hire math whizzes as quantitative analysts, or "quants," who concoct pricing models, probe new ways to quantify risk, and mine data. Now, as automated trading systems take over ever more of the substantive work on Wall Street, many firms are seeking quants who not only know the math but the nuts and bolts of IT systems, too.

"There's just a huge engineering challenge: How do you get that much data, process it very quickly, and act on that?" says Richard Holowczak, a professor of computer information systems at Baruch College of the City University of New York. "It's definitely like an arms race."

Many traditional universities' finance and management schools are introducing courses in quantitative and computational finance. As a result, there are now 40 financial engineering programs on offer throughout the world, about three times as many as five years ago.

Konstantinos Tsahas, a master's degree candidate in Baruch's program, says the best thing about the contest is that it allows students to experiment with real-world trading systems. He compares the competition to "an eight-week internship from your home." If so, then his second-place finish made it one of the best-paid internships on record, at $6250 per week.

INTERACTIVE'S FOUNDER and chief executive, Thomas Peterffy, has been a longtime proponent of electronic trading. In 1983, he developed a handheld computer to assist him on the trading floor—much to the resentment of his fellow traders, who promptly tried to get it removed. Peterffy went on to develop ever more complex pricing and risk-management systems.

Now his company devotes entire floors of a modern orange-

THIS PAGE AND PREVIOUS PAGE: BETH PERKINS brick office complex to an army of software engineers and system administrators. Their main job is to keep on improving the firm's vast trading system, which runs at a data center with 300 Linux-based servers and fiber-optic connections to dozens of exchanges around the world.

Sanders, the vice president, acknowledges that his trading contest is not a cheap way to snare talent, for in addition to the $400 000 prize fund, there are marketing costs, including ads on Web sites such as Facebook. But, he says, it's worth it.

"The contest works as a filter that gives us much more than just a résumé to look at," Sanders says. Last year, after the firm ran the contest for the first time, it hired Bharath Govindarajan and Stan Li, the second- and fifth-place finishers, respectively. This year's contest hadn't led to any new hires by June, but that may change as graduating students enter the job market. The company, which has a dozen technology positions to fill, is already planning next year's contest.

This year's 204 contestants wrote their trading software in C, C++, Java, Visual Basic, and even Excel scripts. To retrieve market data and execute trades, the programs communicated through an application program interface with Interactive's Trader Workstation software, which had to run on the same computer. Professional traders using Interactive's services run their trading algorithms the same way.

Trading strategies varied, but most of them used well-known techniques, such as moving averages, Bollinger bands, and vector analysis. Sanders insists that he's not interested in appropriating the students' strategies. Contestants, he says, don't have to submit their software, only outline their trading plans.

Eckerly, who learned about investing from his grandfather, a stockbroker, won't reveal all the details of his strategy. He says his program analyzes the Standard & Poor's 500 stock index to tell when prices rise or fall to an extreme value, then bets they will move in the opposite direction. It obtained high returns by using a leveraged instrument called a put option, basically a contract from which the holder profits if the stock's price goes down.

Eckerly graduated in March and is off to a job as a data analyst with Capital One Financial Corp. in Dallas. He says he'll invest most of his $100 000 prize, but he doesn't know if he'll use a program to do that. "When you're dealing with real money," he says, "you have to be more serious about your decisions." ■

TO PROBE FURTHER

The U.S. Department of Labor offers details about financial analyst jobs and earnings at http://www.bls.gov/oco/ocos259.htm.

To learn more on how to become a quantitative analyst, visit the Web site of the International Association of Financial Engineers: http://www.iafe.org.

A report on graduate programs in financial engineering is available at http://www.fenews.com/fen54/spec-report/capstone/capstone.html.

TOOLS & TOYS

Deeply Superficial

Hackers must develop new tricks to modify the guts of today's surface-mount hardware BY PAUL WALLICH

RANDI SILBERMAN

A while back I had the idea of taking a cheap MP3 player, a spare infrared sensor, and a bunch of other parts from the back shelf and cobbling them into a motion-activated sound-effects generator. Each time someone walked onto my porch or into the front hall, the gizmo would bombard the intruder with strange noises, perhaps even a series of different voices or animal calls with every approach.

However, as soon as I opened up the player, I knew I was in trouble. The circuit board was about the size of my little finger, the conductors I wanted to solder to were barely visible, there were no posts to wrap a spare wire around and no vias to poke it through. And a few minutes with the manual showed me that even if I managed to connect to the player's controls, I would need something close to artificial intelligence to do anything useful with them. One press of the power button is on, another press of the same button is play, and repeated presses select sound files from a menu pulled up by pressing another button.

The other gadgets I'd planned to cannibalize were pretty much the same—teensy surface-mounted components, complicated controls, questionable outputs. So I put the project aside.

Since then I've been wondering: What's an old-fashioned hardware hacker to do? I've started looking into what it would take to get with the times. Out with the diagonal cutters, in with the tweezers. Out with the soldering iron, in with the miniature hot-air gun and the toaster oven [see photo, "Fat Chance"]. A low-power microscope will come in handy too. And maybe a few microcontroller boards to replace the old on/off switches that used to suffice for controls.

For the hacker with ingenuity, a little cash to spare, and a certain abstract turn of mind, the brave new world of subminiature components and fine-pitch circuits might even be easier to work in than the old one of perfboards (perforated prototyping boards), dead-bug chip packages (whose leads stick up like the legs of a supine insect), and endless jumper wires.

The first thing to go is the soldering iron. For some of the larger-scale surface-

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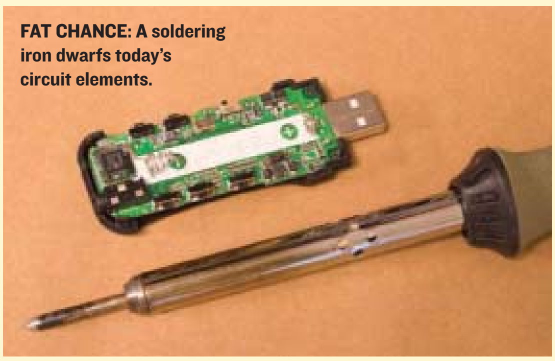
RESOURCES

mounted components, you can work by tacking down a pin here and a pin there to hold the package in place while you solder the rest. But the point of a typical iron is somewhere between 500 and 1000 micrometers across; the distance between the contacts of a small-outline chip package is closer to 200 µm. Practiced technicians may be able to work with such clearances, but I'm not in that class.

For anywhere from US $250 to well over $1000 you can buy the hot-air guns that full-time engineers and technicians use to rework surface-mount circuit boards, or for about $20 you can build your own. Buy a 45-watt solder sucker from RadioShack, pull off the vacuum bulb, and replace it with heat-resistant plastic tubing connected to an aquarium pump.



FAT CHANCE: A soldering iron dwarfs today's circuit elements.

Stuff the nozzle with a little copper floss to improve heat transfer. Oh, and don't forget the syringe of solder paste (store it well marked in the refrigerator), because even fine-gauge solder is generally too clumsy for this kind of work.

For the gizmo I wanted to build, I'd also need a microcontroller. For about $40 to $100 I can get a board that I can program to respond to digital or analog inputs with pretty much any sequence of output signals I choose. Hobbyists have a wide selection of microcontrollers, but the Basic Stamp is the canonical, albeit dated, choice of many hackers. Its few dozen bytes of RAM would be enough for me—all I want it to do is turn on the MP3 player, wait a second, trigger the menu-button circuit for a few hundred milliseconds, wait, trigger it again, and so forth.

If I were building something more complicated, the old way would be to mount a bunch of components on perfboard and connect them with jumper wires. There are a few vendors who sell prototyping boards with surface-mount pads that are electrically connected to vias for soldering in jumper wires, but that just doubles the work. For not much more, I could design my own surface-mount board and have it fabricated by a fast-turn service. PCBexpress, for example, offers batches of boards in less than a week for as little as $60.

All the components on such boards can even be soldered in one shot using a domestic toaster oven (preferably not one also used for food). Infrared rays, after all, have the same effect regardless of whether they're produced by a fancy heating element in a factory or a cheap one in the basement. And if you're worried that your fingers can't position components as well as a pick-and-place robot can, it turns out there's a nice self-aligning effect as the surface tension of the molten solder paste pulls pins and pads together.

Will your carefully designed, painstakingly assembled circuit work the first time out of the box? Probably not. Mine seldom do (or not for long). Will your trusty old multimeter tell you anything useful? Probably not. Thank goodness for Moore's Law and technological obsolescence: oscilloscopes of the kind my generation barely dared touch during college lab courses are now available from surplus dealers for not much more than the cost of shipping. They're no good for debugging the latest multigigahertz, multi-CPU nanomainframe, but they're perfect for watching what goes down a serial line or catching the glitches in my hypothetical button-pressing automaton. And once the malfunction becomes clear, out comes the home-built rework kit to put everything right.

So the next time I have a brainstorm about hacking together some pieces from my junk drawer to make a cool widget, all I have to do is spend a day or two and a few hundred dollars building and buying new tools. I'll need another hundred or so for a microcontroller and a day or two to master its programming idiosyncrasies. Then another few days to learn the software to lay out the printed circuit board. That way I can develop the discipline to think my idea through before I commit it to a circuit design, and the patience to wait until my order comes in. I can hardly wait. ■

ABOUT THE AUTHOR

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CAREERS

Dealing With The Media

You'll probably have to deal with reporters from time to time. Here are guidelines on how to handle them

BY CARL SELINGER

"Dealing With the Media?" What kind of article is that for an engineering magazine? Well, at some point in your career you'll probably need to have this soft skill—to explain, defend, or promote a project to your boss, a reporter, or your company's communications manager. Do this job well, and you'll have a lot of opportunities to do your main job better. Do it badly at a critical point, and you could put your career in jeopardy.

Let me suggest a few guidelines and share some examples from my engineering career.

First, make sure you are authorized to talk with the media. Learn to work with public relations pros, in your company and in the private sector, to develop media strategies, press kits, and so forth. Alert them whenever a reporter calls. Reporters often go straight to the source—you—even if they learned of a piece of news from your PR reps.

When reporters call, ask whether they're on deadline. The media usually operate on short deadlines—often reporters need information immediately for next-day publication or to update Web stories. If so, try to provide as much information as you can right away; you can always supply more later. The reporter will appreciate that courtesy.

Regard reporters as professionals—at least until they prove otherwise—even though they didn't go to engineering school. Find out what they need. Explain things in layman's terms, avoiding jargon. Tell them what's unique and newsy, what will be accomplished, and whatever else is interesting about the project. The reporters may or may not specialize in covering technology, but in any case they will generally need considerable help to understand what you're doing. Ask them to read back the story to you, especially the key technical details; you rarely get to review an article before it's published, but you should at least ask.

Learn how to write a press release. We engineers have our tech memos; the media

RANDI SILBERMAN

RESOURCES

rely on press releases. And we engineers can improve the clarity of our writing by including journalism's "five Ws" in the first sentences: the who, what, when, where, and why of the story.

Prepare for an interview. Bone up on the matter at hand, control your nervousness, and be concise. Never fudge or guess at an answer; it's much better just to say you don't know. You can't just keep on saying that, though, because it would call your expertise into question, so instead tell the reporter that you want to be sure to give an absolutely correct answer, and therefore you'll call back later.

"No comment" is the most damaging phrase you can utter. If you're dealing with a crisis or any other difficult subject, tell the reporter you'll call back later; then work with your PR and legal departments to craft a written statement—and stick to it.

Identify the frequently asked questions for your subject, and prepare answers for each. An engineer recently asked me how to get ready for a difficult presentation to a local audience that was hostile to his project. I told him to anticipate the toughest questions and prepare answers, even if the audience was not going to like them. If you duck a tough question, your credibility will be at risk for the entire story.

Develop contact information for tech publications and for technology reporters working for the general media. This will be useful when you want to promote your projects or yourself. Keep the reporters on your list updated on projects, even on developments you suspect aren't newsy: let the reporters be the judge of whether it's worth covering. Invite them in to inspect your projects if you've got something for them to see.

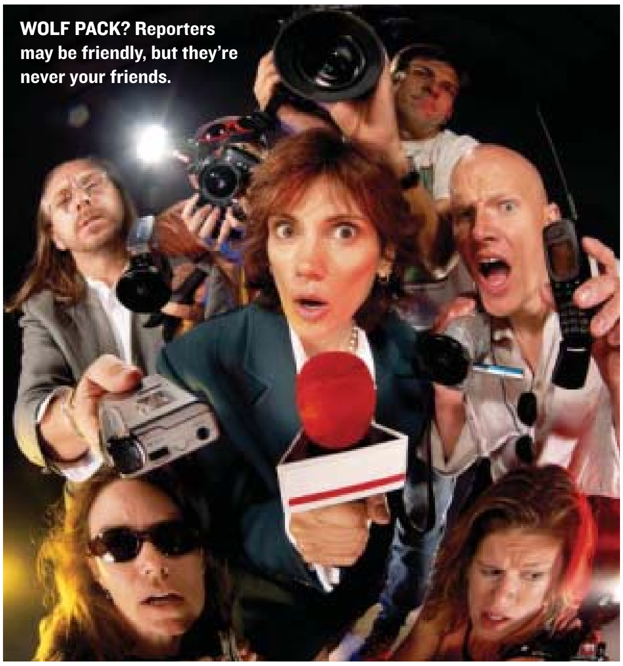
Don't forget the local media. Even if you can't interest the big national media in your work, the local media may well appreciate your calls. They know that their readers care about what's happening in their own backyard. Don't be shy: publicize your talks and other achievements, such as getting promotions.

Look your best for the TV cameras. Get guidance on how to dress and groom yourself; don't depend on the TV folks to do the job for you. Generally, women should use extra makeup, modest jewelry, long sleeves, and high necks. Men should avoid heavily patterned ties and shirts. And always bring powder, a handkerchief, or both to a TV interview. You don't want a shiny forehead to distract viewers from what you're saying.

Following are three of my experiences with the media; I'll call them "the good," "the bad," and "the ugly." Perhaps you can see whether I followed the above guidelines.

The good experience occurred two years ago, when I got a call from "ABC World News Tonight," inviting me to appear on a segment marking the 100th anniversary of aviation, to comment on Boeing's pending decision about whether to undertake the new 787 Dreamliner aircraft. (I suggested Boeing should go ahead, and the plane has been a big success!) I easily could have passed on the interview opportunity—it was not my main area of expertise—but something told me to take a risk, have some fun, and get some publicity for Cooper Union, the New York City college that is my alma mater and where I teach. I was told that the interview went well, and I anxiously waited to see the program, having alerted my family and friends. Well, with the media, expect the unexpected: Saddam Hussein was captured the morning of my program, and my piece was canceled. Lesson: you can always get bumped by breaking news.

Now for the bad experience. One day a colleague came into my office and asked me to talk to a reporter who had left a message for him. "I can't call him back," my colleague told me. "I'll get in trouble." When I called the reporter on my colleague's behalf, the reporter was immediately suspicious and asked about the switch. "Well, to be honest with you, he's scared to talk to reporters—I'm not sure why," I said. "So, how can I help you, and are you on deadline?" I was able to handle his call, and the reporter and I became professional friends. Lesson: always respond to reporters' inquiries, even if only by leaving a message that asks about the subject of the interview and promises that you'll get back.



WOLF PACK? Reporters may be friendly, but they're never your friends.

My ugly media experience came when I was struggling to gain riders for my new airport shuttle so it could reach the break-even point in its first year. To get publicity, we contacted a newspaper that was widely read in the airport's market area. The reporter came by, and we talked at length about the project, its benefits, and its potential. However, the reporter pegged the story to the financial insecurity of the airport shuttle—something that would trouble travelers who need dependable transportation to the airport. We expressed our displeasure to the newspaper. In the end, though, the airport shuttle survived the unfavorable coverage and is still running. Lesson: reporters may be friendly, but they're never your friends. Assume nothing; they often have their own agendas.

More the norm was my relationship with the transportation reporter for *The Star-Ledger*, New Jersey's largest newspaper. After the reporter covered one of my projects early in my career, he called me from time to time for information on stories. On one occasion, he accepted my invitation to speak at our professional society meeting on the topic of "Dealing With the Media."

Catchy title, huh? ■

ABOUT THE AUTHOR

Carl Selinger is an aviation and transportation consultant and the author of *Stuff You Don't Learn in Engineering School: Skills for Success in the Real World* (Wiley-IEEE Press). For more information, see http://www.carlselinger.com.

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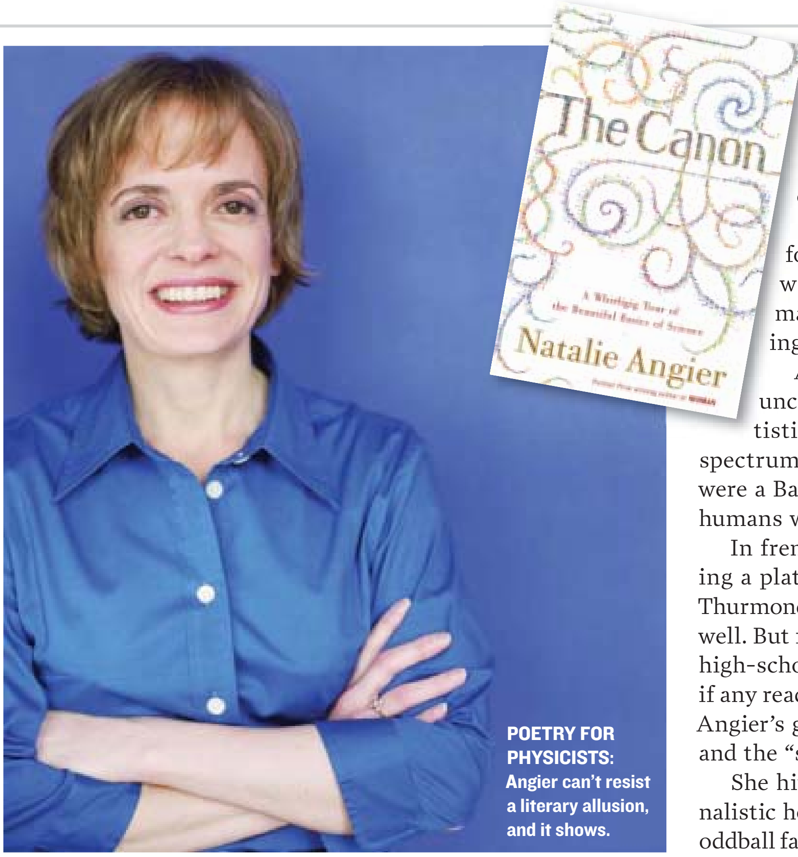

POETRY FOR PHYSICISTS: Angier can't resist a literary allusion, and it shows.

THE CANON: *A Whirligig Tour of the Beautiful Basics of Science*
by Natalie Angier; Houghton Mifflin, Boston, 2007; 304 pp.;
US $27; ISBN-10: 0-61824-295-3; ISBN-13: 978-0-61824-295-5

Science for the Layman

Can you fit everything that everyone needs to know into a single book—and make it fun?

REVIEWED BY SANDRA UPSON

BOOKS

Science in the United States has not fared well lately. Politicians and educators bemoan the diminishing numbers of science and engineering graduates. Scientists complain that the public is unfamiliar with stem cell research, climate change, the difference between a fetus and a blastocyte.

Natalie Angier says the ignorance can be traced to an image problem. "In the civic imagination, science is still considered dull, geeky, hard, abstract and, conveniently, peripheral," she writes. To overcome the ignorance and change the image, she has written a primer that argues that science is exhilarating.

The Canon: A Whirligig Tour of the Beautiful Basics of Science, her ambitious, 304-page sprint through the fundamentals, delivers its lessons via cheerful interviews with hundreds of top-notch scientists. Perfect, one might think, for that misguided uncle, or that troglodyte niece. But Angier's jittery style may alienate most cave dwellers and, presumably—if this reviewer is any indication—most modern humans as well.

That's not to say her premises aren't admirable. Daily life encourages a casual amount of scientific curiosity and experimentation—troubleshooting a computer, say, or even a sick pet—and Angier, who reports on science for *The New York Times*, draws on such familiar associations in her hummingbird-like treatment of science's major branches. She dips into physics, chemistry, and biology, and then flits on to rock formations and planets. She addresses the basic principles in each field, her chatty prose flipping between explanatory depth and comfortable imagery.

Along the way, she proposes some simple algorithms for making day-to-day life more comprehensible. This works well in a trick she calls the "Fermi flex" for estimating the number of piano tuners in Chicago or guessing the circumference of the Earth.

Angier wants her readers to be more aware of the uncertainty of scientific evidence, the slippery side of statistics, the challenges of assessing scale. In explaining the spectrum of visible light, for example, she writes that if the sun were a Baskin-Robbins shop with 100 billion ice cream flavors, humans would be capable of tasting just five of them.

In frenetically hopping from idea to idea—such as comparing a platypus to a Marx brother and heavy quarks to Strom Thurmond—*The Canon* easily lives up to its subtitle. Perhaps too well. But for those readers searching for a madcap blast through high-school-level science, this might be a place to start. That is, if any reader lasts beyond the first 50-odd pages, through which Angier's generalized pronouncements on "scientists," "science" and the "scientific" tend to echo like a Buddhist chant.

She hits her stride when she writes about biology, her journalistic home turf. She sprinkles her narration with compelling oddball factoids—for instance, a single female cockroach can give rise to 40 million offspring in the 12 months or so of her life.

Much of the book reads half like poetry, laced with a subtle internal rhyme, and half like free-associative thinking delivered from a therapist's couch. Her voice lilts through the pages, with colorful and evocative turns of phrase that make the most mundane molecule bounce with anthropomorphic spirit.

Angier aims to make science accessible by relating it to emblems of Americana. She is compromised, however, by an overdeveloped power of association that sends her darting between chemical bonds and James Bond, electrons and Ellis Island. At times, *The Canon* resembles a chemistry textbook that has been tossed in a blender with a Norman Rockwell painting—an outcome that is occasionally tough to stomach.

A somewhat ironic side effect of Angier's reliance on cultural clichés is that her more obscure comparisons end up undermining her goal of making science understandable. One wonders what stunningly erudite reader would immediately recognize that her oblique reference to Nijinsky refers to the ballet dancer, that Zelig is Woody Allen's chameleonesque character, and that Yertle the turtle hailed from a pond called Sala-ma-Sond. And after consulting *Wikipedia* for the umpteenth time, the reader is left unconvinced that such distractions illuminate anything.

Ultimately, Angier's overarching lack of focus robs her readers of anything solid to clasp, and she leaves them itching for a more substantive narrative to connect her ample supply of colorful anecdotes. Compare this to Bill Bryson's similarly spirited epic biography of nature, *A Short History of Nearly Everything* (Broadway Books, 2003), which succeeds where Angier's latest book doesn't by developing extended story lines that ensnare readers. Whereas Bryson ambles through the millennia, Angier writes as if chased by wildfire.

Then again, Angier's book is half the length of Bryson's, and for those readers charmed by her freewheeling style, *The Canon* is one way to tickle the brain. ■

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TECHNICALLY SPEAKING

By Paul McFedries

Tired vs. Wired

The quantitative estimation of the information value of the messages transmitted in the various communications channels, and the identification of a human capacity for information handling by experimental techniques, suggest that the problems of widespread saturation in communications flow may arise within the next half century.—Richard Meier

JOHN HERSEY

Meier, an urban planner who died in April, wrote these words in *Communications Theory of Urban Growth*, published in 1962, in which he also put it much more succinctly by coining the phrase **information overload**. Now here we are, not quite a half century later, and his phrase has almost become a cliché. In fact, some say we have gone beyond mere overload to the point of wallowing in **information pollution**, the contamination of a culture or of a person's life by excessive data. Some people respond with **information environmentalism**, a movement that seeks to reduce information pollution and its effects on people.

But not all of us even know how to begin becoming an **information environmentalist**. Instead, most people simply get tired of the onslaught. They suffer from **information fatigue syndrome (IFS)**, the weariness and stress that result from having to deal with excessive amounts of information. One writer described the symptoms as "the paralysis of the analytical capacity, constant searches for more information, increased anxiety and sleeplessness, as well as increasing self-doubt in decision making." Been there, done that, had a nap after.

IFS takes many different forms, the most common probably being **e-mail fatigue**, caused by receiving a large number of e-mail messages each day. (The analog equivalent is called **junk mail fatigue**, a term used by direct marketers to refer to one's exasperation at receiving a steady flow of ad pieces day after day.) And who among us has not suffered at least a mild case of **feature fatigue**, the mental tiredness and stress caused by products that come with a large number of features? It is an inevitable consequence of **creeping featurism**, the tendency for complex systems to become even more complex over time thanks to the constant addition of new features.

One of the newest forms of IFS is **password fatigue**, the enervation and frustration caused by having to remember a large number of passwords. Whether it's the LAN, online banking, or the untold numbers of accounts we have to juggle for Web destinations such as newspapers, blogs, and social networking sites, we log on to things constantly, and each of those log-ons requires a password. (A similar affliction is **PIN-code overload**, which refers to all those four- and five-number codes we have to remember for the home alarm, the automated banking machine, and on and on.) And speaking of social networking, IFS has hit here too, with the latest malady being **social network fatigue**, the burnout caused by creating and maintaining an excessive number of accounts on MySpace, Facebook, LinkedIn, and other such sites.

Fatigue is by no means a universal reaction to the current information invasion. Some of us positively crave data and turn into extreme **informavores**, people who try to take in as much information as they can. These are the **infohoarders**, the digital version of those people who suffer from **syllogomania** (from the Greek word *sylloge*, which means "a collection"), the pathological hoarding of rubbish. Not that anyone into such hoarding would consider the data they collect to be rubbish—far from it. These are people whose iTunes libraries contain not thousands of songs but *tens* of thousands. These are people with hundreds of hours of recorded TV shows, uncountable numbers of digital photos, and more e-mail addresses and social networking accounts than they can keep track of. These are people who *never* delete anything, meaning that many probably have some form of **disposophobia**, the fear of throwing things out. These are, in short, the new **digital pack rats**. For completeness, I should also mention that **infohoarding** often goes hand-in-hand with **completism**, the obsessive gathering of the complete collection of a particular set of items, such as a musician's recordings or the shows in a TV series.

Whether excessive information gets you down or perks you up, it's clear that the future will bring more information, not less. We are seeing the cultural realization of Parkinson's Law of Data, which tells us that data expands to fill the space available for storage. Unfortunately, with terabyte hard drives about to become commonplace, the culture will simply pick up the pace of data production in an effort to fill those drives. Syllogomaniacs will love it; the rest of us will get tired just thinking about it. ■

PAUL MCFEDRIES is a technical and language writer with more than 40 books to his credit. He also runs Word Spy, a Web site and mailing list that tracks new words and phrases (http://www.wordspy.com).


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