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Are Electric Cars Really Green?

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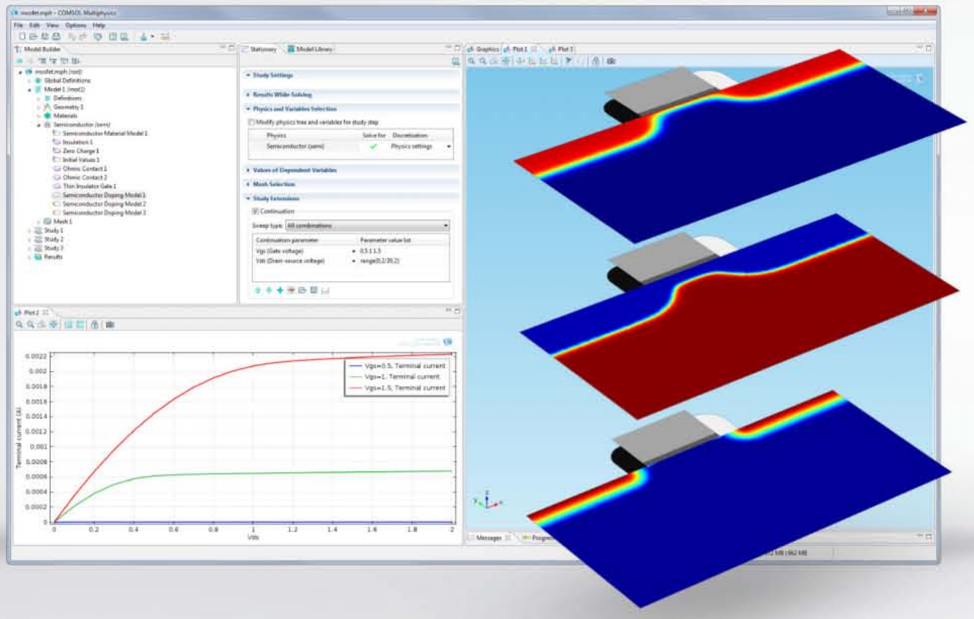

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SMELL-O-VISION IS HERE Ever wish you could smell the objects you see on TV? Two members recently demonstrated a prototype of their Smelling Screen, an LCD monitor that releases scented vapor to correspond with what's on the screen.

REACHING FOR THE STARS Continuing education helped IEEE Member Peter T. Johnson go from being a janitor at an elementary school to an instrumentation engineer at NASA.

CAR TALK This year's IEEE Vehicular Technology Conference, to be held in September in Las Vegas, will focus on what's happening in wireless communication technology and its mobile, vehicular, and transport applications.

FROM LEFT: PROPOSED SWANSEA BAY TIDAL LAGOON; ROLEX/AMBROISE TEZENAS; TOM SIBLEY/CORBIS

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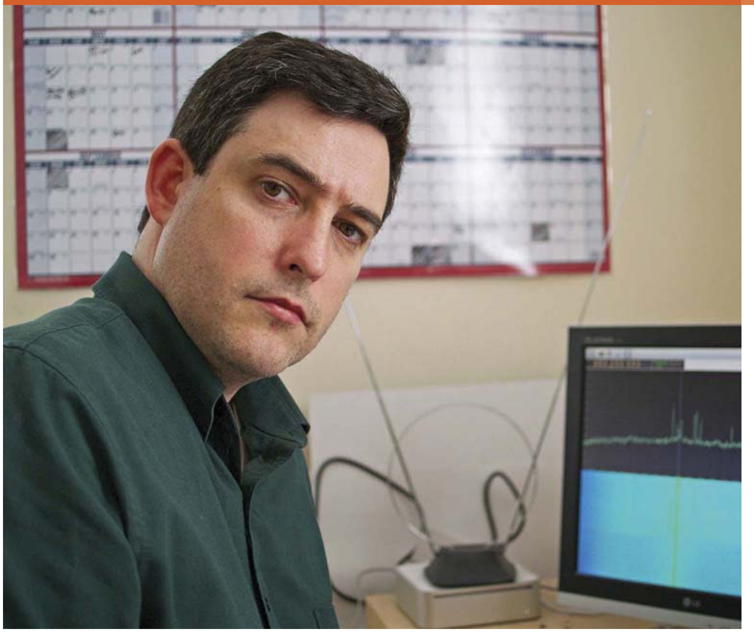

Radio Free Boston

On the morning of 19 April, Contributing Editor Stephen Cass woke to hear Massachusetts governor Deval Patrick asking him, and every other resident of the greater Boston area, to "shelter in place." Following the killing of MIT police office Sean Collier and a pitched gunfight the night before, a massive manhunt was under way for the suspected perpetrators of the Boston Marathon bombings.

As it happened, Cass had just finished writing this month's Hands On article about a software-defined radio, or SDR [see "A $40 Software-Defined Radio," in this issue] Although very inexpensive, this SDR can receive essentially any frequency in the VHF and most of the UHF bands. Cass had already used the powerful little unit as a scanner to monitor simultaneous activity on every UHF FM channel belonging to the Boston Police Department.

So 19 April found Cass sitting in his apartment in Boston, keeping an eye on the level of radio activity in the precincts outside the immediate area of the manhunt: "If the pursuit spilled out of that area and put more of the city at risk, it would be reflected in that level of radio activity," Cass reasoned. "The visual representation of the radio spectrum also meant I could avoid having to constantly listen to audio all day long, so I could get some work done," Cass explains.

When he did listen to the audio, with a click of the mouse, he found it reassuring. It was "calming to hear the professionalism of the police as they responded" to alert after alert until the final capture of Dzhokhar Tsarnaev, says Cass. ■

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes two editions. In the international edition, the abbreviation INT appears at the foot of each page. The North American edition is identified with the letters NA. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, Dataflow is in *IEEE Spectrum*, Vol. 50, no. 7 (INT), July 2013, p. 52, or in *IEEE Spectrum*, Vol. 50, no. 7 (NA), July 2013, p. 60.

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PHOTOGRAPH BY **Stephen Cass**

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07.13

Johannes Traugott, Anna Nesterova, and Gottfried Sachs

When Sachs, a specialist in flight mechanics and control at Munich University of Technology, suggested that Traugott do his doctoral thesis on albatross flight, Traugott says he jumped at "the once-in-a-lifetime chance" to combine his interests in algorithms, flying, and sailing [see "The Flight of the Albatross," p. 42]. Traugott now develops navigation tools for Trimble Navigation, of Sunnyvale, Calif. Nesterova, a biologist at the Center for Functional Ecology and Evolution, in Montpellier, France, collaborated on the albatross study while researching the navigation of penguins; she is now a postdoc at the University of Oxford.

Michael C. Schatz

An assistant professor of quantitative biology at Cold Spring Harbor Laboratory, in New York state, Schatz knows firsthand how much genetics research depends on computer science. His first postcollege job was working as a software engineer in the trenches of a major genomics research institute, where he wrote programs for analyzing all the genetic data generated by high-tech sequencing machines. His latest strategies for keeping up are described in "The DNA Data Deluge" [p. 24].

Ben Langmead

Langmead, coauthor of "The DNA Data Deluge," began collaborating with Schatz when the two were Ph.D. students in bioinformatics and computational biology. Now an assistant professor of computer science at Johns Hopkins University, Langmead relishes the contributions his programs can make to medical and scientific research. "When I'm helping life scientists design an experiment so the data they get can be analyzed, it answers the 'What's the point?' question," he says.

Richard Stevenson

Stevenson, a U.K.-based contributing editor, traveled to Imec, in Belgium, to report on research into alternate materials for transistor channels ["Changing the Channel," p. 30]. Having visited many semiconductor research labs, he was expecting low-slung buildings and a sprawling mess of equipment. But Imec's facility, which is designed to prove manufacturability, was nothing like that. "It was massive," Stevenson says, "decked out with huge, state-of-the-art equipment and clean rooms the size of football pitches. It felt just like a foundry."

Ozzie Zehner

The author of the book *Green Illusions*, Zehner was working for GM when it "killed" its EV1 electric car. A plug-in advocate at the time, he later realized that electrifying cars just trades one set of environmental problems for another. Now a visiting scholar at the University of California, Berkeley, Zehner has many friends in California's growing electric-car industry. "Some think I'm crazy and too persnickety," he says. Judge for yourself by reading "Unclean at Any Speed" [p. 36].

Remembrance of Everything Past

THE PURSUIT OF ENHANCED cognition—from sharper recall to more lucid reasoning—is now the greatest animating impulse behind innovative computer engineering. Across the world, clever designers are leveraging ever-expanding storage, processing power, and communications networks to build personalized encyclopedias that document all aspects of an individual's inner and outer lives. If the engineers have their way, every idea, memory, and feeling—the recorded consciousness of a single lifetime—will be stored in the cloud.

"What's in this for me?" you may ask. For starters, you might very well benefit from retracing your past steps at key junctures of your personal or professional life—perhaps experiencing the breakthrough insight that eluded you the first time around but that can help you the next time you arrive at a similar juncture. Even after you die, your digital files would confer a new kind of immortality that others could inherit, permitting them to traverse the associative trails that made up your life's work.

Engineers, too, stand to benefit. By tapping into the aggregated thoughts of billions of individuals, they could harness the wisdom of crowds, creating a "world brain" like the one imagined by H.G. Wells a century ago and by the big data promoters of today.

The documentation of everyday life will likely accelerate when Google introduces Google Glass, a video-recording device that's worn like a pair of glasses. Google says the wearer can periodically upload captured video into the cloud for permanent storage and editing. Wearers can produce daily highlight reels of their entire lives simply by speaking commands aloud.

"Information overload" once referred to the difficulty of absorbing intelligently the data produced by others. Now we face the peril of choking on our own. "Many of us no longer think clearly," insists Silicon Valley futurist Alex Soojung-Kim Pang, because of our compulsive attachment to the digital world. In a new book, *The Distraction Addiction* (Little, Brown and Co.), Pang argues that humans can kick their habit with the aid of engineers who create "contemplative" computing experiences that enable humans to "restore focus and concentration."

Alas, our distraction addiction could well worsen. In the future, while Google Glass and its inevitable copycats record the outer world, ever-cheaper sensors will chart our inner biological world. How will we make sense out of our personal biometrics when scientists can't even decide how much salt is bad for us? And what happens when our personal data get into the wrong hands? Soldiers and spies might read our lives as if they were books.

Nevertheless, we cannot turn back now, because improved cognition is essential. Like it or not, we are competing with increasingly accurate digital devices that can automatically recognize patterns and react (mostly) appropriately. Software robots can identify faces in the crowd, write news stories, change your address over the phone, and even read X-rays. The best way for people to remain in the loop is to increase the size of the data sets we're working with, which in theory will improve the quality of our reasoning and result in better decisions.

Keeping people at the center of our digital information systems is more important than ever. For instance, we can fight global terrorism by accurately identifying threatening individuals and tracking them through semiautomated satellite- and drone-based monitoring systems, which instantly compare new data against an inventory of person-specific signatures. But to manage these complex systems takes an enhanced human, with reduced capabilities for error, because mistakes can lead to the deaths of innocent people.

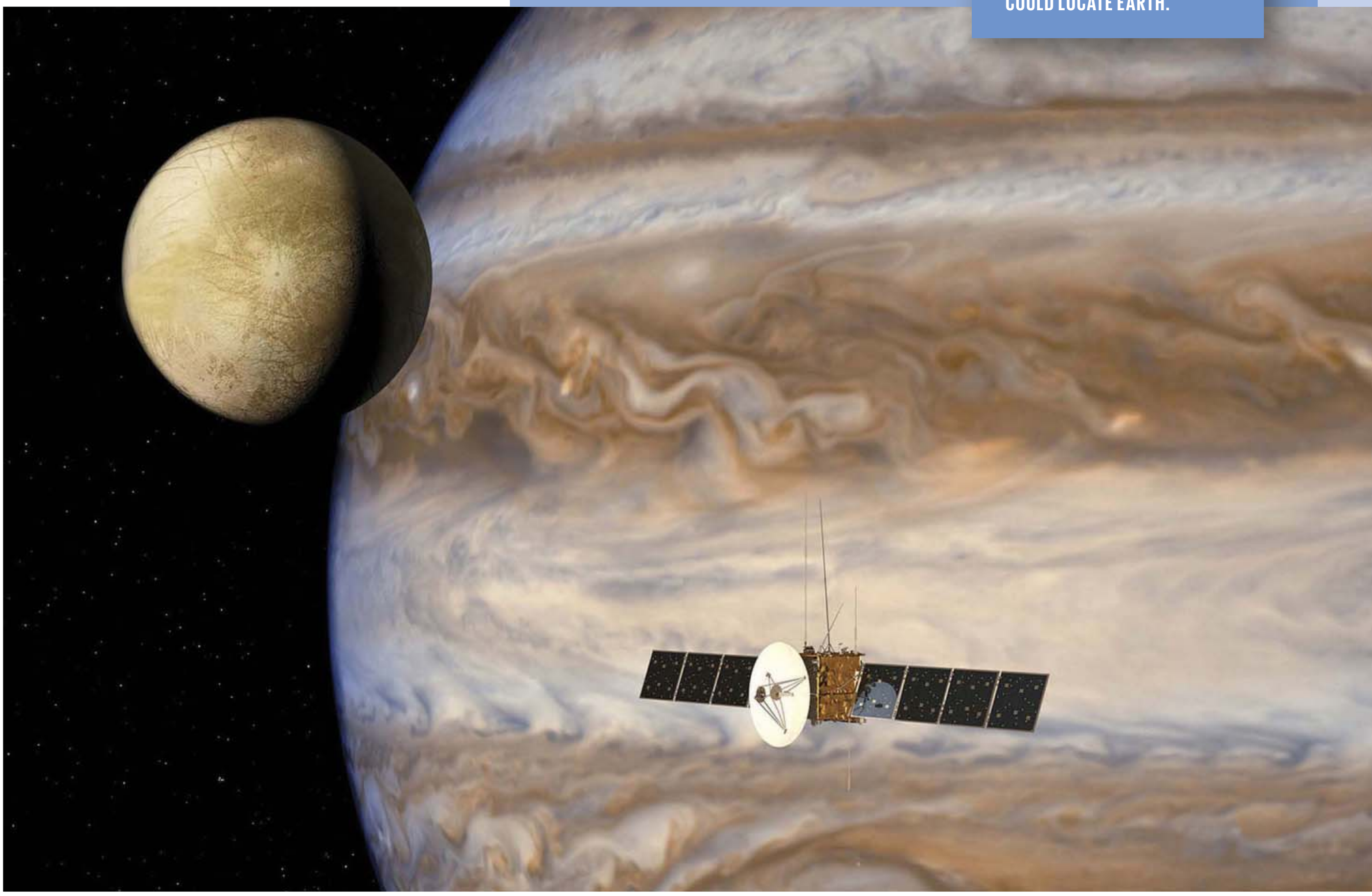
The rational hope for better decisions lies chiefly in better *detection*. Sleuthing is a peculiarly human endeavor that lends itself to engineering. Clues abound, and yet their meaning is often missed, or recognized and then forgotten. By remembering everything, we may become haunted by our pasts and immobilized by digital distractions—or we may gain new powers to prevent the bad and promote the good. —G. PASCAL ZACHARY

G. Pascal Zachary is a professor at Arizona State University's Consortium for Science, Policy & Outcomes.

ILLUSTRATION BY Greg Mably

NEWS

THE POSITION AND PERIOD OF 14 PULSARS WERE INCLUDED ON THE PIONEER 10 AND 11 SPACECRAFT SO THAT ALIENS COULD LOCATE EARTH.



NASA/ESA/AOES/REUTERS

INTERPLANETARY GPS COMES A STEP CLOSER

A ground simulator is constructed and a space-station test is planned

GALACTIC GPS: Interplanetary navigation systems are already being tested for future flights to other planets and beyond. The JUICE spacecraft [above] will have to get to Jupiter the old-fashioned way.

Humans have long used the light of stars to guide them toward their destinations. But in the age of extraterrestrial exploration, it could be the pulses of X-rays from dead stars that guide us through deep space. A NASA team recently built a critical system that will finally let them test such an "interplanetary GPS." A version of the system could be installed on the International Space Station (ISS) as early as 2017.

Pulsar navigation "will allow our descendants to accurately and autonomously navigate not only throughout the solar system but beyond it as well," says Jason Mitchell, an engineer at the Navigation and Mission Design branch of NASA's Goddard Space Flight Center, in Maryland, who helped develop the system. "And maybe in the future, when we're exploring space regularly, we won't need to rely on a gigantic, Earth-based infrastructure."

At present, space navigation relies primarily on a network of earthbound tracking stations. When a craft ventures into deep space, ground crews beam »

PULSAR-ON-A-TABLE: As it shoots X-rays into a detector, this critical system is testing interplanetary GPS that will help spacecraft navigate the solar system and beyond. Its proud parents at NASA include [back row, from left] Monther Hasouneh, John Gaebler, Harry Stello, Jennifer Valdez, and Sam Price, as well as [front row, from left] Jason Mitchell and Luke Winternitz.

NASA

radio waves out to it, which are then retransmitted back. By measuring the round trip time and the Doppler shift of the signal, the crews can calculate the spacecraft's position. But the further away the craft wanders from our planet, the poorer this method's resolution becomes. So it follows that if a space vehicle could calculate its own position independently and accurately, its navigational capabilities would improve by leaps and bounds.

The new system relies on a pulsar (a portmanteau of "pulsating star"), a peculiar type of neutron star that is technically dead. This extremely dense celestial zombie has exhausted its supply of nuclear fuel, yet it still spins rapidly, emitting a powerful beam of electromagnetic radiation. As a result of this spinning, the radiation that appears on Earth resembles the light from a whirling lighthouse beacon, alternately glowing and fading. These regular pulses of light and darkness produce precise, stable intervals that range from milliseconds to seconds and, like the atomic clocks in GPS satellites, can be utilized for high-accuracy navigation.

The easiest way to understand the pulsar navigation method, researchers say, is to compare it to the global positioning system. The GPS is a U.S.-owned constellation of 24 satellites that send signals to equipment on the ground. The satellites transmit both their position and a very precise time; the receiver can use this information plus the speed of light to figure its distance from a satellite. With data from four or more satellites, a typical GPS receiver can determine its location to within 15 meters.

Instead of using GPS satellite signals, a craft heading into space would carry a detector that would accept X-rays from multiple pulsars and use them to resolve its location. These detectors—called XNAV receivers—would sense X-ray photons in the pulsars' sweeping light. For each of four or more pulsars, the receiver would collect multiple X-ray photons and build a "light curve." The peak in each light curve would be tagged with a precise time. The timing of these peaks with respect to one another would change as you traveled through the solar system, drawing nearer to the source of some and farther from others. From this pattern of peaks, the spacecraft could calculate its position.

In order to test the system, the NASA team built the Goddard X-ray Navigation Laboratory Testbed (GXNLT). Nicknamed the "pulsar-on-a-table," it's composed of pulsar-processing software and hardware, a modulated X-ray source, and a built-in detector. With this test bed, the researchers try to mimic the combination of an interplanetary GPS and pulsars.

"We simulate the dynamics of a spacecraft in the computer, and we also simulate models of the pulsars based on how we set the trajectory of the spacecraft," says Luke Winternitz, a navigation engineer at Goddard.

After feeding the GXNLT a desired trajectory through space, the onboard computer looks up all the pulsars the imaginary spacecraft would encounter in flight. Then the test bed's modulated X-ray source generates the X-ray photons these pulsars would emit, and the detector receives and time-stamps them. "The photons emitted by the modulated X-ray source have the orbital information coded in the arrival time," explains Mitchell. The computer processes this information in real time and spits out an estimate of the spacecraft's position, which scientists can compare with their projections. Currently, ground tests show that the navigation system will be accurate within 1 kilometer in low earth orbit, but the aim is to pare this down to hundreds of meters, even in deep space.

The NASA team is especially interested in testing a particular trajectory: the course of the ISS through space. By 2017, an instrument equipped with X-ray navigation technology is set to fly aboard the space station.

"On a computer, it's easy to program in an orbit of the ISS, get your position as a function of time, and run a model," says Paul Ray, an astrophysicist at the Naval Research Laboratory in the Space Science Division. "What the GXNLT does is move this a step closer to reality. Rather than having it simulate some measurement, it really makes the measurement. Then we'll have high confidence that when we put it on the space station, it'll work as expected, and the software will be able to process the data and extract the navigation information." —DAVEY ALBA

A version of this article appeared online in June.

TIDEPOOL POWER MAKES A SURPRISING COMEBACK

Can a U.K. firm's novel plant design defuse environmental concerns?

PROPOSED SWANSEA TIDAL LAGOON

TURNING THE TIDE: A £650 million (US $1 billion) tidal power project would create a lagoon in Wales's Swansea Bay. Environmentalists are pleased.

Fifty years ago this July, Électricité de France began sealing off Normandy's La Rance estuary from the sea. After three years of work, the world's first large-scale tidal power plant was born. The station operates still, generating up to 240 megawatts of renewable power as the twice-daily tides force water in and out of the estuary through the hydroturbines seated within its 750-meter-long seawall.

But the three years of construction were tideless, which devastated La Rance's ecosystem, killing off nearly all of its marine flora and fauna; it would take another decade for the estuary to bounce back. Due in part to that ecological hangover, La Rance would remain the only tidal station of its scale for nearly five decades. Recently, however, capturing tidal energy using impoundments—reservoirs formed by dams—is making a comeback. In 2011 South Korean officials turned on a 254-MW "barrage" style plant akin to La Rance's, and further installations are in development in South Korea and elsewhere, including the United Kingdom and China.

Renewed interest in tidal impoundments is being driven by the global push for renewable energy. Tidal power is an especially attractive option given its predictability, and impoundments are proven technology. Whereas free-standing underwater turbines designed to capture tidal currents are still being tested at the megawatt scale, La Rance has delivered 500 to 600 gigawatt-hours annually since 1967, reliably generating power for more than 15 hours per day.

Of course, tidal stations also have a proven ecological impact even during operation. Tides get delayed as they flow through the turbines, altering currents and sea levels on both sides of the seawall.

South Korea's two-year-old tidal station was ecologically justified as a solution to a more severe problem. Its turbines were a retrofit for the 11-kilometer-long seawall whose completion in 1994 impounded a body of water in the northwest known as Lake Sihwa. After industrial effluent polluted the lake, the seawall was reopened to flush the pollution out. As a legal expert explained it several years ago, generating power while cleaning the lake enabled the government to—as Koreans say—"catch two pigeons with one bean."

Success, however, created an appetite for tidal projects in relatively pristine areas of South Korea. Contracts signed last year, for example, would put an 810-MW plant at Ganghwa Island, which abuts smaller islands where critically endangered black-faced spoonbill seabirds feed and breed. Yekang Ko, a professor of urban and public affairs at the University of Texas, says the plant could flood the spoonbill's habitat. Similar concerns surround a high-profile proposal in the U.K. to build a barrage across the Severn estuary in Wales.

In contrast, a 250-MW tidal plant proposed by Cheltenham, England-based Tidal Lagoon Power for Wales's Swansea Bay is—at least so far—conflict-free. As the firm's name implies, the plant's seawalls would create an artificial lagoon out in the bay rather than isolating an estuary. With just a relatively small link to the shore, the lagoon design should have limited impact on the most sensitive intertidal zones, says Gareth Clubb, Wales director for Friends of the Earth. "We've been strong supporters of the Swansea tidal lagoon and resolute opponents of the Severn barrage," says Clubb.

In fact, Clubb says, lagoon-style plants could buffer the U.K.'s Atlantic exposure against the rising seas and intensifying storms predicted by climate change modelers. And since tides arrive at different times along the coast, the ensemble would deliver a relatively steady flow of renewable power.

Ton Fijen, Tidal Lagoon Power's technical director, predicts that the cost per megawatt-hour of the Swansea project's power will be in line with the cost of onshore wind power—currently the cheapest source of renewable energy. If he is right, and environmentalists remain supportive, tidal power could really take off without taking the world's estuaries with it. —PETER FAIRLEY

NEWS

THE FLAT MENAGERIE

Graphene is getting some serious competition

"Flatland" has never looked so good. A little less than a decade ago, physicists showed they could pull away loosely bound layers of graphite to reveal graphene, a 2-D carbon structure. The material was shown to have very promising electronic properties. But graphene isn't the only game in town. A whole host of 2-D structures are attracting attention. Many can be formed just as graphene is, from layered 3-D materials; one such material, molybdenum disulfide, has been used in recent months to form flexible, transparent transistors and some of the basic building blocks of logic chips. Others are flattened forms of naturally 3-D structures. In April, for example, a team based at Ohio State University reported they had wrangled germanium, a mainstay of the semiconductor industry, into a 2-D structure that transports electrons faster than its 3-D counterpart does.

Rounded up here are some of the most promising materials on the 2-D scene. Some offer smaller and less power-hungry transistors that could be used for future logic and memory chips. Others could be ideal for computing with light and for other far-out applications. Some may work in concert with one another or with graphene, while others are direct competitors.

This list is by no means complete. It does not include, for example, a host of metal oxides that have shown a lot of potential as nanoscale electrical insulators. "People have been trying to figure out how many layered materials there are. A rough count would give you [more than] 100," says Jonathan Coleman, a physicist at Trinity College Dublin. "There is literally an abundance of these things, and we're only just scratching the surface."

—RACHEL COURTLAND

GRAPHENE (ATOMIC ELEMENT C)

First isolated in 2004, graphene is a single layer of carbon that boasts extraordinary properties. At low temperature, for example, electrons can zip through the material 100 times as fast as they do in silicon for a given voltage. Among 2-D materials, graphene manufacturing is the most mature. Chipmakers can now coat entire wafers with the stuff and have used those to construct speedy RF transistors. But making logic will be trickier. Silicon and other semiconductors have a bandgap, the energy barrier that atom-bound electrons must jump over to freely move around the material. Natural graphene has none, so there is no way to turn the current flow off in order to make a switch. There are ways to induce a small bandgap, such as by stacking one layer of graphene on top of another or by cutting the material into nanoribbons, but these approaches tend to reduce electron speed. But the promise of the material for electronics, optics, and energy storage was still enough for the European Commission to announce that it will pump as much as €1 billion into graphene R&D earlier this year.

BORON NITRIDE (BN)

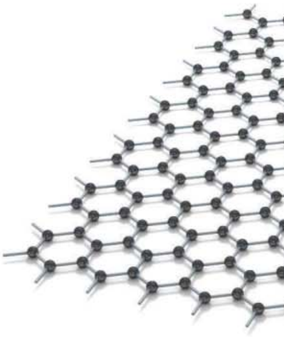
Conductors wouldn't be anywhere without insulators. That's where boron nitride comes in. Two-dimensional boron nitride—a mix of boron and nitrogen atoms that is commonly arranged in hexagonal form—is a semiconductor. But its bandgap is too big to be practical for switches, so the material is often tapped to function as an insulator in devices made from other 2-D materials. Researchers have demonstrated they can form a 2-D structure composed of alternating strips of graphene and boron nitride, which could potentially be stacked to form complex circuitry.

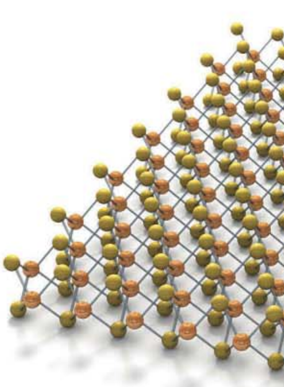
MOLYBDENUM DISULFIDE (MoS_2) AND COMPANY

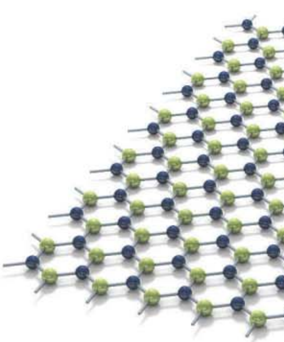
Layers made of molybdenum disulfide, a molecular mix of molybdenum and sulfur, have some advantages over both graphene and silicon. As a semiconductor, the material boasts a bandgap, making it a natural choice for logic. What's more, MoS_2's bandgap is "direct," which means that unlike silicon it can readily emit and absorb light. It would pay to watch this space. MoS_2 is just a fairly well-studied member of a larger group called transition metal dichalcogenides. This family, which also includes tungsten diselenide, consists of materials that combine one of 15 transition metals with one of three members of the chalcogen family: sulfur, selenium, or tellurium. So far, only a handful have been studied for their 2-D electronic properties.

SILICENE (Si) AND GERMANENE (Ge)

As exciting as materials like graphene may be, chipmakers would probably prefer a 2-D alternative that would allow them to continue using common semiconducting materials without fear of contaminating their fabs. Enter the 2-D versions of silicon and germanium: silicene and germanene. Versions of both materials were isolated in only the last two years, and research on them is just beginning. Other 2-D materials, such as graphene, can be readily pulled from bulk material that consists of a 3-D stack of loosely bound 2-D layers. But silicon and germanium don't come in that form; their atoms form tight bonds in all three dimensions. As a result, flattened versions of the materials tend to buckle, which can lead to inconsistent electronic properties.







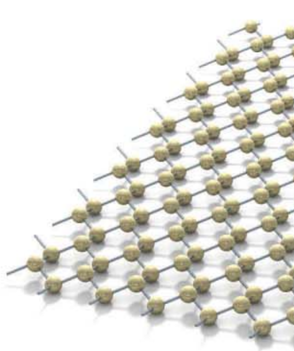
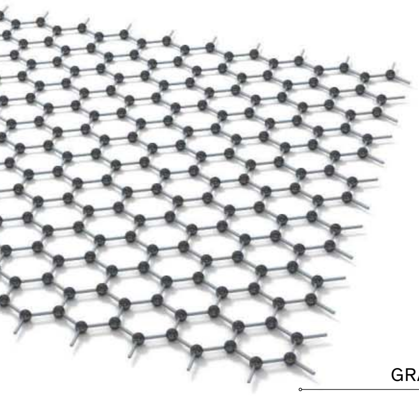
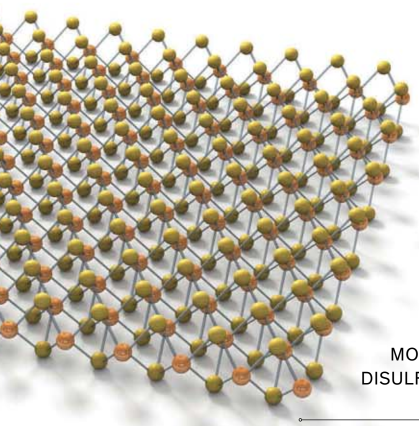


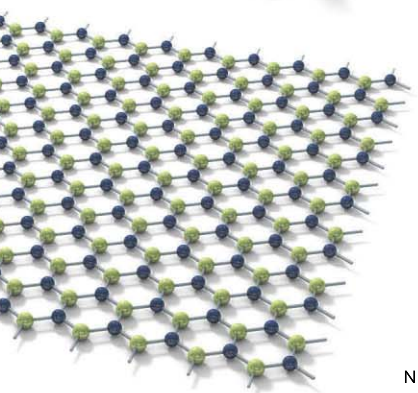
ILLUSTRATION BY Emily Cooper



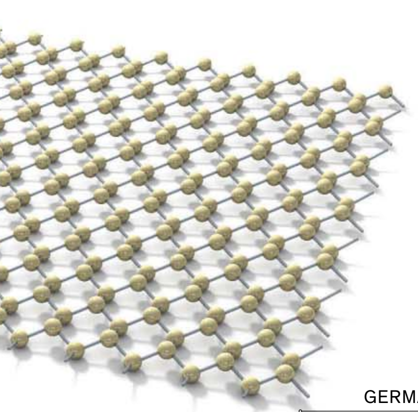
GRAPHENE (C)



MOLYBDENUM DISULFIDE [MoS_2]



BORON NITRIDE [BN]

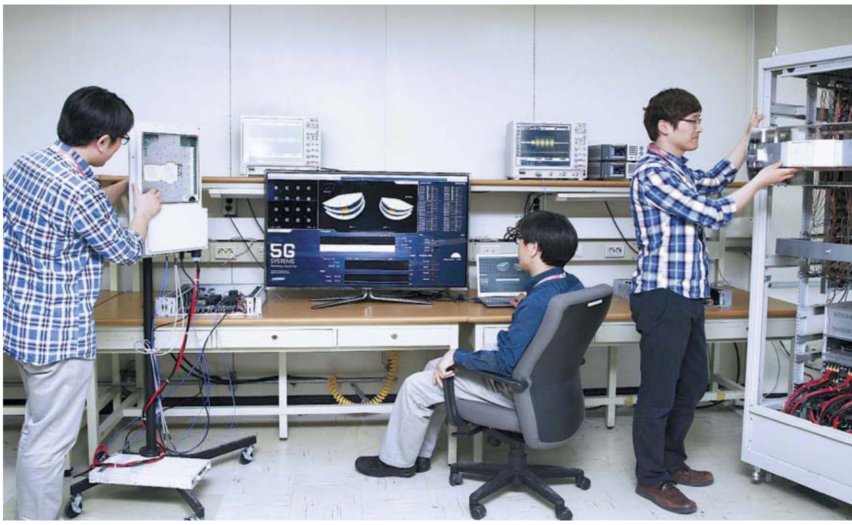


GERMANENE [Ge]

NEWS

THE 5G PHONE FUTURE

Samsung's millimeter-wave transceiver technology could enable ultrafast mobile broadband by 2020



BEYOND 4G: Samsung engineers [from left] Wongsuk Choi, Daeryong Lee, and Byunghwan Lee test next-generation cellular equipment at a lab in Suwon, South Korea.

Clothes, cars, trains, tractors, body sensors, and tracking tags. By the end of this decade, analysts say, 50 billion things such as these will connect to mobile networks. They'll consume 1000 times as much data as today's mobile gadgets, at rates 10 to 100 times as fast as existing networks can support. So as carriers rush to roll out 4G equipment, engineers are already beginning to define a fifth generation of wireless standards.

What will these "5G" technologies look like? It's too early to know for sure, but engineers at Samsung and at New York University say they're onto a promising solution. The South Korea-based electronics giant generated some buzz when it announced a new 5G beam-forming antenna that could send and receive mobile data faster than 1 gigabit per second over distances as great as 2 kilometers. Although the 5G label is premature, the technology could help pave the road to more-advanced mobile applications and faster data transfers.

Samsung's technology is appealing because it's designed to operate at or near "millimeter-wave" frequencies (3 to 300 gigahertz). Cellular networks have always occupied bands lower on the spectrum, where carrier waves tens of centimeters long (hundreds of megahertz) pass easily around obstacles and through the air. But this coveted spectrum is heavily used, making it difficult for operators to acquire more of it. Meanwhile, 4G networks have just about reached the theoretical limit on how many bits they can squeeze into a given amount of spectrum.

So some engineers have begun looking toward higher frequencies, where radio use is lighter. Engineers at Samsung estimate that government regulators could free as much as 100 GHz of millimeter-wave spectrum for mobile communications–

about 200 times what mobile networks use today. This glut of spectrum would allow for larger bandwidth channels and greater data speeds.

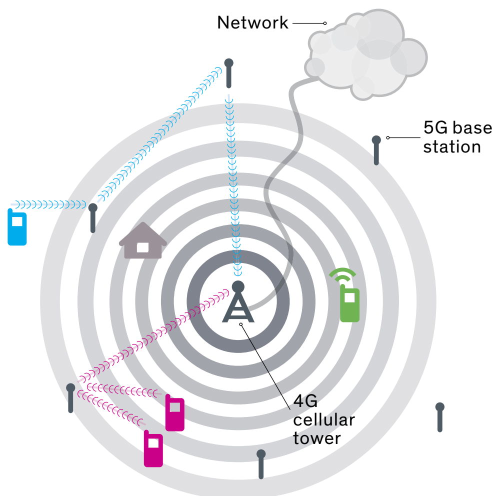
Wireless products that use millimeter waves already exist for fixed, line-of-sight transmissions. And a new indoor wireless standard known as WiGig will soon allow multigigabit data transfers between devices in the same room. But there are reasons engineers have long avoided millimeter waves for broader mobile coverage.

For one thing, these waves don't penetrate solid materials very well. They also tend to lose more energy than do lower frequencies over long distances, because they are readily absorbed or scattered by gases, rain, and foliage. And because a single millimeter-wave antenna has a small aperture, it needs more power to send and receive data than is practical for cellular systems.

Samsung's engineers say their technology can overcome these challenges by using an array of multiple antennas to concentrate radio energy in a narrow, directional beam, thereby increasing gain without upping transmission power. Such beam-forming arrays, long used for radar and space communications, are now being used in more diverse ways. The Intellectual Ventures spin-off Kymeta, for instance, is developing metamaterials-based arrays in an effort to bring high-speed satellite broadband to remote or mobile locations such as airplanes.

Samsung's current prototype is a matchbook-size array of 64 antenna elements connected to custom-built signal-processing components. By dynamically varying the signal phase at each antenna, this transceiver generates a beam just 10 degrees wide that it can switch rapidly in any direction, as if it were a hyperactive searchlight. To connect with one another, a base station and mobile radio would continually sweep their beams to search for the strongest connection, getting around obstructions by taking advantage of reflections.

"The transmitter and receiver work together to find the best beam path," says Farooq Khan, who heads Samsung's R&D center in Dallas. Khan and his colleagues Zhouyue Pi and Jianzhong Zhang filed the first patent describing a millimeter-wave mobile broadband system in 2010. Although the prototype revealed this year is designed to work at 28 GHz, the Samsung engineers say their approach could be applied to most frequencies between about 3 and 300 GHz. "Our technology is not limited to 28 GHz," Pi says. "In the end, where it can be deployed depends on spectrum availability."



5G BEAM SCHEME: Steerable millimeter-wave beams could enable multigigabit mobile connections. Phones at the edge of a 4G cell [blue] could use the beams to route signals around obstacles. Because the beams wouldn't overlap, phones could use the same frequencies [pink] without interference. Phones near the 4G tower could connect directly to it [green].

In outdoor experiments near Samsung's Advanced Communications Lab, in Suwon, South Korea, a prototype transmitter was able to send data at more than 1 Gb/s to two receivers moving up to 8 kilometers per hour—about the speed of a fast jog. Using transmission power "no higher than currently used in 4G base stations," the devices were able to connect up to 2 km away when in sight of one another, says Wonil Roh, who heads the Suwon lab. For non-line-of-sight connections, the range shrank to about 200 to 300 meters.

Theodore Rappaport, a wireless expert at the Polytechnic Institute of NYU, has achieved similar results for crowded urban spaces in New York City and Austin, Texas. His NYU Wireless lab, which has received funding from Samsung, is working to characterize the physical properties of millimeter-wave channels. In recent experiments, he and his students simulated beam-forming arrays using megaphone-like "horn" antennas to steer signals. After measuring path losses between two horn transceivers placed in various configurations, they concluded that a base station operating at 28 or 38 GHz could provide consistent signal coverage up to about 200 meters.

Millimeter-wave transceivers may not make useful replacements for current cellular base stations, which cover up to about a kilometer. But in the future, many base stations will likely be much smaller than today's, Rappaport points out. Already carriers are deploying compact base stations, known as small cells, in congested urban areas to expand data capacity. Not only could millimeter-wave technology add to that capacity, he says, it could also provide a simple, inexpensive alternative to backhaul cables, which link mobile base stations to operators' core networks.

"The beauty of millimeter waves is there's so much spectrum, we can now contemplate systems that use spectrum not only to connect base stations to mobile devices but also to link base stations to other base stations or back to the switch," Rappaport says. "We can imagine a whole new cellular architecture."

Other wireless experts remain skeptical that millimeter waves can be widely used for mobile broadband. "This is still theoretical; it has to be proven," says Afif Osseiran, a master researcher at Ericsson and project coordinator for the Mobile and wireless communication Enablers for the Twenty-twenty Information Society (METIS). The newly formed consortium of European companies and universities is working to identify the most promising 5G solutions by early 2015.

Osseiran says METIS is considering a variety of technologies, including new data coding and modulation techniques, better interference management, densely layered small cells, multihop networks, and advanced receiver designs. He emphasizes that a key characteristic of 5G networks will be the use of many diverse systems that must work together. "Millimeter-wave technology is only one part of a bigger pie," he says. —ARIEL BLEICHER

PREVIOUS PAGE: DMC R&D CENTER, SAMSUNG ELECTRONICS

ILLUSTRATION BY Erik Vrielink

PHOTOGRAPH BY Rick Wilking/Reuters

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BIONIC DOG

Naki'o—Hawaiian for "Puddles"—lost all four paws to frostbite when, as a pup, he got stuck in a frozen puddle inside an abandoned building. As he grew, walking on the stumps that remained became an increasingly painful ordeal. But he wasn't doomed by that inauspicious start. Christie Pace of Colorado Springs, the veterinary assistant who had adopted him, started raising money to get the dog proper treatment. Her goal was to get Naki'o a surgical amputation for a stump that wouldn't heal and a specially designed, biomechanically correct artificial limb with energy-storing hinges. After Pace paid for one prosthesis, OrthoPets V-OP Veterinary Clinic, in Denver, which had handcrafted the new paw, supplied three more free of charge.

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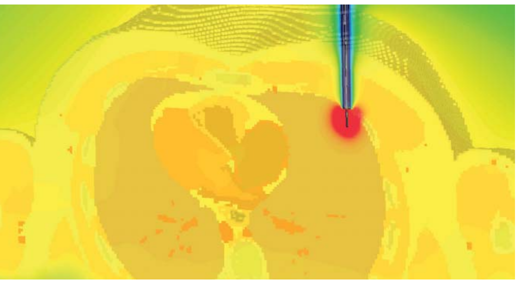


RESOURCES

THE GLOBAL MARKET FOR 3-D PRINTING HAS SEEN RAPID GROWTH; IT WAS WORTH US $2.2 BILLION IN 2012.

RESOURCES_PROFILE

BRE PETTIS MAKERBOT'S FOUNDER IS ON THE EDGE OF THE 3-D PRINTING REVOLUTION

JOE PUGLIESE/AUGUST

In 2008, perennial tinkerer Bre Pettis was toiling away in a warehouse-turned-hacker-space in New York City when he ran into a wall. He and a few friends were participating in the RepRap project, which aims to build a self-replicating device capable of printing all the components needed to duplicate itself. But Pettis and his friends couldn't make it work with the tools they had on hand. • The point of RepRap is to get 3-D printers diffused into communities around the world. "It's a holy grail for tinkerers," Pettis says, "the potential to be able to make anything." In the end he and his friends threw out the self-replication requirement and started from scratch, this time to see if they could at least make a cheap but functional 3-D printer. They soon realized they could. Consequently, MakerBot was founded in January 2009, with Pettis as CEO. ▸

In various forms, 3-D printing has been part of manufacturing for decades. Most 3-D printers apply material—often molten plastic—layer by layer to create prototypes or even finished parts. But these industrial machines tend to be expensive and large. Even a basic model can cost upwards of US $100 000 and be the size of a refrigerator, Pettis says, well out of reach for hobbyists.

With some angel investing, Pettis and his friends introduced MakerBot Industries' first printer kit in March 2009. The tabletop device could make small structures out of plastic—or pretty much any material that could be made to flow steadily through a nozzle onto a moving platform. "We created a tool head for the machine [we] called a frostruder, which was an extruder for frosting," says Pettis. "It worked really well with Nutella." The kits started selling briskly. What started as a small hacking project has ballooned over the past four years into a small empire, fed in part by Pettis's energetic media presence and his plethora of photogenic printed plastic gewgaws.

Pettis now oversees more than 250 employees at MakerBot's New York City headquarters and production facility. The company has shipped nearly 20 000 printers (now as finished units instead of kits), and in November 2012, it opened its first retail store. Earlier this year, Pettis debuted a 3-D laser scanner that could be used to map physical objects, creating a digital model suitable for printing. That's in addition to the company's website, Thingiverse.com, a compendium of user-submitted files that has expanded to include more than 80 000 designs for 3-D printed objects.

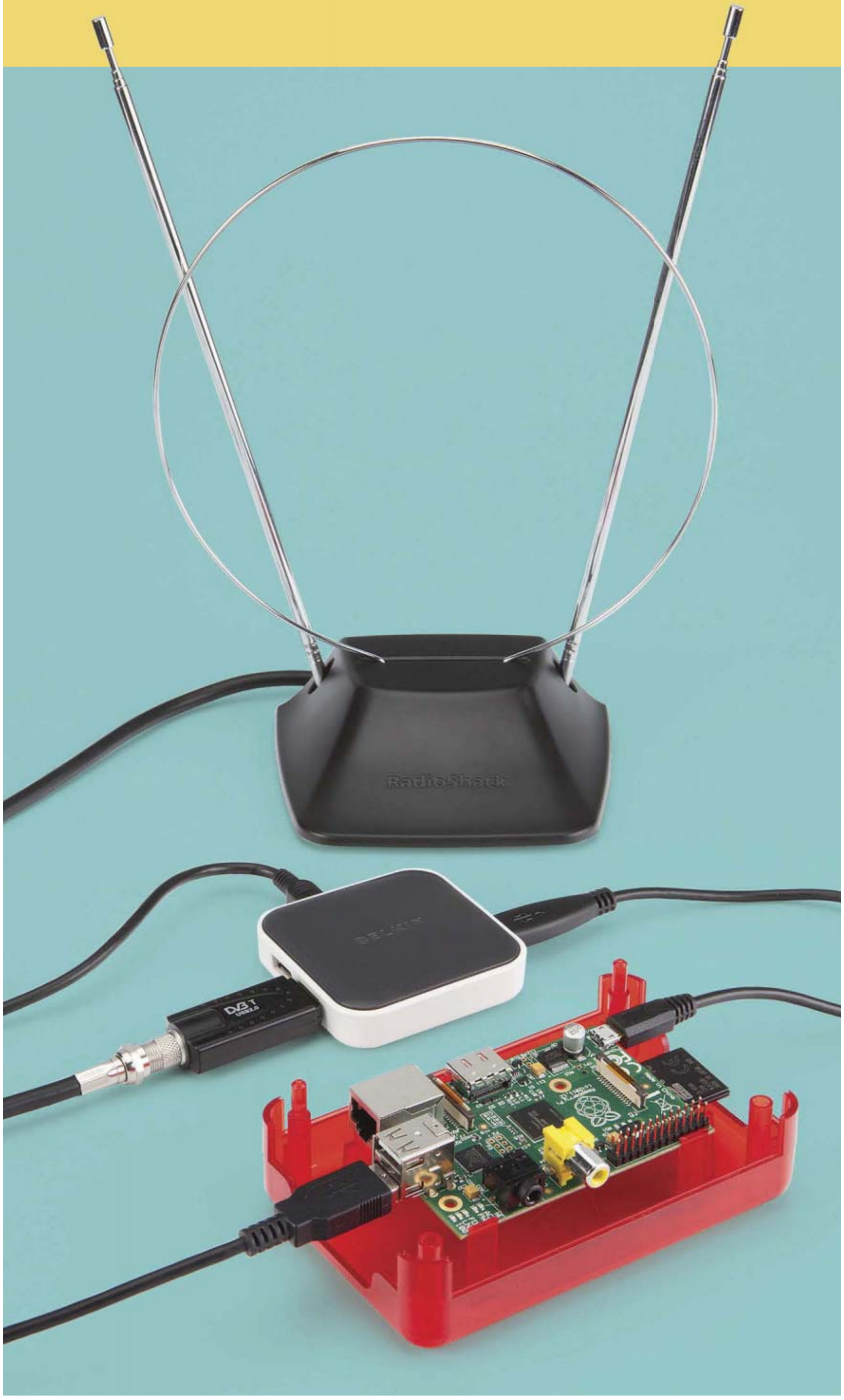
Pettis got his start as an art teacher in Seattle before leaving to make how-to videos for *Make* magazine and the craft-selling site Etsy. He sees few limits to the market for 3-D printers. In 5 years, he says, you'll know someone who has a 3-D printer; in 10, you'll likely have access to one—if not in your home, then at the local library.

The increasing availability of 3-D printers has already turned up some surprises. In May, for example, a project called Robohand uploaded designs to the Thingiverse for 3-D printed fingers, which could be used to build inexpensive but functional pulley-driven prosthetics. "We're going to see all sorts of superinteresting things happen as the technology shifts from being something just for the elite to something that's the price of a laptop," Pettis says.

—RACHEL COURTLAND

A $40 SOFTWARE-DEFINED RADIO

A REPURPOSED TV TUNER CAN REVEAL A WIDE SWATH OF SPECTRUM



PHOTOGRAPH BY NICHOLAS EVELEIGH

T

The last time I ventured into the waters of software-defined radio (SDR) was seven years ago, when I reviewed Matt Ettus's Universal Software Radio Peripheral. While it's an excellent product, the basic motherboard at the time cost US $550; daughterboards for different frequency ranges cost $75 to $275 [see "Hardware for Your Software Radio," *IEEE Spectrum*, October 2006]. And I spent more than a few frustrating hours compiling the needed software on my MacBook Pro. This time I was able to get my feet wet for about $40—and the software took about 2 minutes to download, install, and run.

This minor miracle was made possible by Finnish engineering student and Linux developer Antti Palosaari. Last year, he discovered an unexpected feature of the RTL2832U demodulator chip made by Taiwan's Realtek: Intended for decoding European HDTV broadcasts in inexpensive USB dongle-type receivers, the RTL2832U chip can also output a raw digital stream describing the amplitude and phase (so-called I/Q data) of signals over a wide range of frequencies.

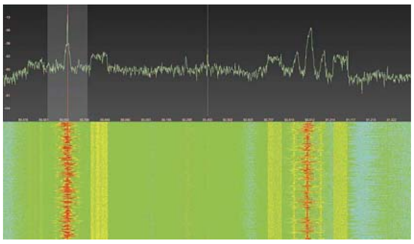
Digital radio enthusiasts immediately began adapting open-source tools that can translate I/Q information into audio and data streams. The result is a low-cost SDR that can pick up a huge variety of transmissions with different modulation schemes, including stereo FM from broadcasters, digital data packets from aircraft transponders, and suppressed-sideband (SSB) dispatches from amateur radio operators. Of course, the system isn't as sensitive as purpose-built SDRs and is incapable of transmitting a signal, but it's enough to see what's going on across a huge chunk of spectrum.

Different receiver dongles pair the RTL2832U with different radio tuners, so the exact range of frequencies that can be received varies. I purchased a Freeview P250 dongle from a Chinese supplier on Amazon.com for $20, which included shipping. The P250 combines the RTL2832U with an Elonics E4000 tuner, allowing it to pick up signals from about 52 megahertz to 2.2 gigahertz, with a gap from about 1.1 to 1.25 GHz.

A small antenna came with the receiver, but I replaced it with a set of $15 rabbit ears from RadioShack. An adapter to connect the rabbit ears' U.S. coaxial cable to the dongle's European socket cost a couple of dollars.

To use the receiver with my MacBook Pro, I downloaded Elias Önal's port of the Gqrx software receiver. Önal's port is precompiled for OS X, so installation was simply a matter of downloading it to my hard disk. The application automatically detected my receiver, and I was off.

Gqrx centers on an oscilloscope-like display, showing a slice of the radio spectrum (along with a waterfall-type display beneath that tracks the last 30 seconds or so). Gqrx allows you to set how wide the slice should be, from 1 to 2.4 MHz. You select the frequency that's passed to the software demodulator by clicking the mouse on that frequency in the oscilloscope display. Demodulation modes include AM, narrowband FM, mono and stereo FM, SSB, and continuous wave (used for Morse code).



WATCHING RADIO: This screenshot from Gqrx shows two FM stations. The central spikes are the analog stereo broadcast, while the squared-off signals on either side are digital radio transmissions. You can tune in and listen to a station by clicking on its center frequency. The gray stripe indicates the bandwidth of the user-selected software demodulator.

Because the receiver can see so much spectrum at once, you can use it to monitor activity on many channels simultaneously. For example, in Boston, where I live, there are 17 narrowband-FM police channels between 460.025 and 460.500 MHz, covering various districts, et cetera. A spike on the display shows when any of those channels is in use, and a click of the mouse has its audio playing over my speakers.

Which brings us to regulatory issues. In some countries, it's illegal to receive any frequency you don't have a license for, apart from public broadcast frequencies. In the United States, you're free to pick up nearly all the signals you can receive. There are, however, important exceptions to this general rule, such as a ban on listening to cellphone frequencies, or operating equipment capable of picking up police signals while you're in a vehicle (the latter is permitted with a ham license).

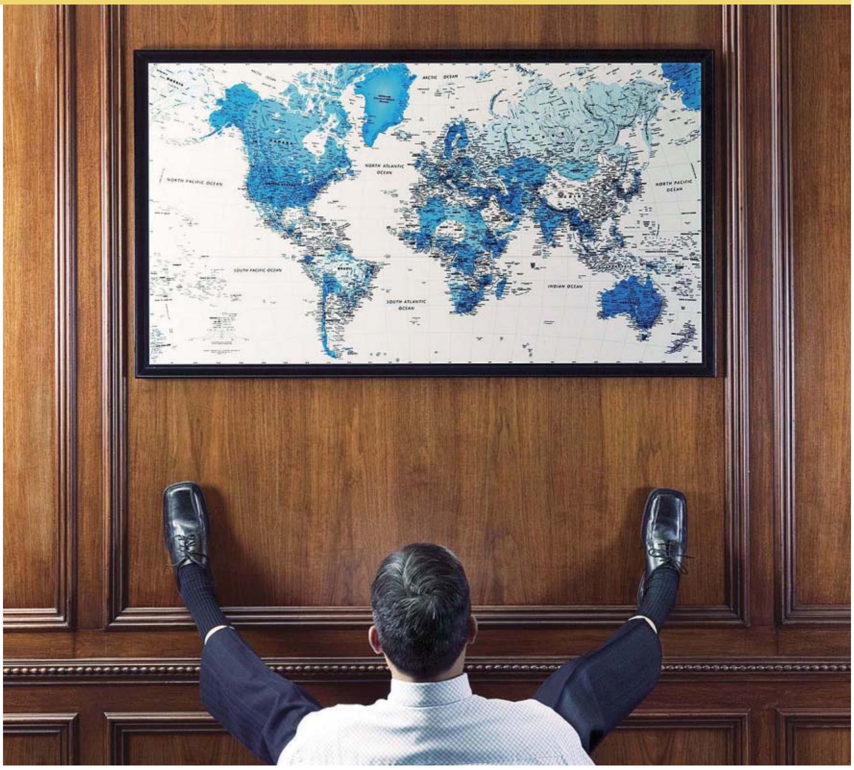
I soon discovered that having the dongle and TV antenna attached to my laptop is cumbersome, and besides, my home office doesn't always get great reception. So I spent another $35 and purchased a Model B Raspberry Pi microcontroller [see "The Gift Guide: Basic Bytes," *Spectrum*, December 2012].

The Raspberry Pi is an ARM-based, Ethernet-capable microcontroller with USB connectors that can run a number of variants of Linux. Following instructions on the Ham Radio Science website (http://www.hamradioscience.com), I was able to download and compile some support software to use the Pi with the dongle (connected via a powered USB hub) in about 30 minutes. In turn, I connected the Pi to the home network hub in my front room via an Ethernet cable. Using the Pi lets me place the receiver farther away from local radio sources (such as my hub's Wi-Fi transmitter) and also allows multiple machines to access the receiver easily; the Pi acts as a centralized SDR server, thanks to a command-line utility called rtl_tcp.

With the Pi running, I was able to call up Gqrx on my Wi-Fi-connected MacBook, feed it the Pi's network address, and then control and decode signals as if the tuner were plugged directly into the laptop. (Admittedly, this represents a degree of engineering overkill when it comes to listening to a local FM station.)

Now that I've got the basic system up and running, I'd like to extend the bottom of my receiver's range to longer wavelength bands, such as the popular amateur 20-meter band between 14.00 and 14.35 MHz. This will require either modifying the dongle or buying or building a frequency converter. But either approach will be pointless unless I swap my rabbit ears for a long-wavelength antenna, which is a whole other kettle of home-brew fish. —STEPHEN CASS

WHERE THE JOBS ARE: 2013
OPPORTUNITIES ARE OPENING UP IN MANUFACTURING



DENNIS GALANTE/CORBIS

Four years after the peak of the financial crisis, the engineering profession continues to rebuild itself. The job growth rate might be modest compared to prerecession numbers, but hiring is increasing, salaries are up, and long-term job prospects look good, most notably in the United States but also in the BRIC countries—Brazil, Russia, India, and China.

Not surprisingly, electrical and computer engineers are still generally in demand at high-tech companies, consulting and finance firms, research institutions, and in government. According to the U.S. Bureau of Labor Statistics, the unemployment rate in the United States for electrical engineers and computer engineers at the end of 2012 was 3.3 percent and 2.8 percent, respectively, compared to the general rate of 3.9 percent for people with bachelor's degrees. (However, there was a sharp spike—to 6.5 percent—in unemployment in the first quarter of this year for U.S. electrical engineers, although still lower than the record-setting level of 8.6 percent in 2009.)

The return of some manufacturing to the United States brought with it high-paying jobs. For newly minted computer engineers hired in manufacturing, the average starting salary was US $74 900 and for aerospace engineers, $70 700, according to an April 2013 salary survey conducted by the National Association of Colleges and Employers (NACE), based in Bethlehem, Pa.

"Automotive jobs that were lost a few years ago are making a comeback," says Richard Zambacca, president of Randstad Engineering, a national technical recruiting firm headquartered in Norcross, Ga. "But there are also jobs for engineers in peripheral companies that support the auto industry."

Zambacca also points to high demand for RF engineers in telecommunications. And electrical engineers should consider that the natural gas boom in the United States has created tens of thousands of jobs, while an aging workforce means that the power industry is desperate for fresh talent, he says.

Hot-button areas like big data and online education are creating demand for information technologists. "Computer science grads are highly sought this year," says Beverly Principal, associate director of employment services at Stanford University. "Pretty much all sectors need candidates with strong programming and Web-building skills, whether it's nonprofit, high tech, or education."

Software developers boast significantly higher salaries than those of other computer science and engineering occupations, and most jobs since the recession have been created for software developers: Since 2010, 70 872 jobs have been added, a growth of 7 percent.

Hiring in the BRIC countries is forecast to be significantly higher than in other regions, according to CareerBuilder's global job forecast. Two-thirds of employers in Brazil and India have listed information technology as one of the top three areas for new hires. The survey also found that employers in the United Kingdom, Germany, Russia, and Japan are having difficulty finding skilled talent to fill engineering and information technology positions.

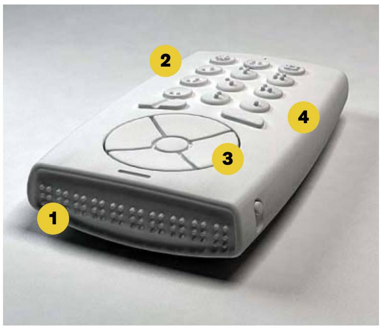
In the U.K., strong automotive, renewable energy, and aerospace sectors keep engineers employed, says Paul Jackson, the chief executive of the nonprofit EngineeringUK. In addition, he says, Europe's rail system is going through dramatic changes and relying on more electrical and electronic control systems, thereby creating tech jobs. Electronics engineers in the U.K. earn more than $70 600 on average, and electrical engineers earn more than $69 000.

Between 2010 and 2020, British engineering companies are expected to have 865 100 job openings for those with engineering diplomas and degrees, a per-year average of 87 000. "Now we just need to attract more young people to the field," says Jackson. —PRACHI PATEL

RESOURCES_FIRST LOOK

INSIDE THE WORLD'S FIRST BRAILLE CELLPHONE

BRINGING SMARTPHONE CAPABILITIES TO INDIA'S BLIND

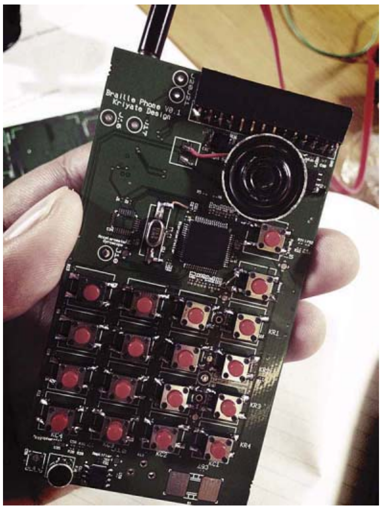


1 **THE PHONE CAN PRESENT** up to 10 braille characters at a time. Many visually impaired users in developed countries enjoy access to smartphones via voice-based systems such as Apple's VoiceOver. But in India, regional dialects and accents can make Western screen readers nearly useless, and braille remains the standard for accessibility for much of the developing world's blind population.

2 **THE NUMERICAL KEYPAD** has braille markings for each of the numbers. Users can enter braille letters, which are formed from a three-by-two grid, by pressing six keys on the keypad in the shape of each letter.

3 **A SIMPLE AND UNCLUTTERED DESIGN** is especially significant for this phone's users, Dagar says. "It has bigger buttons and more reference lines," he says, and "a bigger volume rocker on the side that makes it easier to identify."

4 **THE FIRST-GENERATION** braille phone will have some typical smartphone features such as a music player, an e-mail client, a calendar, and even GPS navigation. But because the CPU has to power only a 10-character display, it doesn't need to be a typical smartphone CPU, keeping the (yet to be announced) price low. "Anybody who can afford a phone can afford this phone," Dagar says.



CLOCKWISE FROM LEFT: ROLEX/AMBROISE TÉZENAS; DINUDEY BAIDYA; RAVI BAGREE

AROUND THE WORLD, 285 MILLION PEOPLE ARE BLIND OR visually impaired; over a fifth of them, or nearly 63 million, live in India. Entrepreneur Sumit Dagar wants to be their Alexander Graham Bell: Sometime in the next 12 months he'll be rolling out the world's first braille cellphone. His company, Kriyate, has drawn up the first prototype, pictured here. Dagar says that test users found it difficult to imagine dynamic braille on such a small device. "But once they comprehend it, the joy is so immense. That's what makes us most happy." On the drawing board are plans for an even more advanced phone with a camera that can translate text to braille and images to raised relief figures on the device's "display." —MARK ANDERSON

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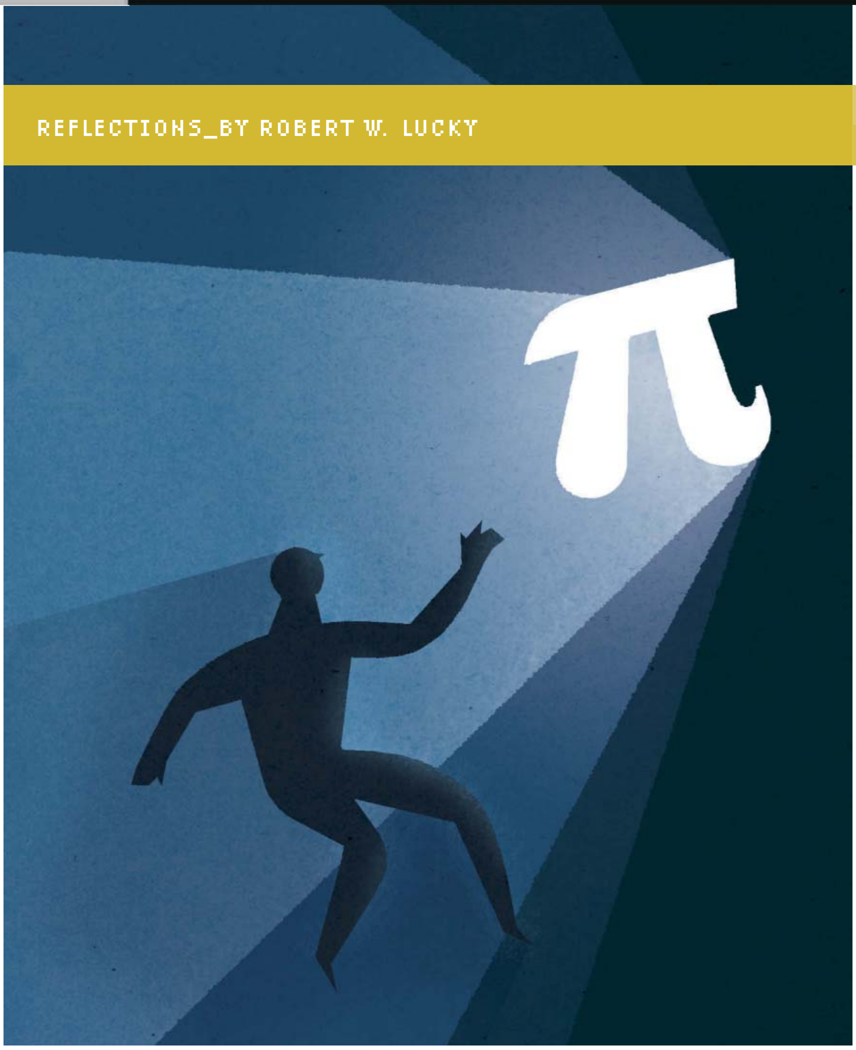
REFLECTIONS_BY ROBERT W. LUCKY

OPINION



ALL OF LIFE IN PI?

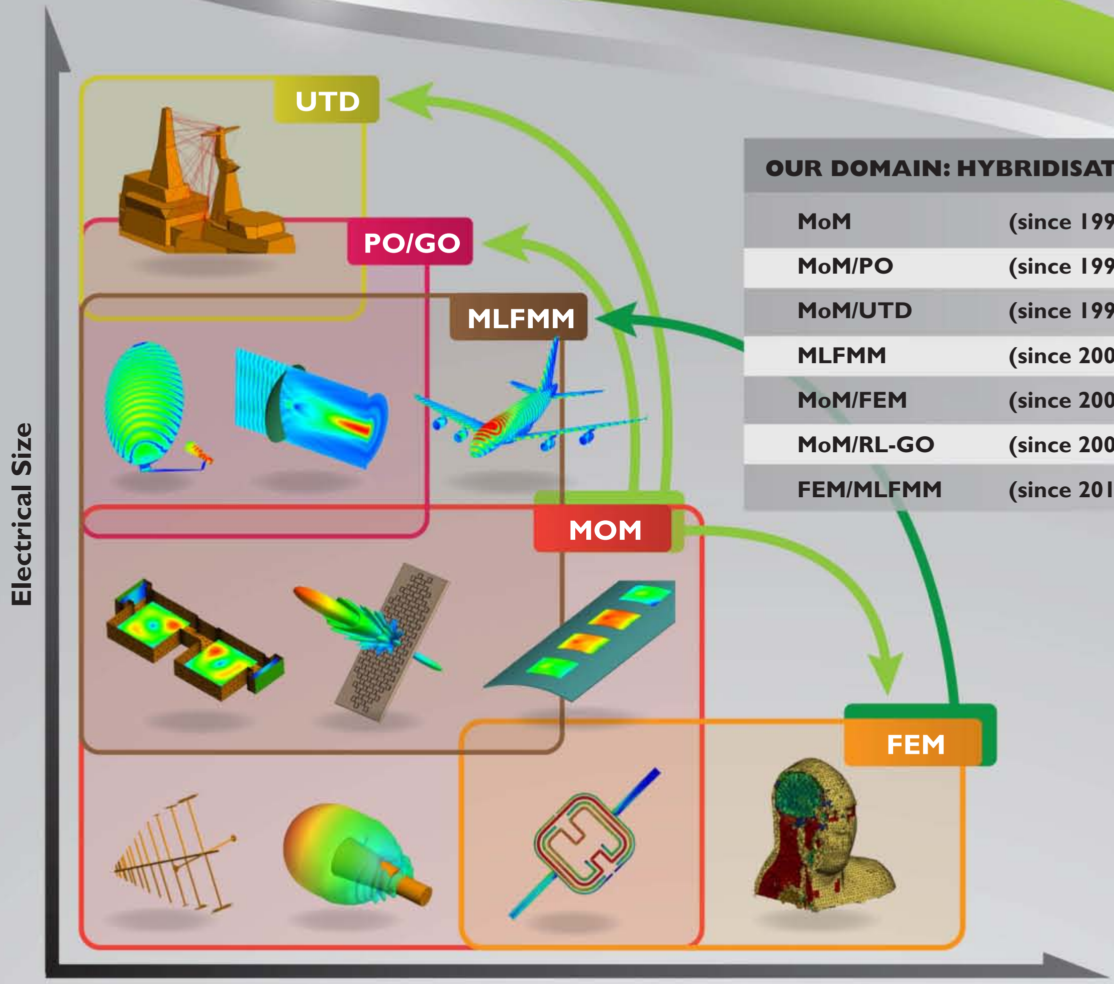
MANY YEARS AGO, WHILE HAVING DINNER WITH AN eminent mathematician, I mentioned a scene regarding the number pi in Carl Sagan's novel, *Contact*. A scientist from Earth (Jodie Foster in the movie) visits a distant planet and learns that the aliens there have calculated pi out to many places. Very far out in the number's expansion the decimal digits turn to a very long string of ones and zeros–a message embedded in pi. • "How can you hide a message inside pi?" asks Foster's character. "It's built into the fabric of the universe. And what does the message say?" • "We don't know. We're still working on it," replies the alien. • This scene made an impression on me. What if there *were* a message in pi? It is an almost mystical number, appearing in many fundamental equations that describe physical reality, including Einstein's theory of general relativity. • But my dinner companion stopped chewing for only a moment. "Well, of course," he said. "It's an irrational number and contains all possible sequences." • "Well, duh," I thought. Feeling stupid–more stupid than necessary, it turns out–I changed the topic of conversation. • I had occasion to remember this exchange recently when there was an outpouring of discussion on Facebook following the posting of a photo showing several thousand digits of pi in a faint background and, in the foreground, the following text: "Pi is an infinite, nonrepeating decimal–meaning that every possible number combination exists somewhere in pi. Somewhere in that infinite string of digits is the name of every person you will love, the date, time, and manner of your death, and the answers to all the great questions of the universe." From a sampling of the thousands of comments and blogs that this posting stimulated, I was made aware of one surprising fact I wish I'd known during that dinner so long ago. It is not true that because pi is an irrational number–a nonrepeating infinite decimal–it therefore contains all possible number combinations. Oh, it almost certainly does, but this has never been proved mathematically. There are examples of irrational numbers that do not contain all possible sequences. The so-called normal numbers do contain all sequences in the same statistical frequencies as true random numbers, but it is not known if pi is normal. It has, however, passed tests for statistical randomness out to many places, and because virtually all numbers are normal anyway, we can assume pi is also.

But is all of life written in pi? No. There is nothing there. For every fact you might find, you would also find the exact opposite. For every name of someone you might love, there would be countless other names. Claude Shannon would tell us that a sequence of random numbers contains no information, which he describes as "the removal of uncertainty." No uncertainty is removed through perusal of the digits of pi.

Moreover, the finding of any specific text is so statistically improbable that I would move it into the "impossible" category, like the old story about monkeys typing Shakespeare. To simply find your own name, for example, might require 15 ASCII characters, which would equate to 36 decimal digits. I haven't worked out the number of digits you'd need to search to have a reasonable probability of finding a run of 36 correct decimals, but I believe it would be far more than the current record for expansion of pi, which is 10^{13} digits.

Still, if we expanded pi out a few more places and a message appeared, that would be scary. Something to think about. ■

ILLUSTRATION BY Jesse Lefkowitz



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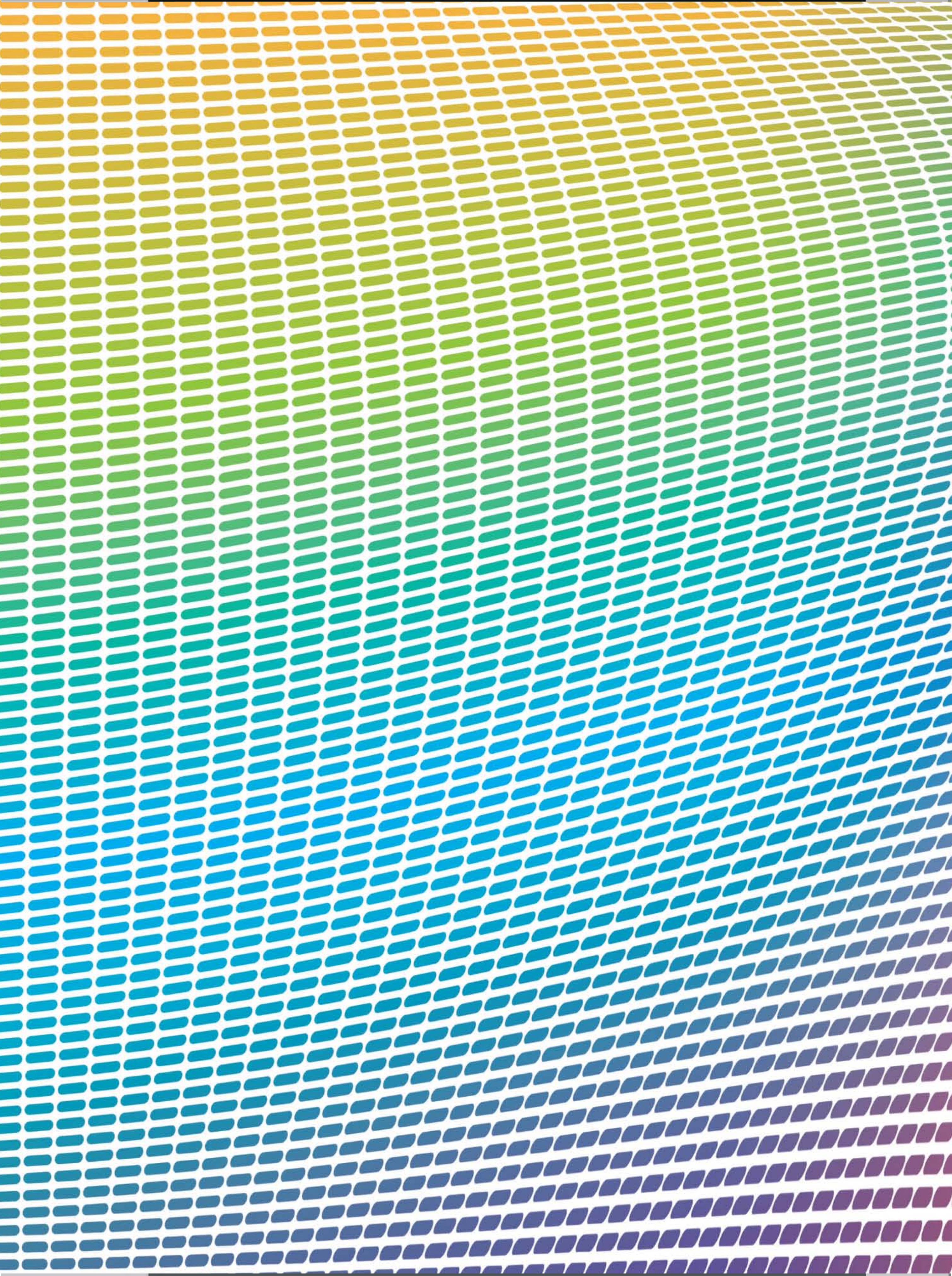

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THE DNA DATA DELUGE

FAST, EFFICIENT GENOME-SEQUENCING MACHINES ARE SPEWING OUT MORE DATA THAN GENETICISTS CAN ANALYZE

BY MICHAEL C. SCHATZ & BEN LANGMEAD
ILLUSTRATION BY CARL DeTORRES

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IN JUNE 2000, A PRESS CONFERENCE WAS HELD IN THE WHITE HOUSE TO ANNOUNCE AN EXTRAORDINARY FEAT: THE COMPLETION OF A DRAFT OF THE HUMAN GENOME.

For the first time, researchers had read all 3 billion of the chemical "letters" that make up a human DNA molecule, which would allow geneticists to investigate how that chemical sequence codes for a human being. In his remarks, President Bill Clinton recalled the moment nearly 50 years prior when Francis Crick and James Watson first discovered the double-helix structure of DNA. "How far we have come since that day," Clinton said.

But the president's comment applies equally well to what has happened in the ensuing years. In little more than a decade, the cost of sequencing one human genome has dropped from hundreds of millions of dollars to just a few thousand dollars. Instead of taking years to sequence a single human genome, it now takes about 10 days to sequence a half dozen at a time using a high-capacity sequencing machine. Scientists have built rich catalogs of genomes from people around the world and have studied the genomes of individuals suffering from diseases; they are also making inventories of the genomes of microbes, plants, and animals. Sequencing is no longer something only wealthy companies and international consortia can afford to do. Now, thousands of benchtop sequencers sit in laboratories and hospitals across the globe.

DNA sequencing is on the path to becoming an everyday tool in life-science research and medicine. Institutions such as the Mayo Clinic and the New York Genome Center are beginning to sequence patients' genomes in order to customize care according to their genetics. For example, sequencing can be used in the diagnosis and treatment of cancer, because the pattern of genetic abnormalities in a tumor can suggest a particular course of action, such as a certain chemotherapy drug and the appropriate dose. Many doctors hope that this kind of personalized medicine will lead to substantially improved outcomes and lower health-care costs.

But while much of the attention is focused on sequencing, that's just the first step. A DNA sequencer doesn't produce a complete genome that researchers can read like a book, nor does it highlight the most important stretches of the vast sequence. Instead, it generates something like an enormous stack of shredded newspapers, without any organization of the fragments. The stack is far too large to deal with manually, so the problem of sifting through all the fragments is delegated to computer programs. A sequencer, like a computer, is useless without software.

But there's the catch. As sequencing machines improve and appear in more laboratories, the total computing burden is growing. It's a problem that threatens to hold back this revolutionary technology. Computing, not sequencing, is now the slower and more costly aspect of genomics research. Consider this: Between 2008 and 2013, the performance of a single DNA sequencer increased about three- to fivefold *per year*. Using Moore's Law as a benchmark, we might estimate that computer processors basically doubled in speed every *two years* over that same period. Sequencers are improving at a faster rate than computers are. Something must be done now, or else we'll need to put vital research on hold while the necessary computational techniques catch up—or are invented.

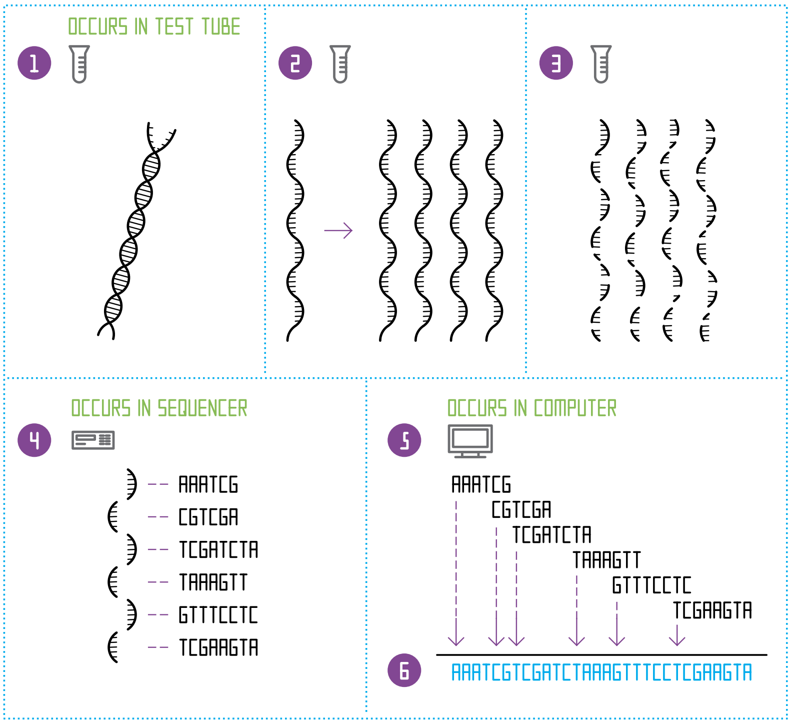
How can we help scientists and doctors cope with the onslaught of data? This is a hot question among researchers in computational genomics, and there is no definitive answer yet. What is clear is that it will involve both better algorithms and a renewed focus on such "big data" approaches as parallelization, distributed data storage, fault tolerance, and economies of scale. In our own research, we've adapted tools and techniques used in text compression to create algorithms that can better package reams of genomic data. And to search through that information, we've borrowed a cloud computing model from companies that know their way around big data—companies like Google, Amazon.com, and Facebook.

THINK OF A DNA MOLECULE as a string of beads. Each bead is one of four different nucleotides: adenine, thymine, cytosine, or guanine, which biologists refer to by the letters A, T, C, and G. Strings of these nucleotides encode the building instructions and control switches for proteins and other molecules that do the work of maintaining life. A specific string of nucleotides that encodes the instructions for a single protein is called a gene. Your body has about 22 000 genes that collectively determine your genetic makeup—including your eye color, body structure, susceptibility to diseases, and even some aspects of your personality.

Thus, many of an organism's traits, abilities, and vulnerabilities hinge on the exact sequence of letters that make up the organism's DNA molecule. For instance, if we know your unique DNA sequence, we can look up information about what diseases you're predisposed to, or how you will respond to certain medicines.

DE NOVO SEQUENCING

To sequence a species' genome for the first time, the double-stranded DNA molecule is first split down the middle [**1**]. This creates a single-stranded template. The template is copied many times [**2**]. All the templates are then diced up at random, to create many small fragments of different lengths [**3**]. A sequencing machine determines the order of nucleotides on each of those short fragments [**4**]. Then a software program looks for the places where the sequences of letters overlap and constructs an "assembly graph" [**5**]. Finally, the program constructs one continuous sequence of letters: the genome [**6**].



The Human Genome Project's goal was to sequence the 3 billion letters that make up the genome of a human being. Because humans are more than 99 percent genetically identical, this first genome has been used as a "reference" to guide future analyses. A larger, ongoing project is the 1000 Genomes Project, aimed at compiling a more comprehensive picture of how genomes vary among individuals and ethnic groups. For the U.S. National Institutes of Health's Cancer Genome Atlas, researchers are sequencing samples from more than 20 different types of tumors to study how the mutated genomes present in cancer cells differ from normal genomes, and how they vary among different types of cancer.

Ideally, a DNA sequencer would simply take a biological sample and churn out, in order, the complete nucleotide sequence of the DNA molecule contained therein. At the moment, though, no sequencing technology is capable of this. Instead, modern sequencers produce a vast number of short strings of letters from the DNA. Each string is called a sequencing read, or "read" for short. A modern sequencer produces reads that are a few hundred or perhaps a few thousand nucleotides long.

The aggregate of the millions of reads generated by the sequencer covers the person's entire genome many times over. For example, the HiSeq 2000 machine, made by the San Diego–based biotech company Illumina, is one of the most powerful sequencers available. It can sequence roughly 600 billion nucleotides in about a week—in the form of 6 billion reads of 100 nucleotides each. For comparison, an entire human genome contains 3 billion nucleotides. And the human genome isn't a particularly long one—a pine tree genome has 24 billion nucleotides.

Thus our first daunting task upon receiving the reads is to stitch them together into longer, more interpretable units, such as genes. For a organism that has never been fully sequenced before, like the pine tree, it's a massive challenge to assemble the genome from scratch, or de novo.

How can we assemble a genome for the first time if we have no knowledge of what the finished product should look like? Imagine taking 100 copies of the Charles Dickens novel *A Tale of Two Cities* and dropping them all into a paper shredder, yielding a huge number of snippets the size of fortune-cookie slips. The first step to reassembling the novel would be to find snippets that overlap: "It was the best" and "the best of times," for example. A de novo assembly algorithm for DNA data does something analogous. It finds reads whose sequences "overlap" and records those overlaps in a huge diagram called an assembly graph. For a large genome, this graph can occupy many terabytes of RAM, and completing the genome sequence can require weeks or months of computation on a world-class supercomputer.

We have an easier job when we're studying a species whose genome has already been assembled. If we're examining mutations in human cancer genomes, for example, we can download the previously assembled human genome from the National Institutes of Health website and use it as a reference. For each read, we find the point where that string of letters best matches the genome, using an approximate matching algorithm; the process is similar to how your spell-check program finds the correct spelling based on your misspelled word. The place where the read sequence most closely matches the reference sequence is our best guess as to where it belongs. Thanks to the Human Genome Project and similar projects for other species (mouse, fruit fly, chicken, cow, and thousands of microbial species, for example), many assembled genomes are available for use as references for this task, which is called read alignment.

In general, these reference genomes are far too long for brute force scanning algorithms—those that simply start at the beginning of the sequence and work their way through the entire genome, looking for the part that best matches the read in question. Instead, researchers have lately focused on building an effective genome *index*, which allows them to rapidly home in on only those portions of the reference genome that contain good matches. Just like

ILLUSTRATION BY **L-Dopa**

an index at the back of a book, a genome index is a list of all the places in the genome where a certain string of letters appears—for example, the roughly 697 000 occurrences of the sequence "GATTACA" in the human genome.

One powerful recent invention is a genome index based on the Burrows-Wheeler transform—an algorithm originally developed for text compression. This efficient index allows us to align many thousands of 100-nucleotide reads per second. The algorithm works by carefully changing the order of a sequence of letters into one that's more compressible—and doing so in a way that's reversible. So, for example, let's say you have 21 As in your jumbled string of As, Ts, Gs, and Cs. That part of the string could then be compressed into A21, thus using 3 characters instead of 21—a sevenfold savings. By compiling a genome index of sequences reordered in this way, the search algorithm can scroll through the entire genome much more quickly, looking for a read's best match.

Once we have the best algorithms and data structures, we arrive at the next massive challenge: scaling up, and getting many computers to divvy up the work of parsing a genome.

THE ROUGHLY 2000 SEQUENCING instruments in labs and hospitals around the world can collectively sequence 15 quadrillion nucleotides per year, which equals about 15 petabytes of compressed genetic data. A petabyte is 2^{50} bytes, or in round numbers, 1000 terabytes. To put this into perspective, if you were to write this data onto standard DVDs, the resulting stack would be more than 2 miles tall. And with sequencing capacity increasing at a rate of around three- to fivefold per year, next year the stack would be around 6 to 10 miles tall. At this rate, within the next five years the stack of DVDs could reach higher than the orbit of the International Space Station.

Clearly, we're dealing with a data deluge in genomics. This data is vital for the advancement of biology and medicine, but storing, analyzing, and sharing such vast quantities is an immense challenge. Still, it's not an unprecedented one: Other fields, notably high-energy physics and astronomy, have already encountered this problem. For example, the four main detectors at the Large Hadron Collider produced around 13 petabytes of data in 2010, and when the Large Synoptic Survey Telescope comes on line in 2016, it's anticipated to produce around 10 petabytes per year.

The crucial difference is that these physics and astronomy data deluges pour forth from just a few major instruments. The DNA data deluge comes from thousands—and soon, tens of thousands—of sources. After all, almost any life-science laboratory can now afford to own and operate a sequencer. Major centers like the Broad Institute, in Cambridge, Mass., or BGI, in Shenzhen, China, have more than 100 high-capacity instruments on site, but smaller institutions like the Malaysia Genome Institute or the International Livestock Research Institute, in Kenya, also have their own instruments. In all these facilities, researchers are struggling to analyze the sequencing data for a wide variety of applications, such as investigations into human health and disease, plant and animal breeding, and monitoring microbial ecology and pathogen outbreaks.

The only hope for these overwhelmed researchers lies in advanced computing technologies. Genomics researchers are investigating a range of options, including very powerful but conventional servers, specialized hardware, and cloud computing. Each has strengths and weaknesses depending on the specific application and analysis. But for many, cloud computing is increasingly the best option, because it allows the close integration of powerful computational resources with extremely high-volume data storage.

One promising solution comes from Google, a company with plenty of experience searching vast troves of data. Google doesn't regularly release information on how much data it processes, but in May 2010 it reported searching 946 petabytes per month. Today, three years later, it's safe to assume that figure is at least an order of magnitude larger.

To mine the Internet, Google developed a parallel computing framework called MapReduce. Outside of Google, an open-source alternative to MapReduce called Apache Hadoop is emerging as a standard platform for analyzing huge data sets in genomics and other fields. Hadoop's two main advantages are its programming model, which harnesses the power of many computers in tandem, and its smart integration of storage and computational power.

While Hadoop and MapReduce are simple by design, their ability to coordinate the activity of many computers makes them powerful. Essentially, they divide a large computational task into small pieces that are distributed to many computers across the network. Those computers perform their jobs (the "map" step), and then communicate with each other to aggregate the results (the "reduce" step). This process can be repeated many times over, and the repetition of computation and aggregation steps quickly produces results. This framework is much more powerful than basic "queue system" software packages like the widely used HTCondor and Grid Engine. These systems also divide up large tasks among many computers but make no provision for the computers to exchange information.

Hadoop has another advantage: It uses the computer cluster's computational nodes for data storage as well. This means that Hadoop can often execute programs on the nodes themselves, thus

GENOME INDEXING

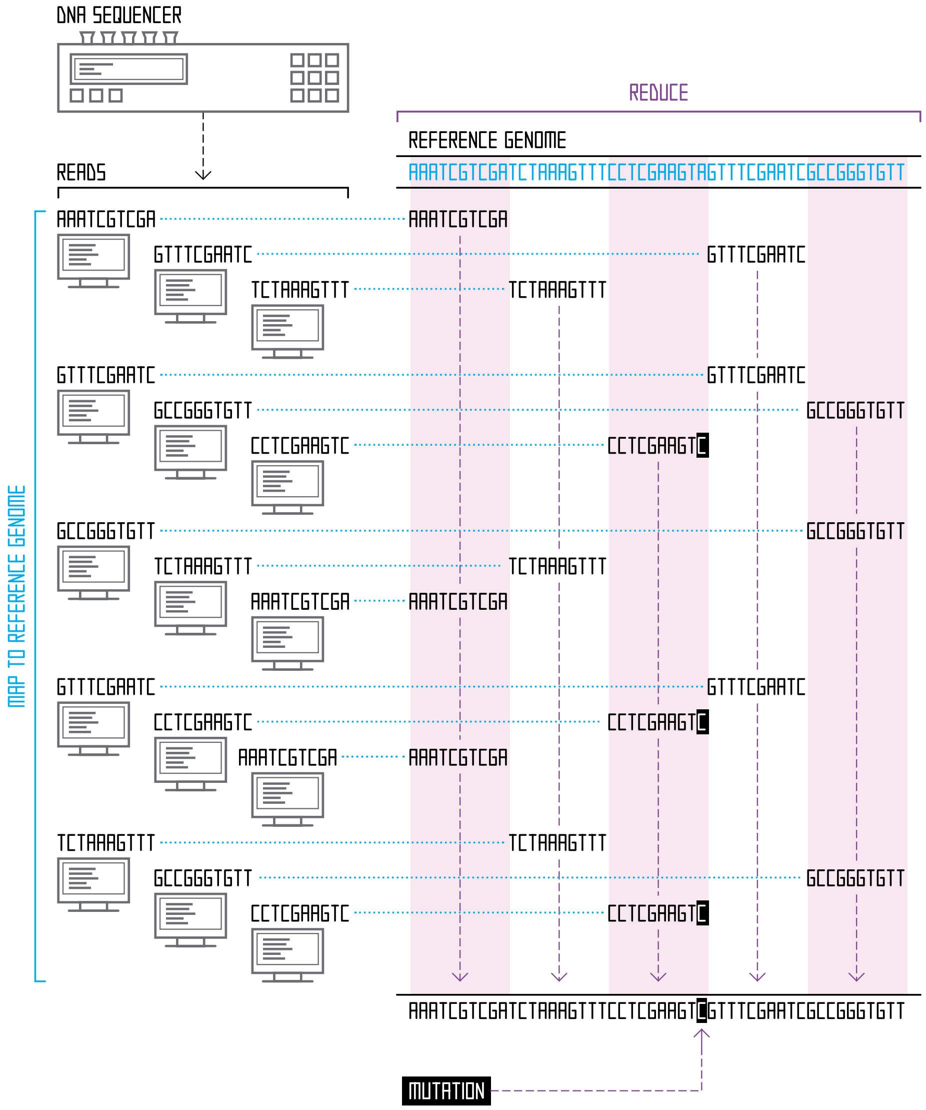
Like the index of a book, a genome index is organized by key terms (in this case, short strings of nucleotides). It lists all the places in the larger text (the genome) where those key terms appear.

G**ATC**ACAG**AAA**TTCCAGCATATGACATCCACG
CGCTAGC**CGG**TATATG**AAA**TGAGAGG**ATC**ATC
ACACTATGTGATGACATACTAGAC**CGG**TGATG
GGGAT**ATC**AGGAATTCCAGCATATGAC**ATC**CA
CGCGCTAGC**CGG**TATATGAAGGATGAGAGGGA
GCCACCACTATGTGATGACATACTAGAC**CGG**T
ACGATGGATTACAGGAATTCCAGCATATGACA
GAGGCCACGCGCTAGCGCGTATATG**AAA**TGAG
AGAGGGACACCACTATGTGATGACATACTAGA
CCC**CGG**TGATGGATTACAGGA**ATC**CCAGCATA
TGACATACACGCGCTAGCCGAGTATATGAGAG
ACATGAGAGGGACACCACTATGTGATGACATA
CCCTAGAC**CGG**TGATGGATTACAGGAATTCCC
GCATATGACACCCACGCGCTAGCACGTATAAG
CATTG**AAA**TGAGAGAGGA**ATC**CACTATGTGAT
GACATACTAGACCGTTTGTGATGGATTACAGG
AATTCCAGCATATGACATCCAC**ATC**CTAGCTC
CAGGTATATG**AAA**TGAGAGGGACACCACTATG

INDEX
AAA OFFSETS: 9, 49, 257, 467, 571
ATC OFFSETS: 2, 60, 104, 127, 319, 480, 551
CGG OFFSETS: 40, 124, 141, 194, 300, 404

IDENTIFYING MUTATIONS

Using the MapReduce software framework, the raw data from a sequencing machine is divided up and distributed among many computers. In the "map" step, these computers try to match strings of nucleotides to locations in the reference genome. Then they compare results in the "reduce" step to either confirm that a string perfectly corresponds to the reference genome or to identify a mismatch—a mutation.



moving the code to the data rather than having to access data in a comparatively slow file server. This structure also brings a reliability bonus, even on off-the-shelf servers and disks. Google created MapReduce to run in data centers packed with cheap commodity computers, some of which were expected to fail every day, so fault tolerance was built into the system. When a data set is loaded into the program, it's split up into manageable chunks, and each chunk is replicated and sent to several computer nodes. If one fails, the others go on. This model also works well in a flexible setting such as the Amazon Elastic Compute Cloud, where nodes can be provisioned for an application as needed, on the fly, and leased on a per-hour basis.

We're still a long way from having anything as powerful as a Web search engine for sequencing data, but our research groups are trying to exploit what we already know about cloud computing and text indexing to make vast sequencing data archives more usable. Right now, agencies like the National Institutes of Health maintain public archives containing petabytes of genetic data. But without easy search methods, such databases are significantly underused, and all that valuable data is essentially dead. We need to develop tools that make each archive a useful living entity the way that Google makes the Web a useful living entity. If we can make these archives more searchable, we will empower researchers to pose scientific questions over much larger collections of data, enabling greater insights.

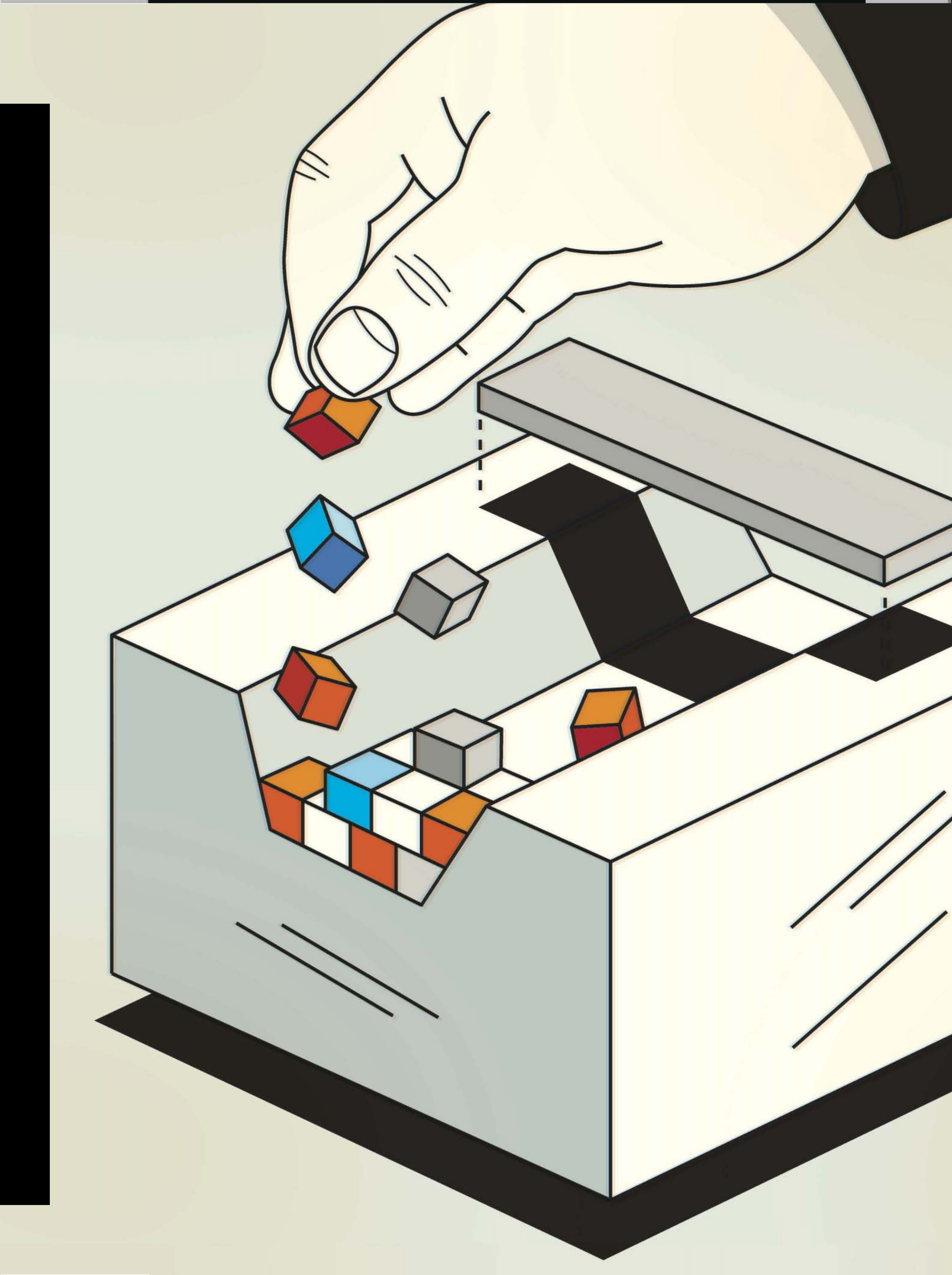
THIS YEAR, GENOMICS researchers may reach a remarkable milestone: the US $1000 genome. Experts have long said that when the cost of sequencing a human genome falls to that level, the technology can be used routinely in biological research and medical care. The high-capacity Illumina systems are nearing this price point, as is the Ion Proton machine from San Diego-based Life Technologies.

Such sequencing capacity is already enabling projects that can reinvent major sectors of technology, science, and medicine. For example, the U.S. Department of Energy recently launched KBase, a knowledge base for biofuel research that integrates hundreds of terabytes of genomic and other biological data inside its own compute cloud. KBase will use state-of-the-art machine learning and data-mining techniques to build predictive models of how genome variations influence the growth of plants and microbes in different environments. Researchers can then select which plants and microbes should be bred or genetically engineered to become more robust, or to produce more usable oils.

This scenario is just a hint of what is to come if we can figure out how to channel the data deluge in genomics. As sequencing machines spew out floods of As, Ts, Cs, and Gs, software and hardware will determine how much we all benefit. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/dnadata0713

ILLUSTRATION BY **L-Dopa**



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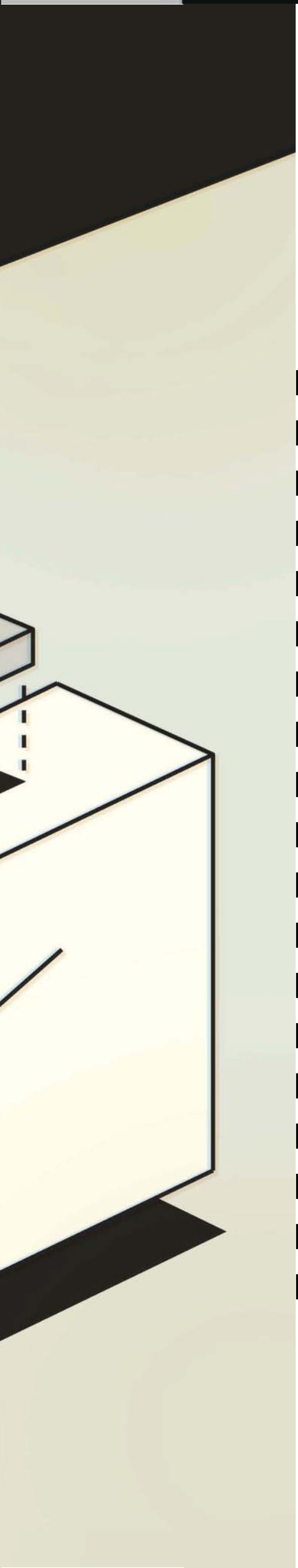


CHANGING THE CHANNEL

Ending silicon's central role in transistors could maintain the march of Moore's Law

By **Richard Stevenson**

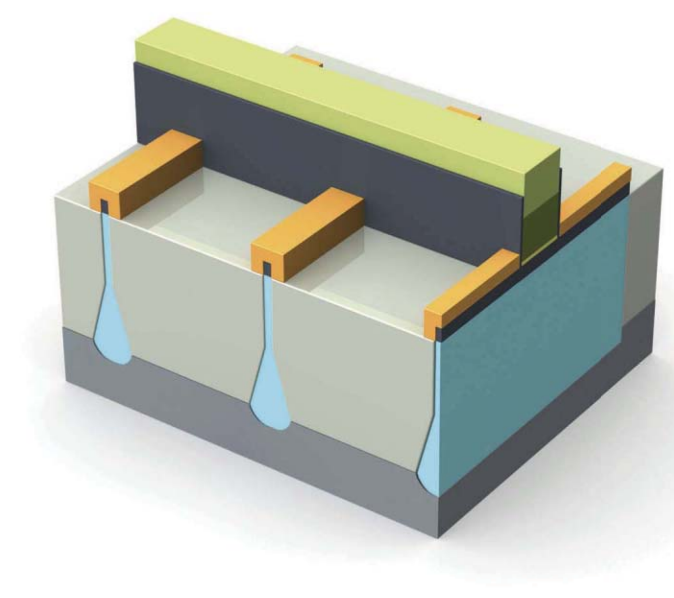
Illustration by **Harry Campbell**

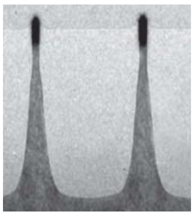
THE TRANSISTOR ISN'T SHRINKING THE WAY IT USED TO. THE BEST ONES WE HAVE TODAY ARE A PATCHWORK OF FIXES AND KLUDGES: SPEED-BOOSTING MATERIALS THAT PUSH OR PULL ON THE SILICON CENTER, EXOTIC INSULATORS ADDED TO STANCH LEAKS, AND A NEW GEOMETRY THAT POPS THINGS OUT OF THE PLANE OF THE CHIP AND INTO THE THIRD DIMENSION. NOW, TO KEEP MOORE'S LAW GOING, CHIPMAKERS ARE EYEING ANOTHER MONUMENTAL CHANGE IN TRANSISTOR ARCHITECTURE.

This time, they're taking aim at the current-carrying channels at the very heart of the device, replacing the silicon there with germanium and compound semiconductors known as III-Vs. If all goes well, these materials could usher in a new generation of speedier, less power-hungry transistors, allowing for denser, faster, cooler-running chips.

But for alternate transistor channels to be accepted, engineers must find a way to build them on industry-standard silicon wafers. That's no small feat. The atoms in the alternative semiconductors are spaced farther apart than in silicon, making the crystals difficult to grow without creating device-killing defects.

Still, industry experts say, it is quite possible that silicon fabs will ramp up production of these transistors as early as 2017. One promising approach, under development in Belgium, saves on materials and minimizes defects by precisely depositing the new materials into nanometer-scale trenches etched into standard silicon wafers. The resulting chips could trim energy consumption at data centers, boost the battery life of mobile devices, and help keep Moore's Law going well into the next decade.





UP AND DOWN

Trenches cut into silicon may be filled with germanium to make higher-speed, lower-power p-channel transistors. Researchers are moving toward building 3-D transistors with this alternate material. In the illustration above, germanium [blue] replaces traditional silicon in the current-carrying channel region. The channel is surrounded by insulating silicon dioxide [light gray] on top of silicon [dark gray]. The micrograph [right] shows the cross-section of trenches for roughly 12-nm-wide channels.

IMEC LOGIC PROGRAM (2)

MODERN TRANSISTORS ARE built into silicon wafers through the addition of trace amounts of other materials, called dopants. Dopant atoms alter the electronic properties of the material in order to form the three core parts of the transistor: the source and drain regions, which spit out and receive charge carriers, and the current-carrying channel, which runs between them.

For decades, chipmakers could speed up their microprocessors simply by shrinking the transistors and packing more of them onto a chip. They relied on a basic rule: Smaller transistors switch faster and consume less energy in the process. But in the late 1990s, this rule started to break down. As chips got more and more dense, power consumption began to put circuits at risk of overheating.

One way to tackle this heat problem is to lower the supply voltage—the voltage that is applied to the drain to pull charge carriers across the channel. This reduces power consumption, but it also means that less current is available to charge capacitors down the line, ultimately resulting in less speedy circuits.

Indeed, by the mid-2000s, CPU clock speeds began to stall. Companies began to work around the problem at the processor level by introducing multiple cores. But heat problems have persisted, and with each successive jump in transistor density, the fraction of transistors that may be active at any one time has gotten smaller.

At the same time, chipmakers have devised new ways to boost performance without adding more heat. One early strategy, debuted by Intel in 2002, was to mix silicon with germanium in the source and drain regions of the transistor. Atoms in this alloy are spaced differently than in pure silicon. The resulting strain alters the crystal properties–and thus the electrical properties–of the silicon channel, boosting the speed with which an electron or a hole (the absence of an electron that responds to an electric field as if it were a positive charge) could be tugged through the device. This hike in mobility resulted in faster-switching transistors that can carry more current for a given voltage, which makes for faster circuits, too.

Now chipmakers are adapting this basic strategy to make a more drastic change: the wholesale replacement of the silicon channel. A few materials have emerged as front-runners for the two kinds of transistors needed for logic circuits. For the positive-channel field-effect transistor (pFET), which carries holes across the channel, the leading candidate is germanium, which sits just below silicon on the periodic table and can transport charge four times as fast. For the negative-channel FET, or nFET, which depends on the movement of electrons, engineers are considering a mix of elements from groups III and V of the periodic table. One of the most promising is indium gallium arsenide (InGaAs), which boasts an electron mobility of about 10 000 square centimeters per volt second, more than six times that of silicon.

Intel, which has traditionally led the industry in transistor design changes, has already done some work on alternative transistor channel materials. In 2009, the company reported it had made InGaAs devices with a gate length of 80 nanometers. Although twice as long as what was then state of the art for plain silicon chips, they were shown to perform just as well with less power. The company has since incorporated the materials into new 3-D devices, called FinFETs, which have channels that pop out of the plane of the wafer.

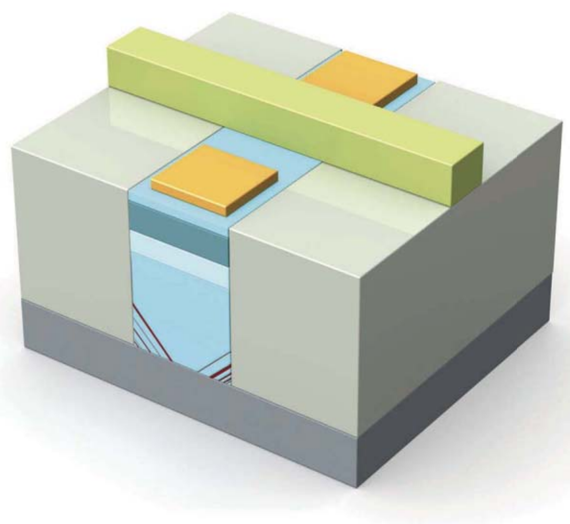
But to build its InGaAs transistors, Intel had to blanket an entire silicon wafer with a fairly thick layer of the III-V material, then etch away the unneeded areas. That's too expensive for high-volume production, says Richard Hill of the U.S.-based nonprofit Sematech, a chip industry research consortium.

The future, Hill says, lies in the alternative approach pioneered by Imec, a research outfit headquartered in Leuven, Belgium. There, a team of engineers, now 50 strong, has been working for more than 10 years on a way to grow each of the billions of transistor channels on a silicon chip in trenches just tens of nanometers across.

The approach is so attractive that last year Sematech abandoned its own wafer-blanketing approach to follow suit. And although Imec cannot disclose which industry heavyweights may want to use the approach, there are strong indications of interest. "[It's] a very valuable option that we are taking into consideration," says Lukas Czornomaz, a researcher in the Advanced Functional Materials Group at IBM Research-Zurich.

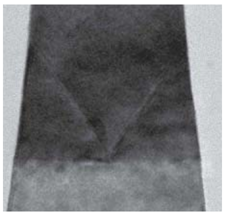
IMEC'S WORK IS based on a simple axiom of crystal growth: The right geometry can make all the difference. The Polish chemist Jan Czochralski discovered this in 1916 when he showed that it's possible to make nearly perfect crystals by drawing a seed crystal from a bath of molten metal. A key lesson was that growing material in narrow columns limits defects. The most common defect occurs when an atom fails to adhere to the right spot, causing an entire plane of atoms to go missing down the line. Fortunately, these defects tend to propagate at an angle of around 45 degrees to the direction of growth, and if crystal growth starts with a long, narrow neck, the dislocation will generally propagate for just a short distance before reaching the edge, where it terminates.

Growing each of the billions of nanometer-scale transistor channels in a tiny vat to make a chip would be impractical. But engineers can still take advantage of this geometric "necking" effect when growing crystals in vapor-filled reactors. The pioneer of this approach was Eugene Fitzgerald, a professor in the materials science and engineering department at MIT. In the 1990s, while based at Bell Laboratories, he showed that small patches of III-V material could be built on silicon if the "neck" that begins the crystal is built into the bottom of a rectangular trench that's about twice as deep as it is wide. By the time the



WHERE THE DEFECTS STOP

Alternate channel materials for n-channel transistors are more difficult to work with; the research has not progressed as quickly toward a 3-D architecture. One approach for a planar transistor [above] is to grow indium gallium arsenide [darker blue] on other compound semiconductor layers. Defects in the crystals [diagonal lines] grow at an angle and terminate on the side of the deep trench instead of reaching the surface. This is also shown in the micrograph [right] of a silicon-germanium mix.



ILLUSTRATIONS BY Emily Cooper

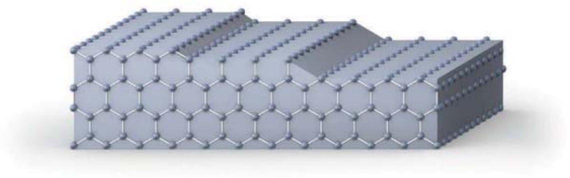
material is flush with the surrounding silicon surface, most of the defects have ended at one of the trench's sidewalls [see illustration, "Where the Defects Stop"].

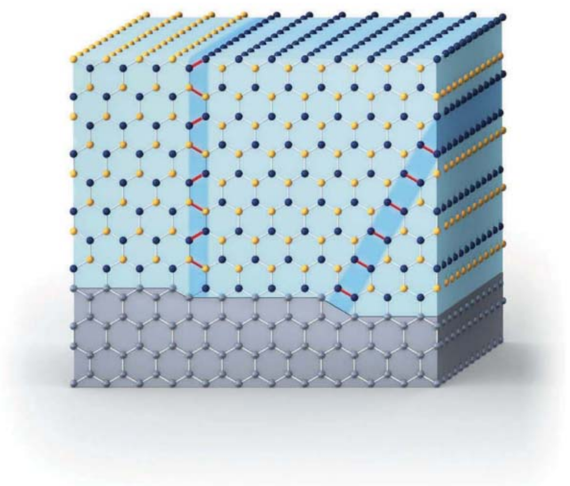
Matty Caymax, a chemist who specializes in postsilicon device fabrication at Imec, set out with his colleagues to see if they could make this approach fast, robust, and reliable enough to work in silicon fabs. Trenches themselves aren't new to the semiconductor industry: For 15 years, fabs have etched away silicon and then refilled the trenches with silicon dioxide. Such "shallow trench isolation" creates stretches of insulating substrate between transistors so they can be packed closer together with minimal electrical interference.

Because silicon dioxide is noncrystalline, it can be packed into a trench without regard to where each individual atom ends up. Filling troughs with materials that have a high charge-carrier mobility is another matter. To work properly, they must form high-quality crystals, even though the spacing between their atoms is quite different from that of the silicon they are grown on. Germanium atoms are spaced, on average, 0.566 nanometers apart, compared with 0.543 nm for silicon atoms. InGaAs is even worse, with a spacing of 0.59 nm. The basic mismatch easily results in stacking errors.

When Caymax and his group began working on alternate channels in 2002, they decided to focus on giving a speed boost to pFETs. The pFET was a natural place to start. Holes don't move as fast through silicon as electrons do. Without straining the crystal, a silicon pFET might carry only about a quarter as much current as an nFET can, Caymax says. Introducing a higher-mobility material can address that imbalance.

Growing pure germanium on pure silicon was a big jump, so Imec first started working with mixtures of silicon and germanium, and then began experimenting with growing a layer of pure germanium on top of the SiGe mix. The SiGe layer helped ease the mismatch in atomic spacing, reducing the number of defects in the Ge. But Caymax and his colleagues also realized this approach gave them an extra knob to turn. By fine-tuning the ratio of silicon and germanium, the team could compress the germanium channel that lies above it and slightly change the spacing between atoms. Hit the sweet spot–enough silicon to boost mobility but not so much that it degrades crystal quality–and germanium hole mobility could in theory jump by as much as a factor of six.





IN 2008, IMEC'S engineers reported a record current for a germanium FET with a 65-nm gate length, a dimension that was a few years behind the state of the art for silicon. But then progress ground to a halt. Part of the delay came as the team transitioned from a 200-millimeter wafer line to a 300-mm line. But they also found they had to tackle an unexpected issue: excess leakage.

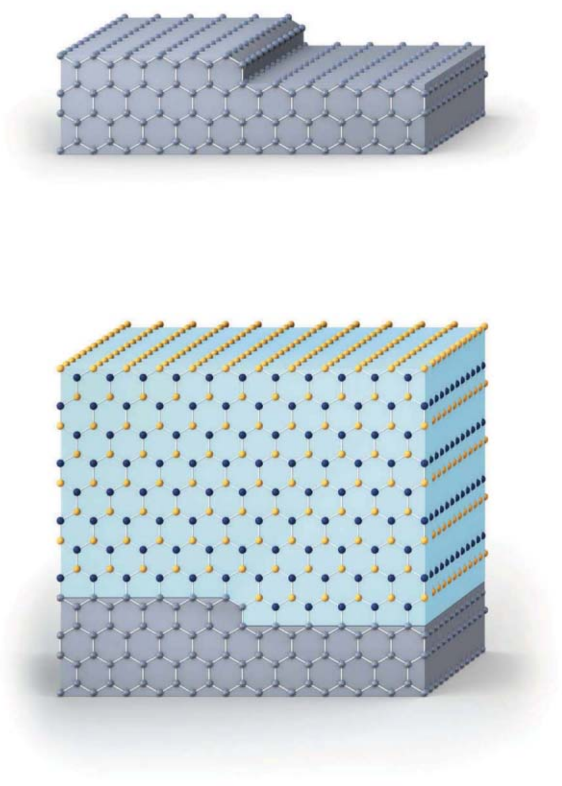
There seemed to be too much strain on the pure germanium channel, so the engineers resumed work on silicon-germanium. They built a ring oscillator that can switch 25 percent faster than silicon equivalents at today's standard operating voltage, 1.1 volts, Caymax says. At 0.9 V, the performance gap grows to 40 percent. The group also demonstrated an 8-bit multiplier that can operate well at 0.6 V, a level where silicon-based circuits struggle.

Now it seems that most of the kinks in pure germanium have been worked out. "I cannot go into details, but we are now in much better shape," says Caymax. In June, at the VLSI Technology symposium in Kyoto, Japan, Caymax's colleague Jérome Mitard presented new results for a pure germanium design that's a stepping-stone toward a germanium-based 3-D transistor, which the team hopes to complete by the end of this year. Their device can transmit holes six times as fast as a silicon equivalent and can operate well at 0.5 V, which could mean significant energy savings.

The only drawback is the size: The channel in the VLSI device is 200 nm wide. The transistors on today's chips boast channels that are about a tenth as wide, and even smaller ones will be required for next-generation CMOS. But Caymax is optimistic. "There are no obvious showstoppers to going further down after this first run," he says, adding that he and his colleagues have achieved "good filling" with germanium in trenches that are just 11 to 12 nm wide. If the team can halve that, they will be in the ballpark needed for the devices at the 7-nm node, about the point at which industry watchers expect alternate channel materials will be needed.

Building the nFET has turned out to be trickier. The speediest materials for electrons are III-V compounds. Caymax's group opted to make III-V transistors that were a mix of two materials: a trench filled with indium phosphide topped with a thin layer of ultraspeedy InGaAs. Filling the bulk of the trench with InP helps cut down on losses. Current tends to leak across a transistor in the deepest part of the transistor channel, the area farthest from the gate. By making the bulk of the trench out of InP, this avenue can be eliminated, because electrons moving through InGaAs don't have enough energy to jump into that material.

But filling a trench with InP is challenging. If the atoms are not ordered correctly,



SETTING THE FOUNDATION

Even the best trench bottom is never flat. Single-atom steps often form in silicon [top left]. This is a challenge when it comes to filling trenches with compound semiconductors, such as indium phosphide. These materials prefer a specific alternating arrangement of atoms. Although one atom in the compound can be made to adhere to the surface first, the single atoms steps will result in same-atom bonds [shown in red] that can cause the material to act more like a metal than a semiconductor [bottom left]. Lining a trench first with germanium can create a better growing environment. The surface of germanium naturally arranges itself into two-atom steps [top right]. This better reflects the natural arrangement of indium phosphide atoms, allowing crystals to grow defect free, with a natural structure of alternating atoms [bottom right].

they will form metallic bonds that can short out a device. This wouldn't be a problem if the bottom of a trench were perfectly flat. But there are often atom-scale variations in surface height. This creates steps that can alter the orientation of a crystal built on top, resulting in planes of indium-indium and phosphor-phosphor bonds that are especially conductive. "If you used these materials for electrical applications, the devices would simply short-circuit," Caymax says.

His team found they could eradicate these bonds by first growing a little germanium in a trench etched to form a concave base and then baking the wafer. The surface rearranges to steps two atoms high, cutting out the geometric defect.

Although the quality of the InGaAs material making up the channel is much higher than that of the underlying InP, it is still riddled with defects–a square centimeter would have hundreds of millions of them, about 100 times as many as are present in Imec's germanium layers and a million or so times more than you would historically find in a patch of silicon wafer. Such a high defect density would likely horrify many within the silicon industry; the number of defects is directly linked to yield and reliability.

But Caymax notes that many of the recent modifications to transistor architecture, such as the introduction of strained silicon, also create a lot of defects. Intel's chips aren't defect free; they're more like "quasi-perfect," Caymax says. His team has set up a program to see how much they must reduce the InGaAs defect density in order to make competitive devices.

THERE ARE STILL more challenges: Any overhaul of the channels will probably require changes in other places, too. New materials may also need to be introduced into the source and drain portions of the transistor, and a layer of insulation will be needed to separate the channels from the gate electrode. Germanium channels should be able to use the standard insulation–a thin silicon dioxide layer capped with a thicker film of hafnium oxide. But this approach won't work for InGaAs. Charge carriers tend to get trapped at the junction between InGaAs and silicon dioxide. Engineers are still working to identify an alternate material that performs well.

At the same time, researchers still haven't shown they can make high-quality transistors small enough for introduction at the 7-nm node, which is slated to go into mass production by 2017. And size isn't the only concern. Alternate materials must also be built to whatever structure is on the books. That could mean FinFETs. But the chip industry may instead decide to move in a different direction–toward nanowires, which offer the possibility of controlling the channel from all sides with a wraparound gate. Chances are, these will first emerge with silicon-based channels.

One big stumbling block in the adoption of III-V materials is the concern over contamination of fab equipment. Arsenic can drastically alter the electronic properties of silicon, and it must be carefully accounted for. "The biggest challenge, even at this stage of R&D, is the stigma, the perception, that the fabs have with respect to arsenic cross-contamination," says Errol Sanchez, a crystal-growth specialist for the equipment vendor Applied Materials.

Finally, there is still a fair amount of uncertainty over the fabrication method. IBM and Imec are exploring a backup should the trenching strategy fall through: Grow the channel materials on separate wafers, then bond them to another silicon wafer, leaving behind a very thin film of either germanium or III-V. This method promises good crystal quality, but it is also expected to be more expensive, since it requires blanketing large wafers with a lot of material that will ultimately be etched away.

Such stumbling blocks are nothing new. The industry faced many challenges as it worked to push strained silicon channels and FinFETs into production, says Chenming Hu, coinventor of the FinFET and TSMC Distinguished Professor of the Graduate School at the University of California, Berkeley. "The challenges will pale compared to what will be faced by the introduction of a very different material," Hu says.

Still, he's convinced silicon's days are numbered. "I'm certain our children or grandchildren will not be using silicon," he says. "The world is large; there must be a better material." ■

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Unclean at Any Speed

ELECTRIC CARS DON'T SOLVE THE AUTOMOBILE'S ENVIRONMENTAL PROBLEMS

BY OZZIE ZEHNER | PHOTO-ILLUSTRATION BY SMALLDOG IMAGEWORKS

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Last summer, California highway police pulled over pop star Justin Bieber as he sped through Los Angeles in an attempt to shake the paparazzi. He was driving a hybrid electric car—not just any hybrid, mind you, but a chrome-plated Fisker Karma, a US $100 000 plug-in hybrid sports sedan he'd received as an 18th-birthday gift from his manager, Scooter Braun, and fellow singer Usher. During an on-camera surprise presentation, Braun remarked, "We wanted to make sure, since you love cars, that when you are on the road you are always looking environmentally friendly, and we decided to get you a car that would make you stand out a little bit." Mission accomplished.

Bieber joins a growing list of celebrities, environmentalists, and politicians who are leveraging electric cars into green credentials. President Obama once dared to envision 1 million electric cars plying U.S. roads by 2015. London's mayor, Boris Johnson, vibrated to the press over his born-again electric conversion after driving a Tesla Roadster, marveling how the American sports coupe produced "no more noxious vapours than a dandelion in an alpine meadow." Meanwhile, environmentalists who once stood entirely against the proliferation of automobiles now champion subsidies for companies selling electric cars and tax credits for people buying them.

Two dozen governments around the world subsidize the purchase of electric vehicles. In Canada, for example, the governments of Ontario and Quebec pay drivers up to C $8500 to drive an electric car. The United Kingdom offers a £5000 Plug-in Car Grant. And the U.S. federal government provides up to $7500 in tax credits for people who buy plug-in electric vehicles, even though many of them are affluent enough not to need such help. (The average Chevy Volt owner, for example, has an income of $170 000 per year.)

Some states offer additional tax incentives. California brings the total credit up to $10 000, and Colorado to $13 500—more than the base price of a brand new Ford Fiesta. West Virginia offers the sweetest deal. The state's mining interests are salivating at the possibility of shifting automotive transportation from petroleum over to coal. Residents can receive a total credit of up to $15 000 for an electric-car purchase and up to $10 000 toward the cost of a personal charging station.

There are other perks. Ten U.S. states open the high-occupancy lanes of their highways to electric cars, even if the car carries a lone driver. Numerous stores offer VIP parking for electric vehicles—and sometimes a free fill-up of electrons. Mayor Johnson even moved to relieve electric-car owners of the burden of London's famed congestion fee.

Alas, these carrots can't overcome the reality that the prices of electric cars are still very high—a reflection of the substantial material and fossil-fuel costs that accrue to the companies constructing them. And some taxpayers understandably feel cheated that these subsidies tend to go to the very rich. Amid all the hype and hyperbole, it's time to look behind the curtain. Are electric cars really so green?

THE IDEA OF ELECTRIFYING AUTOMOBILES to get around their environmental shortcomings isn't new. Twenty years ago, I myself built a hybrid electric car that could be plugged in or run on natural gas. It wasn't very fast, and I'm pretty sure it wasn't safe. But I was convinced that cars like mine would help reduce both pollution and fossil-fuel dependence.

I was wrong.

I've come to this conclusion after many years of studying environmental issues more deeply and taking note of some important questions we need to ask ourselves as concerned citizens. Mine is an unpopular stance, to be sure. The suggestive power of electric cars is a persuasive force—so persuasive that answering the seemingly simple question "Are electric cars indeed green?" quickly gets complicated.

As with most anything else, the answer depends on whom you ask. Dozens of think tanks and scientific organizations have ventured conclusions about the environmental friendliness of electric vehicles. Most are supportive, but a few are critical. For instance, Richard Pike of the Royal Society of Chemistry provocatively determined that electric cars, if widely adopted, stood to lower Britain's carbon dioxide emissions by just 2 percent, given the U.K.'s electricity sources. Last year, a U.S. Congressional Budget Office study found that electric car subsidies "will result in little or no reduction in the total gasoline use and greenhouse-gas emissions of the nation's vehicle fleet over the next several years."

Others are more supportive, including the Union of Concerned Scientists. Its 2012 report on the issue, titled "State of Charge," notes that charging electric cars yields less CO_2 than even the most efficient gasoline vehicles. The report's senior editor, engineer Don Anair, concludes: "We are at a good point to clean up the grid and move to electric vehicles."

Why is the assessment so mixed? Ultimately, it's because this is not just about science. It's about values, which inevitably shape what questions the researchers ask as well as what they choose to count and what they don't. That's true for many kinds of research, of course, but for electric cars, bias abounds, although it's often not obvious to the casual observer.

To get a sense of how biases creep in, first follow the money. Most academic programs carrying out electric-car research receive funding from the auto industry. For instance, the Plug-in Hybrid and Electric Vehicle Research Center at the University of California, Davis, which describes itself as the "hub of collaboration and research on plug-in hybrid and electric vehicles for the State of California," acknowledges on its website partnerships with BMW, Chrysler-Fiat, and Nissan, all of which are selling or developing electric and hybrid models. Stanford's Global Climate & Energy Project, which publishes research on electric vehicles, has received more than $113 million from four firms: ExxonMobil, General Electric, Schlumberger, and Toyota. Georgetown University, MIT, the universities of Colorado, Delaware, and Michigan, and numerous other schools also accept corporate sponsorship for their electric-vehicle research.

I'm not suggesting that corporate sponsorship automatically leads people to massage their research data. But it can shape find-

PREVIOUS PAGES, PHOTO SOURCES: CAR, TRANSTOCK/CORBIS; COAL: NOLIMITPICTURES/ISTOCKPHOTO ings in more subtle ways. For one, it influences which studies get done and therefore which ones eventually receive media attention. After all, companies direct money to researchers who are asking the kinds of questions that stand to benefit their industry. An academic who is studying, say, car-free communities is less likely to receive corporate funding than a colleague who is engineering vehicle-charging stations.

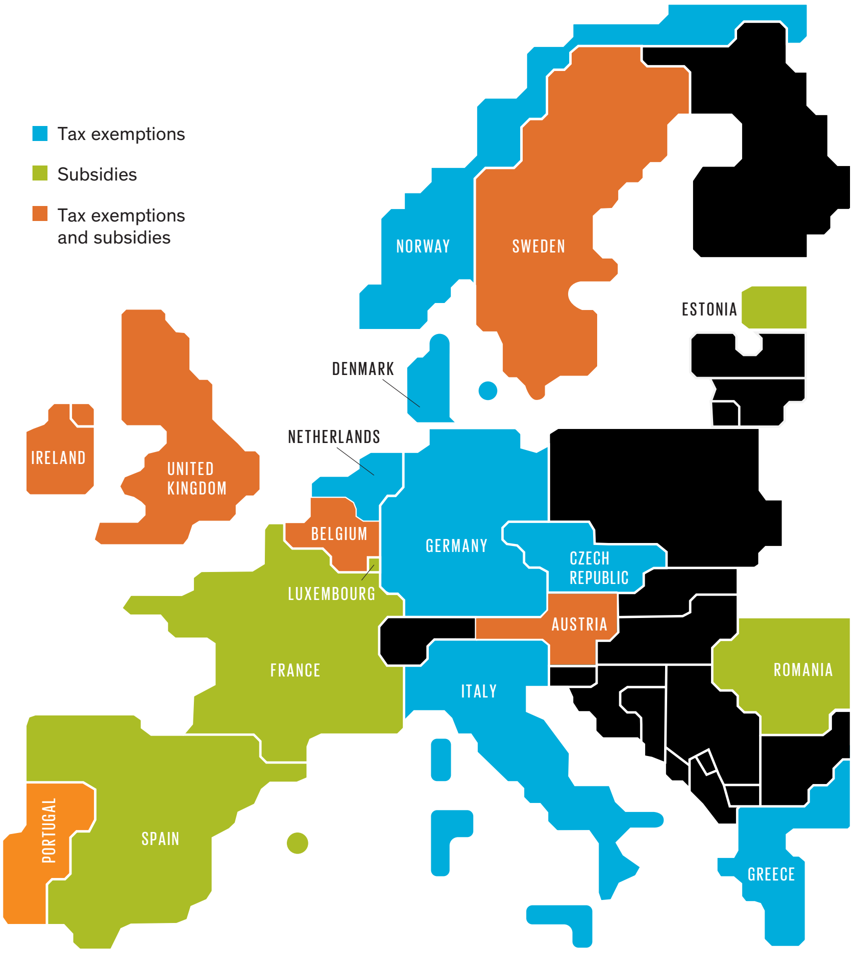
Many of the researchers crafting electric-vehicle studies are eager proponents of the technology. An electric-vehicle report from Indiana University's School of Environmental Affairs, for instance, was led by a former vice president of Ford. It reads like a set of public relations talking points and contains advertising recommendations for the electric-car industry (that it should manage customers' expectations, to avoid a backlash from excessive claims). Even the esteemed Union of Concerned Scientists clad its electric-car report in romantic marketing imagery courtesy of Ford, General Motors, and Nissan, companies whose products it evaluates. Indeed, it's very difficult to find researchers who are looking at the environmental merits of electric cars with a disinterested eye.

turing the vast number of photovoltaic cells required would have venomous side effects. Solar cells contain heavy metals, and their manufacturing releases greenhouse gases such as sulfur hexafluoride, which has 23 000 times as much global warming potential as CO_2, according to the Intergovernmental Panel on Climate Change. What's more, fossil fuels are burned in the extraction of the raw materials needed to make solar cells and wind turbines—and for their fabrication, assembly, and maintenance. The same is true for the redundant backup power plants they require. And even more fossil fuel is burned when all this equipment is decommissioned. Electric-car proponents eagerly embrace renewable energy as a scheme to power their machines, but they conveniently ignore the associated environmental repercussions.

Finally, most electric-car assessments analyze only the charging of the car. This is an important factor indeed. But a more rigorous analysis would consider the environmental impacts over the vehicle's entire life cycle, from its construction through its operation and on to its eventual retirement at the junkyard.

SO HOW DO YOU GAUGE the environmental effects of electric cars when the experts writing about them all seem to be unquestioned car enthusiasts? It's tough. Another impediment to evaluating electric cars is that it's difficult to compare the various vehicle-fueling options. It's relatively easy to calculate the amount of energy required to charge a vehicle's battery. It isn't so straightforward, however, to compare a battery that's been charged by electricity from a natural-gas-fired power plant with one that's been charged using nuclear power. Natural gas requires burning, it produces CO_2, and it often demands environmentally problematic methods to release it from the ground. Nuclear power yields hard-to-store wastes as well as proliferation and fallout risks. There's no clear-cut way to compare those impacts. Focusing only on greenhouse gases, however important, misses much of the picture.

Manufacturers and marketing agencies exploit the fact that every power source carries its own unique portfolio of side effects to create the terms of discussion that best suit their needs. Electric-car makers like to point out, for instance, that their vehicles can be charged from renewable sources, such as solar energy. Even if that were possible to do on a large scale, manufac-



GENEROUS EV INCENTIVES: Governments around the world offer drivers various inducements to buy electric cars. The monetary incentives in western Europe, for example, include direct subsidies on vehicle purchases as well as certain tax exemptions. Some of these countries also provide the drivers of electric cars with free parking and other perks.

SOURCE: WIKIPEDIA

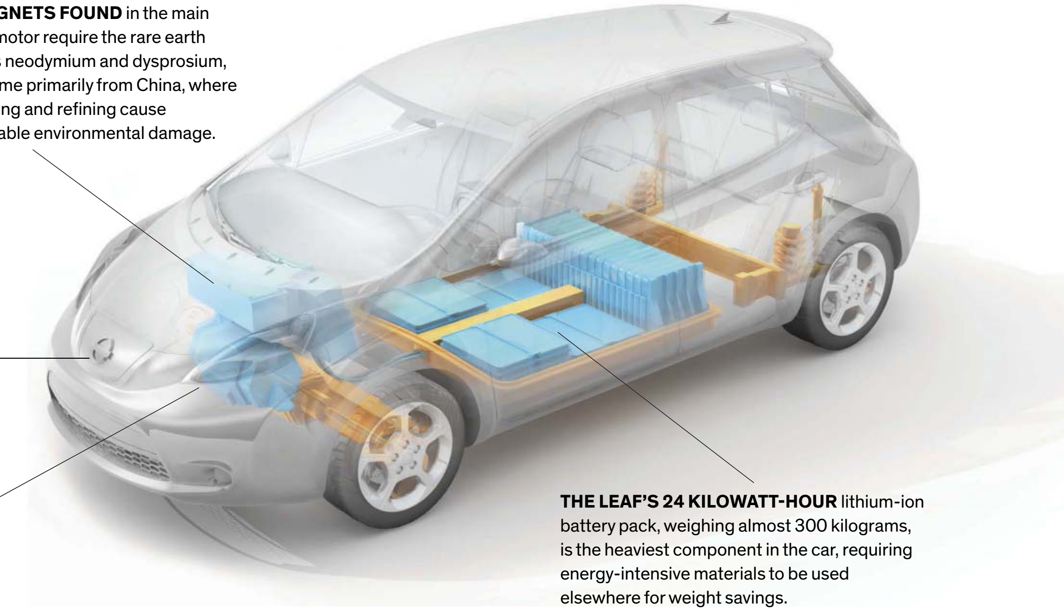
WHAT'S IN YOUR EV?

Don't just think about the missing tailpipe. Manufacturing the specialized components that go into electric cars, such as the Nissan Leaf, has significant environmental costs.

THE MAGNETS FOUND in the main traction motor require the rare earth elements neodymium and dysprosium, which come primarily from China, where their mining and refining cause considerable environmental damage.

THE ALUMINUM used in the Leaf's hood and doors reduces weight but requires much more energy to produce than steel.

THE LARGE AMOUNT OF COPPER used in the traction motor, power electronics, and wiring adds considerably to the burden that the Leaf's manufacturing places on the environment.



THE LEAF'S 24 KILOWATT-HOUR lithium-ion battery pack, weighing almost 300 kilograms, is the heaviest component in the car, requiring energy-intensive materials to be used elsewhere for weight savings.

ONE STUDY ATTEMPTED to paint a complete picture. Published by the National Academies in 2010 and overseen by two dozen of the United States' leading scientists, it is perhaps the most comprehensive account of electric-car effects to date. Its findings are sobering.

It's worth noting that this investigation was commissioned by the U.S. Congress and therefore funded entirely with public, not corporate, money. As with many earlier studies, it found that operating an electric car was less damaging than refueling a gasoline-powered one. It isn't that simple, however, according to Maureen Cropper, the report committee's vice chair and a professor of economics at the University of Maryland. "Whether we are talking about a conventional gasoline-powered automobile, an electric vehicle, or a hybrid, most of the damages are actually coming from stages other than just the driving of the vehicle," she points out.

Part of the impact arises from manufacturing. Because battery packs are heavy (the battery accounts for more than a third of the weight of the Tesla Roadster, for example), manufacturers work to lighten the rest of the vehicle. As a result, electric car components contain many lightweight materials that are energy intensive to produce and process—carbon composites and aluminum in particular. Electric motors and batteries add to the energy of electric-car manufacture.

In addition, the magnets in the motors of some electric vehicles contain rare earth metals. Curiously, these metals are not as rare as their name might suggest. They are, however, sprinkled thinly across the globe, making their extraction uneconomical in most places. In a study released last year, a group of MIT researchers calculated that global mining of two rare earth metals, neodymium and dysprosium, would need to increase 700 percent and 2600 percent, respectively, over the next 25 years to keep pace with various green-tech plans. Complicating matters is the fact that China, the world's leading producer of rare earths, has been attempting to restrict its exports of late. Substitute strategies exist, but deploying them introduces trade-offs in efficiency or cost.

The materials used in batteries are no less burdensome to the environment, the MIT study noted. Compounds such as lithium, copper, and nickel must be coaxed from the earth and processed in ways that demand energy and can release toxic wastes. And in regions with poor regulations, mineral extraction can extend risks beyond just the workers directly involved. Surrounding populations may be exposed to toxic substances through air and groundwater contamination.

At the end of their useful lives, batteries can also pose a problem. If recycled properly, the compounds are rather benign—although not something you'd want to spread on a bagel. But handled improperly, disposed batteries can release toxic chemicals. Such factors are difficult to measure, though, which is why they are often left out of studies on electric-car impacts.

78% of China's electricity is produced from coal, the dirtiest of fossil fuels.

The National Academies' assessment didn't ignore those difficult-to-measure realities. It drew together the effects of vehicle construction, fuel extraction, refining, emissions, and other factors. In a gut punch to electric-car advocates, it concluded that the vehicles' lifetime health and environmental damages (excluding long-term climatic effects) are actually *greater* than those of gasoline-powered cars. Indeed, the study found that an electric car is likely worse than a car fueled exclusively by gasoline derived from Canadian tar sands!

As for greenhouse-gas emissions and their influence on future climate, the researchers didn't ignore those either. The investigators, like many others who have probed this issue, found that electric vehicles generally produce fewer of these emissions than their gasoline- or diesel-fueled counterparts—but only marginally so when full life-cycle effects are accounted for. The lifetime dif-

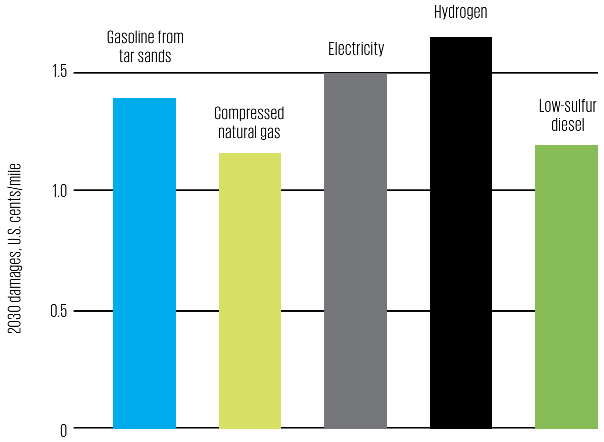
ILLUSTRATION BY Bryan Christie Design

ference in greenhouse-gas emissions between vehicles powered by batteries and those powered by low-sulfur diesel, for example, was hardly discernible.

The National Academies' study stood out for its comprehensiveness, but it's not the only one to make such grim assessments. A Norwegian study published last October in the *Journal of Industrial Ecology* compared life-cycle impacts of electric vehicles. The researchers considered acid rain, airborne particulates, water pollution, smog, and toxicity to humans, as well as depletion of fossil fuel and mineral resources. According to coauthor Anders Stromman, "electric vehicles consistently perform worse or on par with modern internal combustion engine vehicles, despite virtually zero direct emissions during operation."

Earlier last year, investigators from the University of Tennessee studied five vehicle types in 34 Chinese cities and came to a similar conclusion. These researchers focused on health impacts from emissions and particulate matter such as airborne acids, organic chemicals, metals, and dust particles. For a conventional vehicle, these are worst in urban areas, whereas the emissions associated with electric vehicles are concentrated in the less populated regions surrounding China's mostly coal-fired power stations. Even when this difference of exposure was taken into account, however, the total negative health consequences of electric vehicles in China exceeded those of conventional vehicles.

North American power station emissions also largely occur outside of urban areas, as do the damaging consequences of nuclear- and fossil-fuel extraction. And that leads to some critical questions. Do electric cars simply move pollution from upper-middle-class communities in Beverly Hills and Virginia Beach to poor communities in the backwaters of West Virginia and the nation's industrial exurbs? Are electric cars a sleight of hand that allows peace of mind for those who are already comfortable at the expense of intensifying asthma, heart problems, and radiation risks among the poor and politically disconnected?



THEY ALL POLLUTE: Even assuming 2030 vehicle technology and grid enhancements, the National Academies concluded that the health and nonclimate damage from electric cars would still exceed the damage from conventional fueling options.

SOURCE: NATIONAL ACADEMIES PRESS

The hope, of course, is that electric-car technology and power grids will improve and become cleaner over time. Modern electric-car technology is still quite young, so it should get much better. But don't expect batteries, solar cells, and other clean-energy technologies to ride a Moore's Law–like curve of exponential development. Rather, they'll experience asymptotic growth toward some ultimate efficiency ceiling. When the National Academies researchers projected technology advancements and improvement to the U.S. electrical grid out to 2030, they still found no benefit to driving an electric vehicle.

If those estimates are correct, the sorcery surrounding electric cars stands to worsen public health and the environment rather than the intended opposite. But even if the researchers are wrong, there is a more fundamental illusion at work on the electric-car stage.

ALL OF THE AFOREMENTIONED STUDIES compare electric vehicles with petroleum-powered ones. In doing so, their findings draw attention away from the broad array of transportation options available—such as walking, bicycling, and using mass transit.

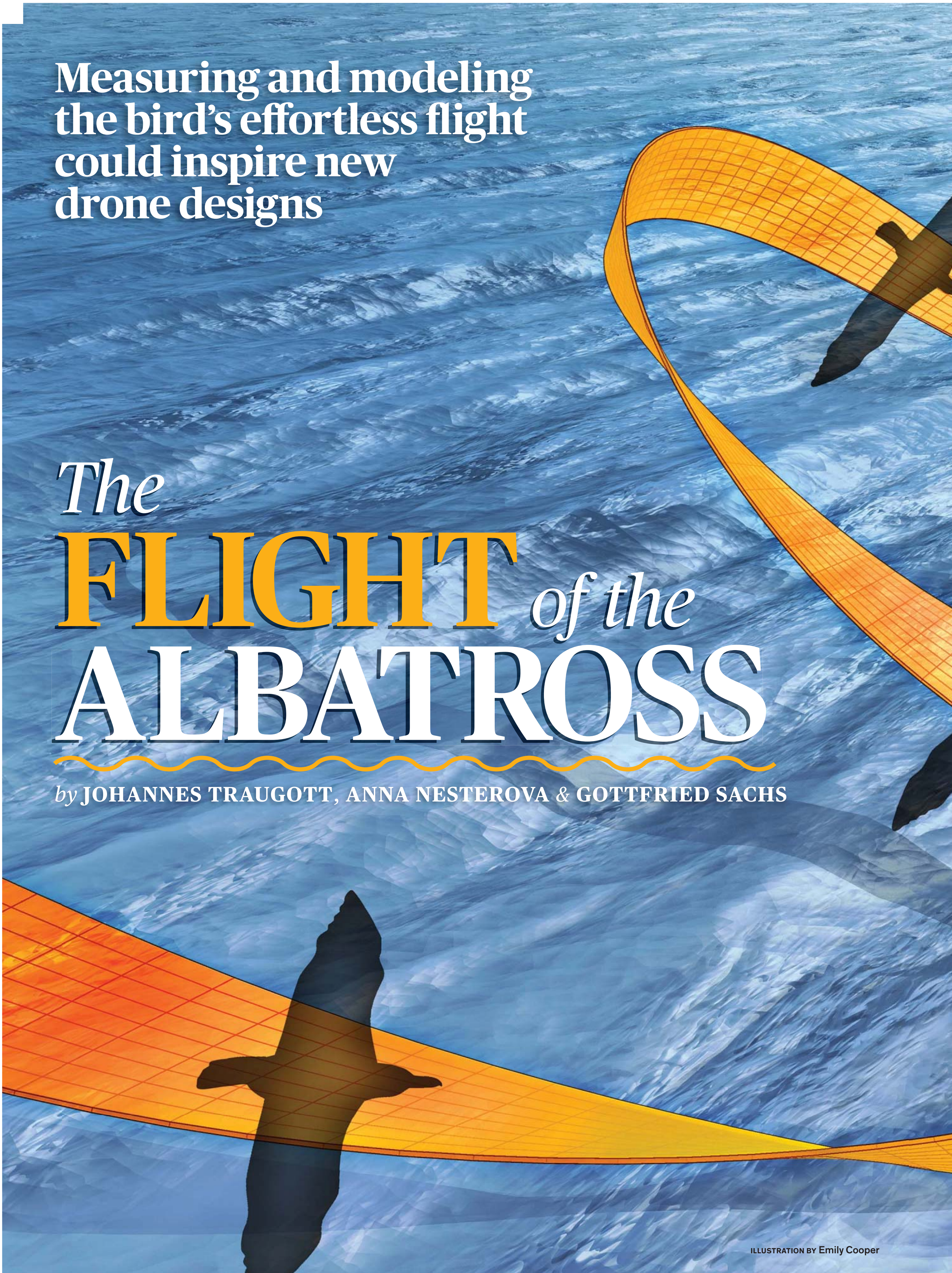
There's no doubt that gasoline- and diesel-fueled cars are expensive and dirty. Road accidents kill tens of thousands of people annually in the United States alone and injure countless more. Using these kinds of vehicles as a standard against which to judge another technology sets a remarkably low bar. Even if electric cars someday clear that bar, how will they stack up against other alternatives?

For instance, if policymakers wish to reduce urban smog, they might note that vehicle pollution follows the Pareto principle, or 80-20 rule. Some 80 percent of tailpipe pollutants flow from just 20 percent of vehicles on the road—those with incomplete combustion. Using engineering and remote monitoring stations, communities could identify those cars and force them into the shop. That would be far less expensive and more effective than subsidizing a fleet of electric cars.

If legislators truly wish to reduce fossil-fuel dependence, they could prioritize the transition to pedestrian- and bike-friendly neighborhoods. That won't be easy everywhere—even less so where the focus is on electric cars. Studies from the National Academies point to better land-use planning to reduce suburban sprawl and, most important, fuel taxes to reduce petroleum dependence. Following that prescription would solve many problems that a proliferation of electric cars could not begin to address—including automotive injuries, deaths, and the frustrations of being stuck in traffic.

Upon closer consideration, moving from petroleum-fueled vehicles to electric cars begins to look more and more like shifting from one brand of cigarettes to another. We wouldn't expect doctors to endorse such a thing. Should environmentally minded people really revere electric cars? Perhaps we should look beyond the shiny gadgets now being offered and revisit some less sexy but potent options—smog reduction, bike lanes, energy taxes, and land-use changes to start. Let's not be seduced by high-tech illusions. ■

POST YOUR COMMENTS at http://www.spectrumieee.org/electricskeptic0713



Measuring and modeling the bird's effortless flight could inspire new drone designs

The FLIGHT *of the* ALBATROSS

by JOHANNES TRAUGOTT, ANNA NESTEROVA & GOTTFRIED SACHS

ILLUSTRATION BY Emily Cooper

THE MALE ALBATROSS IS FINALLY BACK FROM his foraging, and now there is no time to lose. His mate has been patiently sitting on their nest awaiting his return, without food, for nearly a month, and we have to get to her before she flies off to forage for herself. ● Our colleague, biologist Anna Nesterova, crawls slowly toward the bird. All of a sudden, she lunges: With her left hand she expertly grabs the 10-kilogram albatross by the beak, and with her right arm she hugs its body and lifts it off the nest and its precious cargo, a single egg. Together we then fix a GPS logger onto the feathers of the bird's back with adhesive tape and glue. ● Soon after we release her, the mother albatross takes two or three steps into the furious wind, opens her 3-meter-wide wings, and takes flight. Four weeks from now, she'll return to this island in the southern Indian Ocean bearing a data log of where and how she flew—data that at last will put to the test our theories of how she stays aloft so long, almost never touching down, barely even flapping her long, elegant wings. If we could get our aerial robots to emulate that feat, they might someday orbit Earth for months, surfers of the winds of the uttermost sky.

JASON EDWARDS/GETTY IMAGES

SINCE AT LEAST THE 1880S, scientists have wondered how the wandering albatross (*Diomedea exulans*), soars for as long and as far as it does, over open water, without a bit of thermal updraft. It's no accident that the bird makes its home in exceptionally windy places–the wind is essential for such a heavy animal to get airborne in the first place. Once in the air, the bird performs a flying trick that seems to involve characteristic repetitive up and down maneuvers, sometimes dipping nearly to the water's surface, and all in the face of more wind than most cruise passengers can withstand without going green with seasickness.

This type of flight is known as dynamic soaring. Just watch an albatross, and you can easily discriminate its four phases of flight: There's a windward climb, then a curve from windward to leeward at peak altitude, then a leeward descent, and finally a reverse turn close to the sea surface that leads seamlessly into the next cycle of flight.

Although any human pilot who tried to use dynamic soaring to take passengers from Munich to New York City would lose his license 2 minutes after landing, a computer that's controlling an unmanned aerial vehicle, or UAV, isn't quite so constrained. The engineers who program it need merely to understand this trick of nature and adapt it to their ends. And this is exactly what we are up to.

Students of the albatross's flight understood early on that the bottommost layer of wind blowing above any surface, including that of water, will incur friction and thus slow down. This layer itself then becomes an obstacle that slows the layer just above it (though not by much), in a process that continues upward. The result is a 10- to 20-meter-high region known as a boundary layer or shear wind field, through which the wind speed increases smoothly and dramatically the higher you go in the field. Dynamic soaring maneuvers extract energy from that field, enabling the albatross to fly in any direction, even against the wind, with hardly any effort.

Exactly how the bird extracts energy from a horizontally blowing wind, however, was a puzzle. Scientists over the decades have attempted to find the solution using increasingly sophisticated computer simulations. Yet elaborate as they may be, these models can't capture the full complexity of what's happening. How do you simulate, for example, a sea troubled by strong winds that breaks up into irregular, meter-high waves, chopping the air into discontinuous blocks? Because of such unknowns, researchers long debated whether the shear wind field alone explained the soaring or whether there might also be other effects, such as gusts or vertical wind components.

We finally resolved this controversy at the Institute of Flight System Dynamics, at the Technische Universität München (Munich University of Technology), using an optimization method known as periodic optimal control. This same methodology had previously proved effective in aeronautical engineering, to calculate the aircraft trajectory that saves the most fuel, for example.

At the institute, we had also used it to optimize the flight trajectories of space gliders to deal with emergency cases. Under normal conditions, the vehicle would just glide home, adjusting its attitude with tiny thrusters and flaps and other aerodynamic control surfaces. But it also had to be able to survive failures of the control surfaces. So we looked at the interaction between the vehicle's glide and Earth's gravitational field and atmosphere, with an eye toward minimizing the thrusters' consumption of propellant. We also had to factor in the time of failure, possible airfields for landing, and the physical limitations of the vehicle, such as maximum *g*-load factor and maximum heat flow.

When we set out to apply optimization theory to the albatross, some groundwork had already been laid. The drag and lift characteristics of the bird, for example, had been analyzed back in the 1920s by Pierre Idrac of France; in the 1960s by Vance A. Tucker and G. Christian Parrott of the United States and by M. Berger & Wolfgang Göhde of Germany; and in the 1980s by Colin J. Pennycuick of the United Kingdom. Furthermore, the distribution of the wind speed above the sea surface had been well described in previous research.

Combining these results, we worked out a set of differential equations that describe the dynamics of flight. We also expressed the wind profile close to the water's surface as a function of the wind speed at higher altitudes. Together, the two elements of our model were able to simulate the flight of the bird based on the lift coefficient, the bank angle, and the wind speed.

We then plugged our model into high-performance optimal control tools. We instructed our computer program to find the control inputs that would yield a trajectory an albatross could trace without flapping its wings under the following constraints: first, that the direction of flight and the total energy state—the sum of kinetic and potential energies—were the same at the beginning and the end of a flight cycle (as it must be in the endlessly repeating soaring cycle); and second, that the program search for the maneuver that worked at the lowest possible wind speed.

The result we got was a minimum wind speed of 8.6 to 8.9 meters per second, at a

FLYING FREE *as a* BREEZE

UNFLAPPING FLIGHT, CALLED DYNAMIC SOARING, allows the wandering albatross to extract energy from the shear wind field, in which the wind's strength increases with each additional meter above the water's surface. Beginning near the surface, the bird climbs into the wind [1], turns to leeward [2], descends [3], and again turns into the wind [4].

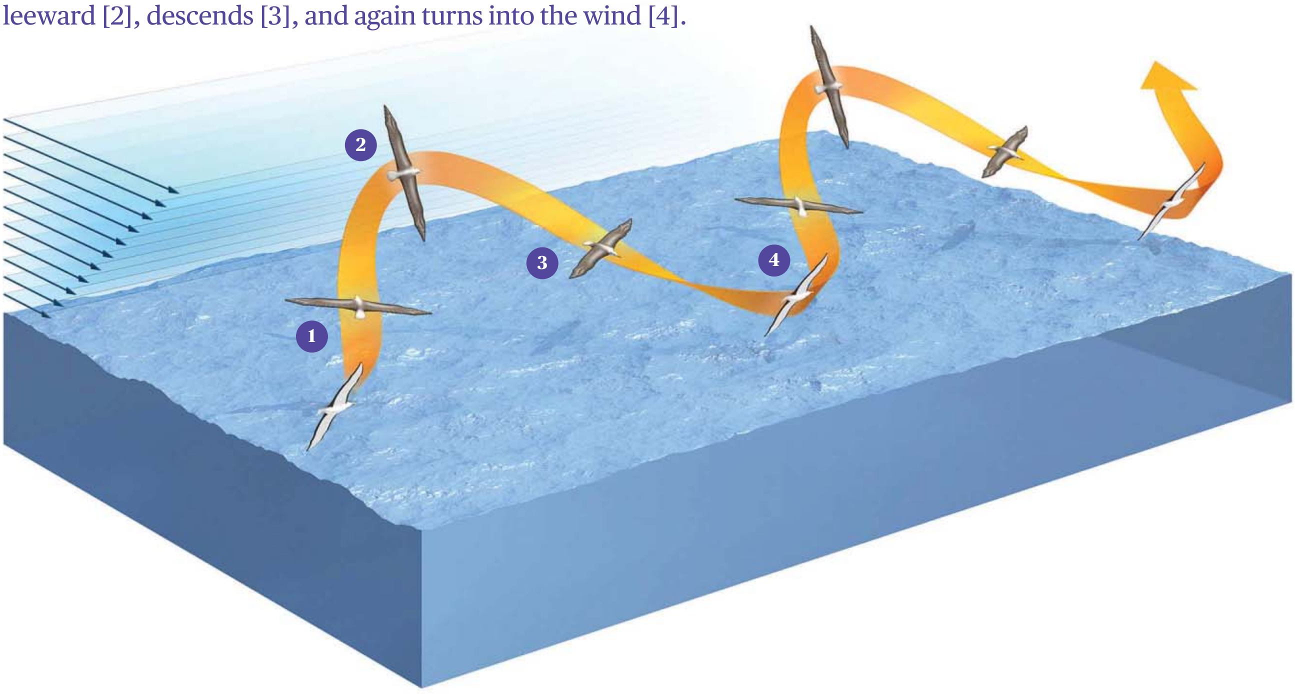


ILLUSTRATION BY Emily Cooper

APPROACHING A MAN-SIZE nesting bird requires tact, but no harm is done in gluing an ultralight GPS logger onto the back feathers. There it can track the bird's flight over many days.

reference altitude of 10 meters. Our boundary condition ensured that the predicted trajectory would be energy neutral, so that once started it would continue to repeat itself.

Our model thus predicted that albatrosses could soar dynamically as long as the wind speed is a bit more than 30 kilometers per hour (16 knots). It is no coincidence, then, that these birds live in the far southern latitudes known as the Roaring Forties and the Furious Fifties, where typical wind speeds are much higher than that. What is more, our results indicated that the shear wind field alone could enable the flight of the birds. No effects from waves, turbulence, or anything else are required. Proving our calculations, however, required getting some real measurements.

TO PROVE THE THEORY EXPERImentally, we knew we would need to capture the albatross's quick-changing flight vectors. The meter-level accuracy and once-per-second readings of the GPS receiver in your car aren't fine grained enough for that job. We needed decimeter precision and an update rate of 10 hertz. We did find some geodetic units that deliver GPS readings to the centimeter level, but they came with constraints that no wandering albatross would stomach: hardware far too big and heavy to fly with, a range to the base station's receiver far shorter than the bird naturally travels, and, in many cases, an initial calibration that would require the bird to stay completely still for up to 15 minutes.

After some head scratching, we came up with a solution: We used miniaturized mass-market receivers that normally calculate positions to meter-level accuracy at 1 Hz. But instead of having the device calculate its position in real time, we rigged it to log GPS raw data at 10 Hz, so that we could process the information at our leisure, back in the office. We were able to do this because we didn't care about the unit's absolute accuracy, only its precision—that is, we wanted to know the shape of a particular soaring maneuver relative to its starting point, wherever that starting point might be. And so we didn't need to initialize the system or keep it close to a base station.

We came up with a novel, time-differential algorithm that exploits the same type of raw measurements used by most geodesy software: highly precise albeit ambiguous measurements of the phase of a GPS satellite's carrier signal (or L1). Normally, a navigation system will rely mainly on tracking a coarse yet robust code modulated on a high-frequency carrier signal. That way the system can measure the absolute distance between the receiver and each satellite in view to within a meter. Our strategy of directly exploiting the fragile carrier signal let us measure merely the change in the range since signal acquisition, but to do so to within a centimeter. We could thus precisely distill dynamic soaring maneuvers out of the carrier-phase data without knowing exactly where the maneuvers started.

IN DECEMBER 2008, TWO OF US (Traugott and Nesterova) headed out to the field to put our ideas and our equipment to the test. We flew to Réunion, east of Madagascar; the French island constitutes one of the outermost parts of the eurozone. There we boarded the southbound French research vessel *Marion Dufresne II*. Two weeks later we reached the Kerguelen Islands, 2800 kilometers east of South Africa, getting off at the research station in Port-aux-Français. We then had an 8-hour eastward hike to our base camp, a simple hut without running water or electricity. Our expedition included several other researchers working with two French organizations: the Center for Functional and Evolutionary Ecology, directed by Francesco Bonadonna of the University of Montpellier, and the French Polar Institute Paul Émile Victor.

Nesterova, the biologist, had come mainly to study king penguins, not albatrosses. But it was well that she was there. As an aerospace engineer, Traugott had never handled a wild animal, much less one with a beak as long and sharp as a carving knife; he had never even seen a wandering albatross up close.

One of our main tasks during the six weeks we spent in the field was to watch for the brief changings of the guard between breeding pairs. Only at such a hand-off could we capture and tag a bird we knew would fly out soon. We kept an eye on about 35 albatross nests scattered quite widely in the vicinity of our hut. We had permission from the French administration of the archi-

LEFT: JOHANNES TRAUGOTT; RIGHT: INSTITUT POLAIRE FRANÇAIS PAUL EMILE VICTOR (IPEV, PROGRAM NO. 354) pelago to fit up to 20 birds with loggers, and we didn't want to miss a single opportunity.

We equipped our first bird the week before Christmas. The procedure by which we mounted the GPS logger has been widely used by other researchers; it exposes the animals to a minimum stress level, and, just as important, it keeps the device in place. We taped the logger to second-layer feathers right below the shoulder joints and secured the tape with superglue.

Three days later, our first bird returned. As Traugott approached the nest, his heart was pounding. But the GPS logger was gone! All that effort for a small piece of electronics that now lay at the bottom of the ocean. Head bowed, he returned to the hut to tell Nesterova. She frowned. "Let's have a closer look," she said. Back at the nest, our bird had already taken over for his mate, who had left to go find breakfast.

Nesterova crawled to the nest, took the bird firmly but gently in hand, and then carefully examined it. The logger was still there! It had simply been covered up with plumage. We used a pair of scissors to cut the tape. Finally we had the bird's precious payload in our hands.

Back in the hut, we eagerly downloaded the data to a laptop. The in-depth processing would be done back in our Munich office, but we wanted to find out if we had managed to log any in-flight data, how good the data were, and whether we needed to tweak some system parameters to make the next logging trip more successful. Indeed, a first check revealed that the raw data on the carrier phase were not of the quality we'd hoped for, but still good enough to work with. It seems that the quality problem stemmed partly from the multiple paths taken by the reflections of the signal from the waves. Processing this data back in Munich was challenging.

BACK HOME, OUR ANALYSIS CONtinued. As we described earlier, dynamic soaring involves a climb into the wind, a curve to leeward, a leeward descent, and a reverse turn close to the sea surface, where the cycle begins anew. Our measurements were the first to demonstrate that the total energy in these maneuvers is the same at the beginning and the end of the trajectory. We also found that the closer the bird got to the water's surface, the lower the total energy; right near the water, there was no gain at all. Our work therefore proved that the waves and related turbulence play no significant role in the bird's flight. We discovered that total energy tops out after the bird makes its upper turn, so this has to be the part of the cycle in which it extracts the most energy from the wind.

On top of this energy analysis we looked at the aerodynamic forces acting on the bird, which were quite complex. The es-

THE KERGUELEN ISLANDS are a base for wandering albatrosses, which circumnavigate the Furious Fifties and other latitudes of the uttermost south.

sence is as follows: The local shear wind lets the bird change the direction of the lift it generates as a kind of propulsive force during the upper curve of the cycle. At that moment, the strong wind acts like a kind of outboard engine. Afterward, the bird dives close to the water and then turns back up, in the process incurring a braking effect. The bird still has a "propulsion profit" over the whole cycle that just manages to overcome drag. As long as it keeps up that pattern of dips, swoops, and turns, it can keep on flying—flying for free.

In short, the insights offered by our GPS measurements largely confirmed the findings of our optimization-based analysis. We now know a lot more about the fascinating flight of these beautiful animals than we did before. Of course, there is always room for refinement.

For one thing, we weren't able to measure the birds' air speed directly because any appropriate sensor, such as a pitot tube, would stick out of the plumage quite a bit—probably enough to affect flight and surely enough to annoy the birds. Instead we had to rely on rather coarse remote wind information provided by satellite measurements (QuickSCAT ocean surface wind vectors).

In the future, we'd also like to measure attitude—the angles of roll, pitch, and yaw. The rapid development of inertial sensors made with microelectromechanical systems should allow us to do that the next time around.

This project is more than a sideline in natural history. The open sea isn't the only place that offers a shear wind field suitable for dynamic soaring, and wandering albatrosses aren't the only pilots that rely on it to conserve energy. Such boundary layers also exist within the high-altitude jet streams that encircle Earth; even though these layers are much thicker than the one the albatross flies in, the physics are the same. That means that UAVs with the proper aerodynamics and programming might one day exploit them to stay aloft for weeks or months on end, allowing them to serve as surveillance nodes or radio relay links.

And indeed, flight optimizations we've done in related research show that aircraft having the aerodynamics of today's gliders or sailplanes could perform sustained dynamic soaring in these atmospheric layers by accordingly scaled maneuvers. "Surfing the jet stream" is no mere fantasy; it is a reasonable strategy for aeronautical engineers to pursue. ■

POST YOUR COMMENTS online at http://spectrum.ieee.org/albatross0713

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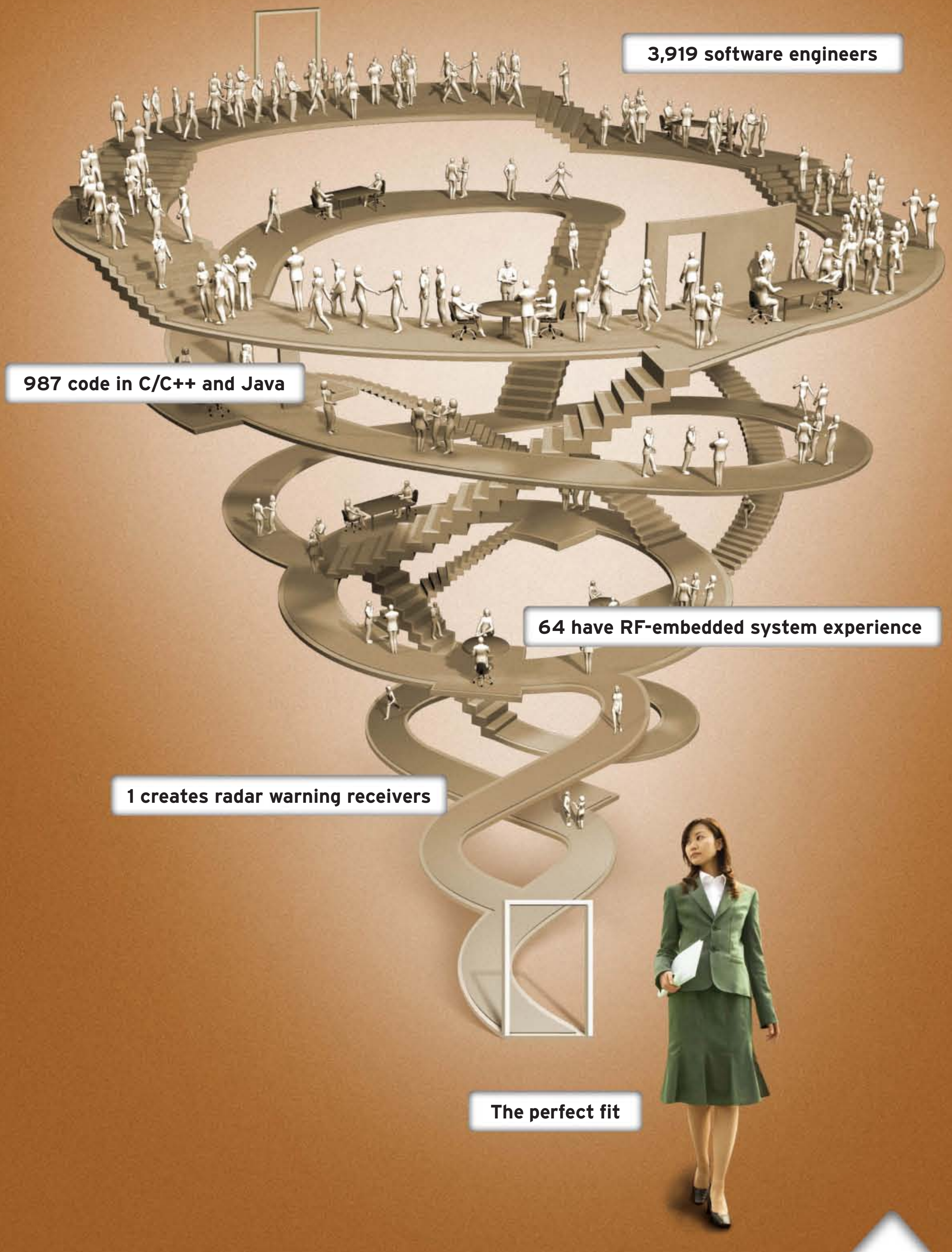
3,919 software engineers
987 code in C/C++ and Java
64 have RF-embedded system experience
1 creates radar warning receivers
The perfect fit

A **Postdoctoral** position is available in the Renewable Energy laboratory at the Petroleum Institute (PI) in Abu Dhabi. Renewable Energy lab is one of the richest labs in the PI which facilitates advance researches in the area of distributed generation systems, smart-grid, linear and non-linear control theories and applications. The recruited researcher will work on funded research projects initiated by Dr. Ahmed Al-Durra from EE Department of PI. The projects work includes fundamental/applied research on various renewable energy sources (wind, solar, tidal, etc.), modeling and simulation, and controller-hardware-in-the-loop (CHIL) testing using real time digital simulator (RTDS) along with experimental validation using wind turbine test rig, PV and energy storage systems, etc. The experimental setup will facilitate real time testing using DSP, MATLAB/Simulink, and Simulink coder. The successful candidate will join a group of researchers (faculty and graduate students) specialized in both control and power systems.

Qualifications: Interested candidates should have a Ph.D. in Electrical engineering with strong background in Advance Control Systems as well as Power Systems in addition to be expertise in Data Acquisition System and DSP.

We are particularly interested in candidates with the following qualities:

1.Strong background in Advance Control System and Power System
2.Ability to effectively build and troubleshoot embedded hardware boards
3.Good hands on experience with power electronic converter and PCB
4.Self-independent and self-motivated
5.Very good mathematical background. Experience in Modeling is a great advantage
6.Very good written and oral communication skills
7.Work experience in relevant research projects is preferable.

Salary/Benefits: Salary and benefits will be commensurate with qualifications and experience. The total compensation package includes a tax-free 12-month base salary, and a benefits allowance that covers relocation, housing, initial furnishings, utilities, transportation (automobile purchase loan), health insurance, child(ren) education, end-of-service benefit and annual leave travel. Applicants must be in excellent health and will be required to pass a pre-employment physical examination.

To Apply: Interested candidates must submit all materials online at our website at http://www.pi.ac.ae/jobs or by email Academic.Recruitment@pi.ac.ae.

This is a fixed term position for three years and is available immediately. The deadline for applications is 31st July, 2013. Only shortlisted applicants will be notified.

Additional information about the position may be obtained by contacting Dr. Ahmed Al-Durra by telephone: +971 2 607 5511 or by email: aaldurra@pi.ac.ae.

National Cheng Kung University
Department of Electrical Engineering
Macronix International Chair Professorship

The Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan, invites applications for full-time Macronix International Chair Professorship. A cash award of NTD 1,500,000 (approximately 50,000 USD) will be granted. The Department of Electrical Engineering currently has 80 faculty members, about 700 undergraduates, and 1300 graduate students in the following areas: Instrumentation Systems and Medical Chip Design, Microelectronics, Computer and Network, Communication and Network, Power Systems and Power Electronics, VLSI/CAD, Control, and Electronic Materials. Applications will be processed upon receipt of application materials until the position is filled. To apply, please send your curriculum vitae, contact information for three references, reprints of one or two representative publications to:

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Website: http://www.ee.ncku.edu.tw/

Note: Besides, several full-time faculty positions in semiconductor nanoelectronics (devices and nanofabrication), microelectronics and electronic materials, and power electronics and systems are also available. To apply, please send your application materials by September 15, 2013.

XJTU–HKUST
Joint School of Sustainable Development

under planning

西安交通大學 XI'AN JIAOTONG UNIVERSITY | 香港科技大學 THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Founding Department Heads for (I) Sustainable Energy; & (II) Sustainable Materials

We seek established academics to be founding Heads of the Joint School of Sustainable Development (JSSD) being built in partnership between The Hong Kong University of Science and Technology (HKUST) and Xi'an Jiaotong University (XJTU). Located in Xi'an, the gateway to the fast emerging western region of China, the Joint School aims at combining the strengths of the two universities to train a new generation of graduates who are capable of contributing to sustainable development and to undertake interdisciplinary high-impact research in energy conservation, resource management and environmental protection. Within the next 5 years, the School is expected to have up to 60 faculty members and an enrollment of more than 1,000 undergraduate and postgraduate students. English is the language of instruction.

Sustainable Energy and Sustainable Materials are two of the three planned departments of the Joint School. Identified core research areas include:

Sustainable Energy — sustainable use of fossil fuels and environmental impact; alternative energy sources; energy distribution and storage; system and engineering design for sustainability; energy policy and management.

Sustainable Materials — fundamentals of materials science and engineering for sustainability; sustainable adoption of materials; design of new materials; application of sustainable materials.

The founding Department Heads will be senior faculty members of HKUST appointed for posting to JSSD in Xian to lead the formation of the departments. Expected to be world-class scholars with a vision to advance education and research in sustainable development, they will typically have substantial experience and proven leadership skills in managing major research programs and human resources in an academic or large-scale research setting. For details please visit https://www.ab.ust.hk/hro/PubDoc/careers/ (Job ID: 1425). Remuneration is highly competitive.

Nominations and applications, including a curriculum vitae, a vision statement of the development of the new department, a brief statement of current interests, as well as the contacts of at least three references should be sent to: **The JSSD Search Committee, c/o Human Resources Office, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong**, or by email to: **jssdsearch@ust.hk**.

GRADUATE RESEARCH ASSISTANTSHIPS / POST DOCTORAL POSITIONS

HCAC Hawaii Center for Advanced Communications

in wireless communications, computational electromagnetics, digital signal processing, microwave devices, radar technology, and antennas, are available at Hawaii Center for Advanced Communications (HCAC), **College of Engineering, University of Hawai'i at Manoa** (**http://hcac.hawaii.edu**). HCAC's variety of projects/sponsors (NSF, ONR, Army-CERDEC) and state-of-the-art laboratories provide excellent research opportunities leading to Ph.D. Minimum qualifications (RA): Bachelor's degree from accredited four-year university in EE. (Post Doc): Ph.D. within last 3 years. Email CV, transcripts, 3 references to imanaka@hawaii.edu. University of Hawai'i is an Equal Opportunity/Affirmative Action Institute.

The Petroleum Institute, Abu Dhabi, United Arab Emirates

Postdoctoral Position – Electrical Engineering Program

PI THE PETROLEUM INSTITUTE

The Electrical Engineering Department at The Petroleum Institute in Abu Dhabi, United Arab Emirates, is inviting applications for a full-time postdoctoral position in the area of Electric Machines and Drives. Applicants who are either recent PhD graduates or have held postdoctoral positions will be considered.

Position Description: The postdoctoral research position is focused on predicting the behavior of electric machine, application of developed methods in condition monitoring techniques. Developing drives for electric machines to work in certain environment.

Qualifications: The applicant must hold a PhD degree in electrical engineering, and have:Solid background in electric machine and drives as well as control techniques. Strong knowledge of conducting experimental works, design of PCBs, testing etc.Strong background of using Matlab/Simulink, FEMM, D-space, and any other programming software. Experience in building test-rigs and conducting experimental work. Fluent in English, both writing and speaking. Ability to work independently and as part of a research team.

Salary/Benefits: The total compensation package includes a tax-free 12-month base salary, and a benefits allowance that covers relocation, housing, children education, initial furnishings, utilities; transportation (automobile purchase loan), health insurance, and annual leave travel. Applicants must be in excellent health and will be required to pass a pre-employment physical examination.

Institution: The Petroleum Institute was created in 2001 with the goal of establishing itself as a world-class institution in engineering education and research in areas of significance to the oil, gas, and the broader energy industries. The PI's sponsors include Abu Dhabi National Oil Company and four major international oil companies. The campus has modern instructional laboratories and classroom facilities. For additional information, please refer to the PI website: www.pi.ac.ae.

To Apply: Interested candidates must submit all materials online at our website at http://www.pi.ac.ae/jobs or by email Academic.Recruitment@pi.ac.ae.

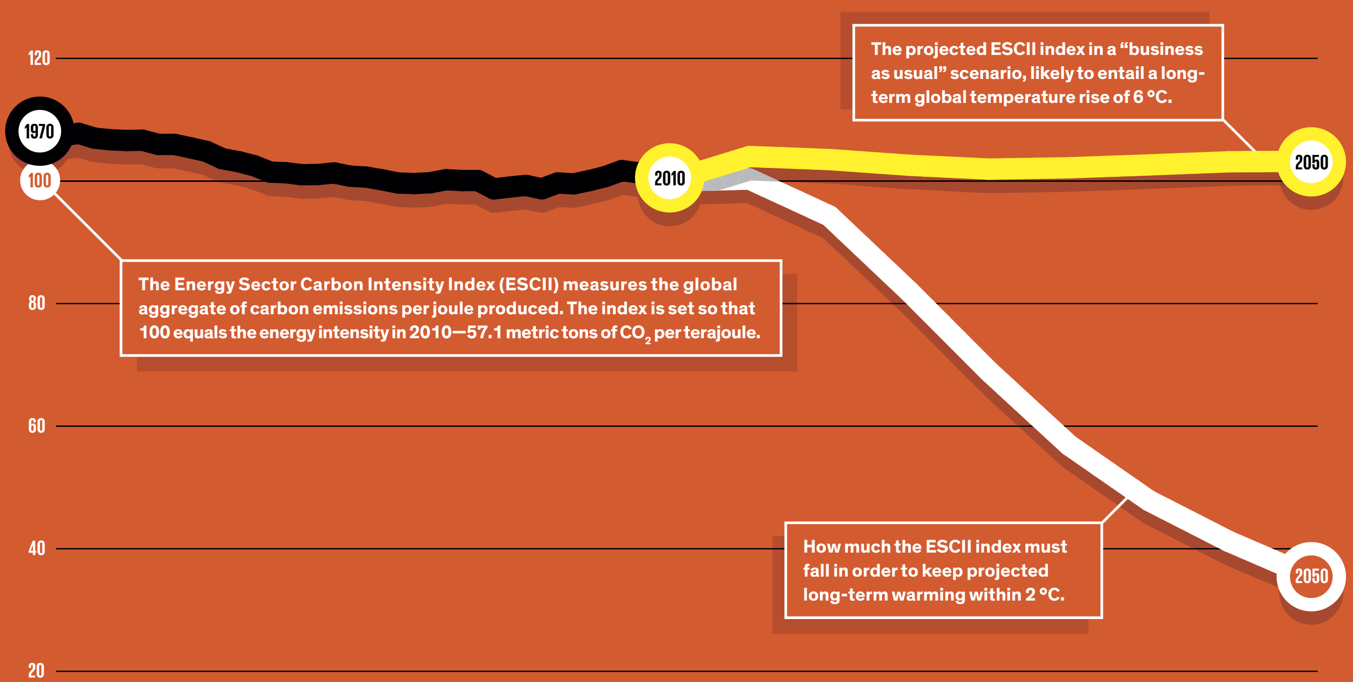
To be considered, applicants need to submit a cover letter, curriculum vitae summarizing their educational and professional background, statements of research and teaching interests, and the names and contact details of at least three referees. Only shortlisted applicants will be notified.

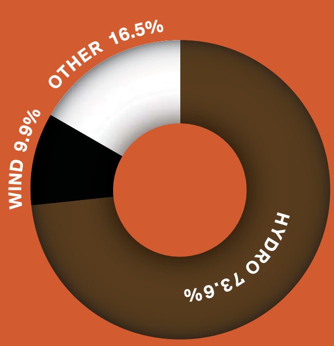
DATAFLOW_

FIGHTING COAL TO A DRAW

RENEWABLES ARE MAKING PROGRESS, BUT NOT ENOUGH TO DENT EMISSIONS

In April, the International Energy Agency, in Paris, introduced a new index that will track the carbon intensity of global energy production. In a result that the IEA calls "grim," the index reveals that despite the growing deployment of renewables, we are still producing, per joule, virtually as much carbon as we produced two decades ago. Most of this production is due to the growth of coal-fired electricity generation driven by soaring energy demands in Asia. Consequently, in addition to cleaner generation, the IEA is urging stronger efforts in deploying carbon capture and storage technologies and developing more-efficient industrial processes. —STEPHEN CASS



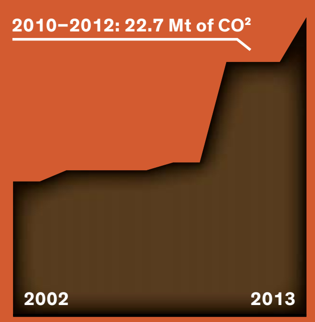


SLOW RENEWABLES

Despite robust growth, renewable energy still accounted for only 19 percent of global electricity generation in 2011. In order to keep global warming within 2 °C, the IEA projects that by 2020, renewables must account for 25 percent of generation. Wind power has seen the most rapid development, going from 31 terawatt-hours in 2000 to 447 TWh in 2011, a 1539 percent growth rate.

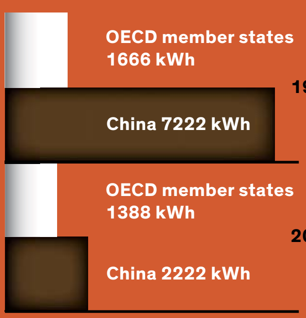
COAL IS STILL KING

Although coal is also used for heating and industrial processes, much of global coal demand is due to electricity generation. Between 2000 and 2010, coal-based generation increased 45 percent. The demand for coal is expected to increase to 50 000 TWh by 2017.



CAPTURE SPUTTERS

Large-scale deployment of carbon-capture technology has been slow to develop, with the annual capacity of all projects not exceeding 25 million metric tons of CO_2 per year until 2013. However, more projects are currently in the advanced planning stages that represent an additional 27 megatons per year of CO_2 capacity. Eight planned capture projects were canceled in 2012.



FACTORY SETTINGS

Industry around the world has reduced the amount of energy required to add a dollar in value to materials or components, mostly through modernization, but progress has stalled. Despite greatly reducing its industrial energy intensity, large absolute growth in Chinese industry means that by 2010 China was responsible for 28 percent of global industrial energy consumption, up from 14 percent in 2000.

SOURCE: INTERNATIONAL ENERGY AGENCY, TRACKING CLEAN ENERGY PROGRESS 2013, ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT/IEA, PARIS

INFOGRAPHIC BY Carl DeTorres

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