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THE MARTIAN SPACE SUIT

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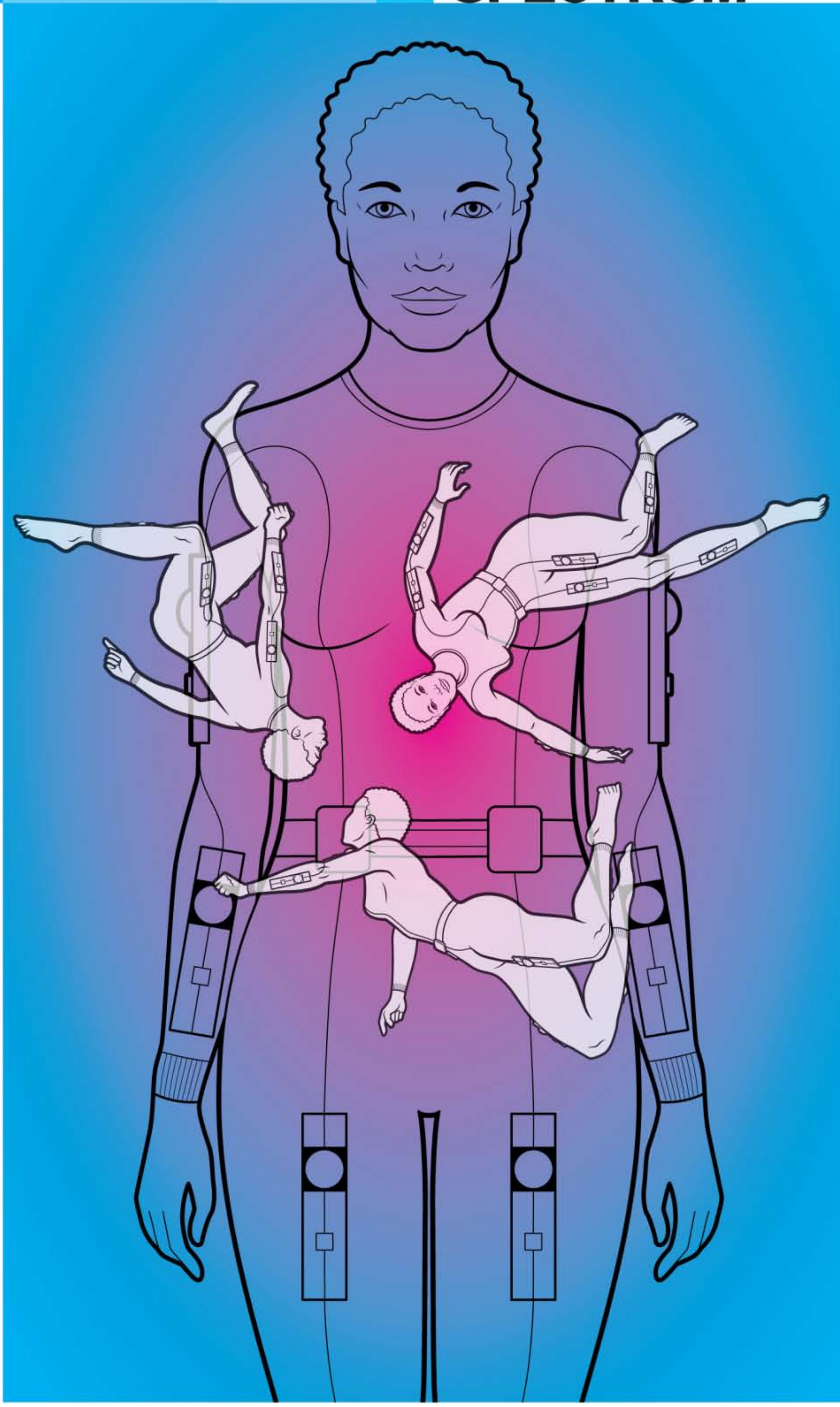

On the Cover **Illustration for *IEEE Spectrum* by Flavio Montiel Cezaretti**

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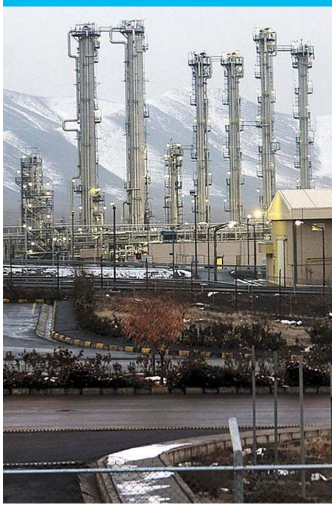

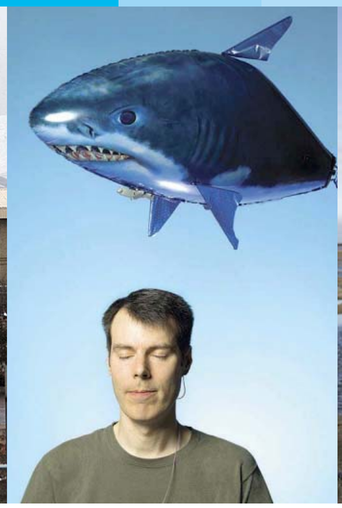

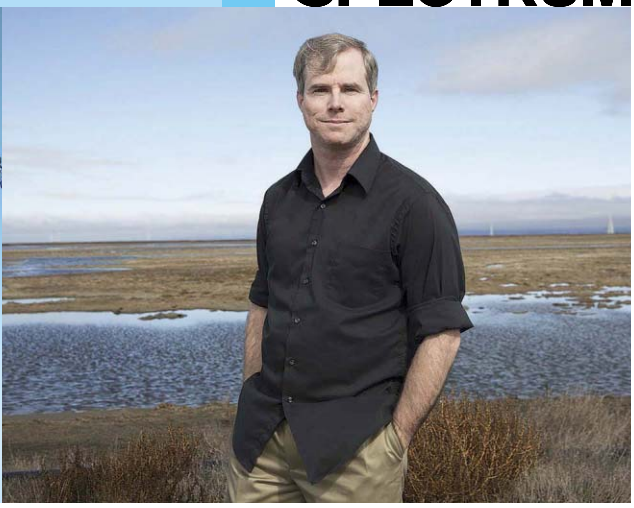

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Interactive video: Andy Weir talks Mars, *The Martian*, and the movie
Explore this interactive video feature to see Andy Weir, author of the adapted novel, discuss the science behind his plot twists, his visit to Johnson Space Center, and exactly why Mark Watney got stuck eating potatoes. See http://spectrum.ieee.org/weir1015

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- **THEME PARK TECHNOLOGY** To mark the 60th anniversary of Disneyland, *The Institute* caught up with IEEE Member Glenn Birket, who has helped design the control systems for rides and attractions at nearly all of Disney's parks—including the one opening next year in Shanghai.

- **IEEE HONORS THE FIRST VIDEO GAME** Long before PlayStation 4 and Xbox One, there was the Brown Box, invented by IEEE Life Fellow Ralph Baer. The console, which debuted in 1972 as the Magnavox Odyssey, received an IEEE Milestone.

- **COMING SOON: THE INTERNET OF THINGS** It's projected that billions of devices will soon communicate with their users and each other. From 14 to 16 December, 350 attendees will gather in Milan at the IEEE World Forum on Internet of Things, with the goal of bringing the IoT closer to reality.

FROM LEFT: HAMID FOROUTAN/AFP/GETTY IMAGES; DAVID YELLEN; CHLOE AFTEL/CONTOUR BY GETTY IMAGES

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BACK STORY_

In an Astronaut's Shoes

MICHELE CARPENTER HAS SPENT the past several years developing technology to help astronauts work in zero gravity. But the possibility that she herself might get a chance to experience weightlessness seemed rather remote, until earlier this year.

Carpenter, an engineer at Draper Laboratory, investigates how control moment gyroscopes in astronaut jet packs can provide rotational nudges that will help stabilize spacefarers and give them leverage as they work in the weightlessness of space [see "A New Spin on Space Suits," in this issue]. In August, Carpenter joined a group from MIT to test some of her lab's gyroscopes on a series of parabolic flights aboard NASA's famous zero-gravity aircraft, nicknamed the "Vomit Comet." In such flights, an airplane performs steep climbs and dives, producing a half-minute period of weightlessness around the top of each arc.

DRAPER LABORATORY

After taking off with her collaborators from Ellington Airport, in Houston, Carpenter [center] felt some disorientation as the plane went into its initial zero-*g* arc. "The very first parabola felt like when you're going down the very first drop on a roller coaster–your stomach flips," she says.

Over four days, the team performed experiments using two SPHERES, special thruster- and sensor-equipped test platforms. In one test, the SPHERES were connected; one fired its thrusters while the other used its control moment gyroscopes (CMGs) to stop the resulting rotation. This mimicked one of the aims of the CMG-equipped jet-pack design–creating better attitude stability.

The tests could be challenging. "Not all the parabolas are equally useful," Carpenter explains. An experiment could be cut short if a SPHERE was released in the wrong way, bouncing into other equipment or a cabin wall. Imperfections in the airplane's motion sometimes produce a strong drift. But Carpenter was nevertheless happy with the experiments. Now comes the moment of truth: analyzing the data to see exactly how well the SPHERES performed. ■

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes an international and a North American edition, as indicated at the bottom of each page. 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, And Now This... is in *IEEE Spectrum*, Vol. 52, no. 10 (INT), October 2015, p. 60, or in *IEEE Spectrum*, Vol. 52, no. 10 (NA), October 2015, p. 72.

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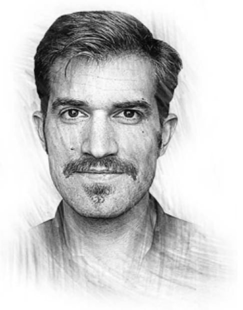
CONTRIBUTORS_

Barbara Han

In this issue, Han, a research scientist at the Cary Institute of Ecosystem Studies, in Millbrook, N.Y., describes the machine-learning methods she uses to identify animal species that may carry dangerous pathogens [p. 42]. While she has done biological fieldwork in the past, these days she interacts with animals through her data sets. She's somewhat surprised to have ended up as a computer programmer, but there are aspects of fieldwork that she doesn't miss. "I like working with animals, but I don't like being bitten by animals," Han says.

Richard B. Kaner

Kaner, a chemistry professor at the University of California, Los Angeles, and his graduate student, Maher F. El-Kady, found they could create graphene-based supercapacitors with the laser in a DVD burner [see "Introducing the Microsupercapacitor," p. 36]. "Maher dragged me into the lab," Kaner says. "He took a lightbulb, and he just turned it on with this little piece of graphene. After charging for 2 or 3 seconds, he ran this light for over 5 minutes. I thought we had something important. I thought the world changed at that point."



Lucas Laursen

A while back, Laursen, a freelance science and technology journalist, stumbled upon a job ad for an electrical engineer based in Antarctica. And he wondered, if you wanted to start a career in Antarctica, what would you need to do to get there? For this issue, he writes about several such intrepid engineers [p. 19], as well as juiced-up Formula E race cars in Beijing [p. 9]. While Laursen has reported all over the world, he calls Madrid his home.

Cyrus C.M. Mody

Mody is a historian at Maastrict University, in the Netherlands. In this issue, he and Kevin F. Kelly, a physicist at Rice University, write about the bumpy history of molecular electronics [p. 48]. A course they taught together on technological disasters included several potentially relevant case studies, Mody says. "Only time will tell if molecular electronics is like the successful leap from propeller to jet engine propulsion, or the feasible but too costly supersonic commercial jet, or the much touted but failed nuclear-powered plane."

Lauren J. Young

Young was *IEEE Spectrum*'s summer intern this year. In this issue, she explains the direction that 5G wireless is likely to take [see "Telecom Experts Plot a Path to 5G," p. 10]. "The sheer number of technological developments that will have to happen in order to get to 5G is really exciting," she says. We expect her to continue reporting about those and other science and engineering developments after she graduates from New York University's Science, Health and Environmental Reporting Program in December.

PHOTO-ILLUSTRATIONS BY **Gluekit**

FLYING FASHION: Testing Final Frontier Design's 3G Mark III space suit.

Space Suits for the Mars Generation

The Martian's Matt Damon looks great lost in space, but what will next-gen space suits really require?

WHENEVER HOLLYWOOD STARS VENTURE OUT into infinity and beyond, they get a slick new wardrobe upgrade. *Gravity*'s Sandra Bullock has her hip-hugging Sokol suit. *The Martian*'s Matt Damon sports color-coordinated Red Planet gear.

But real astronauts aren't as lucky. They get stuck wearing the same old space duds, sometimes for decades. Space travel is expensive, and space attire itself is costly and difficult to make. So even if some of our current space suits are based on patents from the 1950s, why not keep using those same designs if they've already been tested and still work?

Nonetheless, because of the burgeoning human-travel commercial space industry, and renewed interest in going to Mars spurred on by the spectacular Curiosity rover mission and the Mars One space settler effort, space suits are getting another look.

In this issue we have two articles on Mars-generation space suits. "A New Spin on Space Suits," by Michele Carpenter and Kevin Duda from Draper Laboratory, describes how personal "gravity packs"—suits with gyroscopes embedded in them—could help astronauts stay upright and aware of their orientation, as well as help protect them from the physical deterioration experienced in zero-*g* environments. Senior Associate Editor Rachel Courtland's piece, "Suiting Up for the Red Planet," walks us through NASA's extravehicular Z-2 suit, which could be used for Mars exploration.

NASA has also, through its Small Business Innovation Research program and Commercial Crew Program, been reaching out beyond traditional space-suit manufacturers like David Clark Co. and ILC Dover to seek out new intravehicular activity (IVA) suit designs that are lighter, less expensive, and more flexible.

Out in New York City's resurging Brooklyn Navy Yard, Final Frontier Design (FFD), under the leadership of Ted Southern and Nikolay Moiseev, is hard at work trying to meet these requirements. Southern is a tech-infused designer with a background in body armor and costume design. For over 20 years, Moiseev was the lead engineer at NPP Zvevda, the Russian space-equipment manufacturer. Together with Kari Love and Virgil Calejesan, this four-person company has come up with a new space suit well regarded enough to be awarded a NASA Space Act Agreement. FFD shares the distinction with SpaceX, which has about 4,000 employees; Alliant Techsystems, which has several thousand employees; and United Launch Alliance, a joint venture of Boeing and Lockheed Martin, with more than 3,000 workers.

FFD is hoping to sell its pressurized IVA suit to the commercial market—companies like Boeing, SpaceX, and Virgin Galactic. Its garment is 4.5 kilograms lighter than the current NASA IVA suit and about a third of the cost. It is highly adjustable and now, through the magic of 3-D metal printing, it can be readily reconfigured for different flight vehicles.

FFD recently got a new contract from NASA to develop a mechanical counterpressure glove for the Mars mission. Space gloves are notoriously difficult to make flexible and protective; spacewalkers have said that working on the International Space Station in them is like trying to change a tire wearing baseball gloves.

Ultimately, FFD would like to produce mechanical counterpressure suits as well. These would be like MIT's proof-of-concept BioSuit, pioneered by Dava Newman, who is now NASA's deputy administrator. Mechanical counterpressure gloves and suits would be safer than their pressurized counterparts and have a much better range of motion.

When we did our "Why Mars? Why Now?" issue in 2009, we got a lot of the usual comments: complaints about the expense and about prioritizing space exploration over our many intractable earthbound problems. But it's not an either/or proposition. Those of us who grew up during the 45 years since the Apollo landing expected humans to be on Mars already. Space travel captures people's imagination. Technologies that benefit earthlings will undoubtedly stream out of developing the technologies to go to Mars, as they have from previous space programs. The kids who will make up our future generations of scientists and technologists assume we are going to Mars. Why not suit up? —SUSAN HASSLER

FINAL FRONTIER DESIGN

NEWS

€132,540,092

ANNUAL BUDGET FOR THE IAEA'S NUCLEAR VERIFICATION ACTIVITIES

HAMID FOROUTAN/AFP/GETTY IMAGES

KEEP CLOSE WATCH: Iran's Arak nuclear facility is one that the IAEA wants to monitor.

ANTINEUTRINOS COULD REVEAL ROGUE NUCLEAR PROGRAMS

Advanced detectors are in the works, but better low-tech approaches are also needed

Any deal to keep an aspiring nuclear-armed state from acquiring a weapon must be based on verification, not trust, as President Obama has repeatedly asserted. That verification is charged to the International Atomic Energy Agency (IAEA), whose inspectors would visit a country such as Iran to ensure its facilities are in compliance.

Critics of the current deal between Iran and major world powers point to the agency's limited verification tools. However, several advanced monitoring technologies that could make verification easier and more accurate are in the works. And with 60-plus nuclear power plants under construction around the world and spent-fuel stores piling up, these safeguard technologies might be useful in other places as well.

There's a real need for them, says Nancy Jo Nicholas, associate director for threat identification and response at Los Alamos National Laboratory (LANL). "There is talk about a global renaissance in the nuclear industry," she says. "There will be more facilities, so giving inspectors tools that allow them to do their »

SOLID ANTINEUTRINO DETECTOR: A new kind of antineutrino detector that uses solid scintillators was tested in February 2015.

job in an efficient and effective way is a clear benefit."

For now, the IAEA, based in Vienna, relies on a combination of surveillance cameras, satellite imagery, and site visits. Inspectors conduct a suite of measurements on-site and check when electronic and optical seals placed on fuel containers were last opened. (Newer seals use RF links to send encrypted data to a central data collector, which passes the information on to the IAEA offices.)

But these technologies are not accurate enough and can be fooled. Radiation monitors can be befuddled by signals from natural or legitimate radioactive materials. Seals–of which there are hundreds of types–can be hacked, says Roger Johnston, past head of LANL's vulnerability assessment team, who cofounded and runs the security consulting firm Right Brain Sekurity.

One particular technology promises to make up for these shortcomings: antineutrino detectors. Nuclear reactors are the largest man-made source of antineutrinos–subatomic particles with tiny mass and no electric charge. The number and energy spectrum of antineutrinos boiling out of a reactor indicates reactor power and the precise amount of nuclear isotopes in the core. This means that inspectors could verify if the reactor is running as intended or if uranium has been added or plutonium removed.

The challenge is in detecting the elusive particles: Only one in 100 billion passing through matter interact with it. Today's detectors capture the particles using gadolinium-spiked water or solvent inside tanks several meters on a side. In the tanks, an antineutrino occasionally collides with protons in the liquid, creating a neutron and a positron. Photodetectors sense light flashes produced when the positron crashes into an electron and when the neutron is captured by the gadolinium.

The large tank of liquid must be put underground to block out cosmic rays that can lead to false positives, and that can be a problem. So a team of British and French researchers has designed a lithium-based solid detector that should be portable and easy to deploy at a reactor. Neutrons don't travel as far in the solid as they do in a liquid before running into an atom to produce light.

"We can detect positron and neutron events exactly where they happen in a cube as small as 5 by 5 centimeters," says University of Oxford physicist Antonin Vacheret, who is leading the project. By imaging that small volume, the researchers can precisely measure the distance between the positron and neutron events. This distance is unique for antineutrinos born in a nuclear reactor. The accuracy should allow for a compact detector that doesn't need to be underground or shielded against cosmic rays, Vacheret says. A 1-metric-ton detector measuring 20 by 80 by 45 cm has recorded data from a Belgian research reactor since August 2014, detecting about 260 antineutrinos per day. Detailed results aren't public yet, but "what we're seeing is very encouraging," Vacheret says. A larger prototype should be installed at a commercial reactor in Virginia by the end of 2015.

Small antineutrino detectors would have to sit within tens of meters of a reactor core to do any good. What nuclear safety agencies could really benefit from is a detector that could monitor reactors and maybe even spot clandestine ones from kilometers away. One proposed project in the United States offered that hope: The WATer CHerenkov Monitor for AntiNeutrinos, or Watchman, a collaboration among several universities and national laboratories.

Watchman would have built on a series of recent experiments at the San Onofre nuclear power plant in California. It was to use 3,500 tons of gadolinium-doped water to monitor a nuclear power station 13 kilometers away. If the technology proved itself, a giant million-ton detector could spot antineutrinos from a reactor 1,000 km away, the project's masterminds say in their proposal. Such a reactor could potentially be built in a neighboring nation to keep tabs on an uncooperative state.

However, on 28 May, the U.S. Energy Department informed researchers that it would not fund the project. "This was disappointing and somewhat surprising to me personally, given the current importance of nonproliferation detection to our current national interest," says Bob Svoboda, a University of California, Davis, physicist and co-spokesperson for the project.

Antineutrino detection holds tremendous promise, says Thomas Shea, an independent consultant who has worked as an IAEA inspector. But it's still at an early stage, and the IAEA will need to see a conclusive demonstration to consider adoption, he says: "The question is how much longer and what it might cost."

While new technologies are worth developing, "what we lack now is not a magic technology," says security consultant Johnston. "We don't do simple, low-tech stuff right."

In the end, the fate of any monitoring technology depends on the IAEA's woefully small budget. In 2015, the agency had a budget of just over US $390 million. Around $147 million will go to nuclear verification activities, which includes monitoring more than 1,250 facilities around the world. The agency estimates that monitoring Iran alone costs about $1 million a month. –PRACHI PATEL

ANTONIN VACHERET

A NEW FORMULA FOR FORMULA E

Electric racing returns this month with new power trains and other improvements

FIA

UNDER THE HOOD: The Amlin Andretti team tested a custom-built power train in August but had to replace the motor later in the month.

Formula E cars emerge from their team garages with a suddenness that seems incongruous. Even on their way to practice laps, the drivers turn their cars sharply from the garages and accelerate in apparent anger along the asphalt leading to the circuit. When the second season of the electric formula-racing series begins in late October, in Beijing, they may be able to drive with even more aggression: Unlike during the competition's first season, each team can now choose its own power train and will also employ a host of smaller technology tricks learned from last year's racing.

The first season was dominated by close jostling among the drivers: It began in Beijing with a crash that upset the two front-runners. Over the course of the next 10 races, no single team or driver took a definitive lead, and the championship was up in the air until the final lap of the last race. That may have been in part because the 10 teams were all using the same hardware. "This is the last year of such close racing," predicts Deogracias Vidal, a mechanic for NextEV TCR, the team whose driver, Nelson Piquet Jr., won the first season's individual championship. "Next year's motors will make a big difference," Vidal says.

In addition to the motors, the other big changes will be in the inverters and the gearboxes, but the teams have let only limited details emerge. McLaren built the power trains in the first series, but eight manufacturers have stepped into the fray for the second season of Formula E. McLaren will offer an upgraded version of its motor, dropping the number of forward gears from five to four. The Abt Schaeffler Audi team will use three gears, the e.dams-Renault team will use two gears, and NextEV TCR and DS Virgin Racing are using direct-drive systems, which are effectively just one gear—although Virgin will use a twin motor.

Fewer gears means less time spent switching among them: In one race last year, there were 23 gear changes per lap on average, adding up to more than a second of lost power and charging. But less shifting comes with an efficiency cost, as the motor will spend more time outside its best performing range.

The Amlin Andretti team is replacing its off-the-shelf inverter with a custom one. "People who are buying qualified, highly reliable things may not get to enjoy the latest improvements in what's on the market today," says Nicolaus Radford, chief technology officer of NASA parts supplier Houston Mechatronics, the company that built Andretti's new motor and inverter. But custom gear can come with more integration challenges, as Andretti experienced when it missed days of track testing in August and wound up changing back to its old motor.

In addition to hardware changes, there is room for applying lessons from the first season to racing strategies, says Peter McCool, technical director of Team Aguri. Teams now have a complete set of performance data from 10 racecourses, at least eight of which will feature in the second season. McCool's team has written its own software to guide battery management, he says, and it should be able to get better performance next year. Battery management is particularly important because rules limit both maximum power output (150 kilowatts last season) and total energy use (28 kilowatt-hours last season). Drivers can recharge the battery a little by coasting and braking, but "energy

NEWS

in and energy out doesn't come for free," says Gérry Hughes, chief engineer of Team Aguri. For example, charging and discharging raises the battery's temperature, altering its performance.

Formula E's unique restrictions have forced teams with more experience on the gas-guzzling Formula One races and endurance races such as Le Mans to be more creative. Hughes calls it a selling point for engineers like him, who have worked on more conventional motor-sport series. Formula E "allows me to sort of broaden my horizons in new technology," Hughes says. For one thing, batteries are so foreign to most motor-sport engineers that they have had to seek outside expertise. "Anything you can learn over and above your competition can stand you in good stead," he says.

Throughout the second season, the battery maker Williams Advanced Engineering will be in the best position to learn about battery use, since it has access to all the data and it supplies the battery's controller. The 10 teams generated about 60,000 kilometers' worth of racing data over the first season's 11 races, says Okan Tur, Williams's chief technical specialist for the batteries. "We'll see how we can use that data in the best way and to guide us in our future battery designs," he says. In the second season, teams will reuse the first season's batteries' outer structure and electronics, but Williams will swap in new cells and thermal control structures. "We had some cell-level improvements in the past year," Tur says. "We're quite optimistic that it will result in improved performance with no design changes."

Formula E's founder, Alejandro Agag, has made a lot of noise about how the technology tested in the series will someday reach everyday hybrids and electric cars. But that may not be the most lucrative place to market high-performance electric motors and batteries. Hughes says, with more mystery than specificity, that one of Team Aguri's technology partners is already "applying these types of tech to other forms of transport that don't have wheels."
—LUCAS LAURSEN

ISTOCKPHOTO

TELECOM EXPERTS PLOT A PATH TO 5G

The ITU is sorting through likely approaches to the next-generation mobile standard

Even before the 4G technology your smartphone uses was rolled out in earnest, telecommunications experts were dreaming of the next generation: 5G. But what 5G will do and how it will do it have remained pretty nebulous. "5G is a plethora of technologies that people are trying to bring together. What technology should be prioritized in what way?" says Thyagarajan Nandagopal, the director of the Networking Technologies and Systems program at the U.S. National Science Foundation.

But pressure to answer that question is mounting: Within five years, mobile service providers will need the new networks to power the Internet of Things, where just about everything, including smart cars, homes, thermometers, and portable sonar fish detectors, will be online.

In October, the International Telecommunication Union (ITU) will try to give 5G a definition. The ITU's IMT-2020 Focus Group reviewed more than 60 research proposals and will pitch the first 5G network blueprint. The draft lays out major gaps in the 5G wire-line network infrastructure, such as software and high-level network architecture, according to Peter Ashwood-Smith, chairman of the focus group. It will suggest potential technology improvements and a timeline for when each component of 5G needs to be ready before deployment, he says.

In June, the working group released goals for 5G such as support for data rates up to 20 gigabits per second, the ability to allow massive armies of devices to connect in a small area, and reduced energy consumption. With all the combined network upgrades, surfing the Web on 5G may be even faster than using your laptop's Wi-Fi. Theodore Rappaport, director of the NYU Wireless research center, in New York City, says 5G will be like "fiber optics in the air."

"As wireless devices become more plentiful, we're going to need more data and more spectrum," Rappaport says. Mobile data traffic across the globe grew 69 percent between 2013 and 2014, reaching 2.5 exabytes (over a billion billion bytes) per month, according to Cisco. And analysts expect data consumption to climb to 24.3 exabytes per month by 2019. 4G LTE, today's technology, "can never accommodate this new demand," says Rappaport.

Ashwood-Smith expects that the group will produce an even clearer picture of the wire-line broadband requirements by December 2015. "5G is going to affect us all," he says. —LAUREN J. YOUNG

WHAT 5G WILL DO AND HOW IT COULD DO IT

Data Rate

The maximum transmission data rate (gigabits per second) will be 20 times as fast as 4G LTE, while the average user will experience rates 10 to 100 times as fast.

4G: 1 Gb/s; 0.01 Gb/s
5G: 20 Gb/s; 0.1 Gb/s

Proposed Technologies
- Massive multiple-input, multiple-output (MIMO)
- Millimeter wavelength spectrum

Spectral Efficiency

5G will improve downlink spectral efficiency (bits per second per hertz) threefold.

4G: 1.5 b/s/Hz
5G: 4.5 b/s/Hz

- Device-to-device (D2D) communication
- Full duplex system
- Massive MIMO

Data Processing

The network will be able to process 100 times as much data in a given area (megabits per second per square meter).

4G: 0.1 Mb/s/m²
5G: 10 Mb/s/m²

- D2D
- Millimeter wavelength spectrum
- Radio-access network virtualization
- Small cells

Device Density

About 900,000 more devices per square kilometer will be able to connect to the network.

4G: 100K/km²
5G: 1M/km²

- D2D
- Small cells

Mobility

4G can provide data to devices moving at up to 350 kilometers per hour.

5G will provide data to devices moving at up to 500 km/h.

4G: 350 km/h
5G: 500 km/h

- Heterogeneous network architectures

Transmission Delay

5G will have one-tenth the latency (milliseconds) of 4G

5G
4G

- D2D
- Content caching close to users

Energy

4G takes 1 millijoule to transfer a 1,000-bit data packet.

5G will be able to transfer packets 100 times as efficiently

4G
5G

- Massive MIMO

PROPOSED TECHNOLOGIES EXPLAINED

Millimeter wavelength spectrum: To the surprise of many, engineers have demonstrated mobile data speeds higher than 1 gigabit per second on millimeter-wave frequencies (30 to 300 gigahertz). This will expand the amount of cellular spectrum beyond the prized but limited ultrahigh-frequency band used today.

Massive multiple-input, multiple-output (MIMO): One way to use the millimeter wavelength is through massive MIMO, which uses a huge array of antennas to steer and finely focus a radio beam so that it hits a receiver. Engineers have been able to fit 64 antennas in a space the size of a Post-it note.

Device-to-device (D2D) communication: D2D will allow direct communication between devices in close proximity without network assistance. Skipping the base station means one less step in getting information to devices.

Full duplex system: This allows the transmitting and receiving of data at the same time and on the same frequency.

Small cells: Increasing the number of small-cell base stations will increase bandwidth. This will provide enough capacity for devices to consume hundreds of megabits per second.

Radio-access network virtualization: General radio-access network processor functions will be virtualized into the cloud. Today's radio-access network is built with many individual base stations. By virtualizing the network, multiple service providers can physically share the same data center platform without any impact on connection strength.

Heterogeneous network architectures: Made of a combination of pico cells, small cells, macro cells, and different layers, these networks will provide appropriate coverage as the distance between a device and a base station changes. This kind of network will also be able to handle real-time location tracking and quick handoffs between base stations so that devices can keep working even when they're moving at high speeds.

Content caching close to users: Information that is accessed frequently will be cached closer to the user so that it takes less time to get the data.

NEWS

IS BLACK PHOSPHORUS THE NEW GRAPHENE?

Atoms-thin flakes of phosphorus have a crucial property that graphene lacks

THE DARK CRYSTAL: A sliver of black arsenic phosphorus was used to make 2-D transistors with easily adjustable properties.

Chemists first synthesized black phosphorus over a hundred years ago. But it was only last year when anybody really took interest in the flaky black stuff. In a series of experiments reported in the first half of 2014, researchers were able to exfoliate black phosphorus into very thin films of only about 10 to 20 atoms thick. Now black phosphorus has become the new darling of two-dimensional materials research and a new hope for a postsilicon world.

The excitement around black phosphorus, which is also called phosphorene in reference to its 2-D cousin graphene, stems mainly from the fact that it has an inherent bandgap, something that graphene lacks. A bandgap, an energy band in which no electron states can exist, is essential for creating the on/off flow of electrons that are needed in digital logic and for the generation of photons for LEDs and lasers.

Black phosphorus doesn't just have any bandgap. Its bandgap can be fine-tuned by adjusting the number of layers of the material, explains Philip Feng, an assistant professor of electrical engineering and computer science at Case Western Reserve University. His team has demonstrated some of the first black phosphorous mechanical and electronic devices.

The bandgap can be dialed up from 0.3 to 2.0 electron volts. That's a range covering a regime otherwise unavailable to all other recently discovered 2-D materials. It bridges the bandgaps of graphene (0 eV) and of transition-metal dichalcogenides such as molybdenum disulfide, which range from 1.0 to 2.5 eV.

By combining this bandgap tuning with different choices of contact materials, scientists at Sungkyunkwan University, in South Korea, were recently able to build both *n*-type transistors—those conducting electrons—and ambipolar transistors, which conduct both holes and electrons. Such a mix brings the material closer to mimicking the complementary logic used in today's silicon chips.

Scientists are also excited about black phosphorus for photonics, "since optoelectronic functions, including light absorption, emission, and modulation, of semiconductor materials depend on the size of the bandgap," says Mo Li, a photonics expert at the University of Minnesota. Black phosphorus's bandgap range means it can absorb and emit light with wavelengths of 0.6 to 4.0 micrometers—covering the visible to infrared. That spectrum could be key to its use in sensors and in optical communications. Li's group built a black phosphorous photodetector that was able to convert 3 gigabits per second of optical data to electronic signals.

Another cool property, Feng points out, is that black phosphorus possesses an intrinsic, strong in-plane anisotropy, which means its properties are dependent on the direction of the crystal. "This in-plane anisotropy is not readily found in other 2-D crystals derived from layered materials," he says. His team recently demonstrated the first black phosphorous high-frequency nanoelectromechanical systems resonator. The resonator took advantage of the material's in-plane anisotropy to generate new elastic behaviors and frequency scaling abilities.

Unfortunately, black phosphorus is hard to make and hard to keep. Currently, it's made by treating an amorphous form of the element called red phosphorus with high pressure (1 gigapascal) and high temperature (1,000 °C). The resulting millimeter-scale crystals are then exfoliated into atoms-thick flakes for making nanostructures and nanoscale devices.

More troubling is that "when exposed in air, black phosphorous film degrades within a few hours, due to reaction with water vapor and oxygen in air," explains Li. "Luckily, many inert materials can be used as passivation to preserve black phosphorous devices for weeks or longer."

If the manufacturing and preservation problems can be solved, perhaps silicon could finally fade to black.

—DEXTER JOHNSON

ANDREAS BATTENBERG/TUM

PHOTOGRAPH BY Akio Kon/Bloomberg/Getty Images

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

ROBOT ROOM SERVICE

WELCOME TO THE Henn na Hotel at the Huis Ten Bosch theme park in Nagasaki prefecture, Japan. The word *henn* (literal translation "change") alludes to the changes that cutting-edge technology will bring. The staff here are wired a little differently than the workers at most places you've stayed. That's because they have actual wires. At the reception desk, the two humanoid robots greet Japanese-speaking guests; English speakers have to check in with the robotic dinosaur on the right. In fact, most of the staff at the 72-room hotel have electric motors for muscles, including droids that tote luggage and clean the rooms. The company that owns the hotel, which opened on 17 July, says it plans to open a thousand robot-themed hotels around the world.

THE BIG PICTURE NEWS

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

RESOURCES

10–100 MICROVOLTS: TYPICAL VOLTAGE LEVELS AT THE SCALP FROM BRAIN WAVES

PHOTOGRAPH BY David Yellen

MIND CONTROL

THE OPENBCI LETS YOU PLUG YOURSELF INTO YOUR DEVICES

Let's be clear: This is a parlor trick, not neuroscience. Nonetheless, with the help of some friends, I was able to make a toy shark fly through the air using brain waves. So even if it's a parlor trick, it's a trick worth doing! • First things first. When attempting to make something fly using your mind, it is important to choose a target object that compels attention. It's also important that the object have the power to move itself in some way. This project uses brain waves to control an object's movements; we cannot move the object directly with our minds. This is not the Force, after all. • So I chose to use an Air Swimmers toy: a remote-controlled helium balloon that's shaped like a shark. When you press some buttons on a remote control, the shark swishes its tail and "swims" through the air with a mesmerizing motion. I started by modifying the remote control. ▸

Some friends and I opened up the remote and soldered wires to the connections of the various push buttons. We then attached the wires to the pins on an Arduino microcontroller. By sending commands from a PC to the Arduino, I could pull the voltage of the pins high or low, making the shark respond as if I had pressed the corresponding button on the remote.

Now I had to feed the PC information from my brain. The key piece of hardware needed for mind control is an electroencephalograph system. EEG systems use electrodes placed on the scalp to pick up electrical signals produced by brain activity. Usually, they are bulky and expensive. A while back, however, I had a hand in helping my friends at OpenBCI develop a low-cost, open-source EEG system that can be easily hooked up to a computer.

The current version of OpenBCI's kit is a US $450 board built around a 32-bit PIC microcontroller. The 6- by 6-centimeter board can record up to eight EEG channels at once. Microvolt-level signals from the electrodes are amplified and fed into a 24-bit, low-noise, analog-to-digital converter chip. EEG data can be stored locally on an SD memory card or transmitted in real time via a Bluetooth connection.

The hardest part of this mind control project was figuring out how to interpret the data streaming in from the board. EEG interpretation is not easy because, to be technical, EEG signals are a crazy mess. EEG recordings are a jumble of the signatures of many brain processes. Detecting conscious thoughts like "Shark, please swim forward" is way beyond even state-of-the-art equipment. The electrical signature of a single thought is lost in the furious chatter of 100 billion neurons.

To accommodate this limitation, I chose to alter my expectations for how the system would work. Instead of looking for specific thoughts, I looked for an EEG signature that would be naturally easy to detect and that I could use to signal intent. The easiest such signal occurs whenever you close your eyes: For most people, when the eyes are closed, a strong 10-hertz brain wave begins across the back of the head, where the brain's visual processing centers are located. The 10-Hz brain wave is such an obvious feature that it was one of the first signals identified when the EEG was initially developed (which is why waves with a similar frequency are called *alpha* waves). So to control my shark, I decided to focus on the brain signature of closing my eyes.

I pulled out my OpenBCI EEG kit and connected two electrodes to it. I placed one EEG electrode on the back of my head and then the other on a neutral location (my earlobe) to provide a reference signal. On my computer, I used software developed by OpenBCI to receive the data and to convert the raw time-varying signal data into the frequency domain, which made it much easier to look for peaks of activity at specific frequencies. I modified the software to look for a peak at 10 Hz and, if detected, to send a shark command out to the Arduino. As a result, whenever I closed my eyes, the shark swam forward.

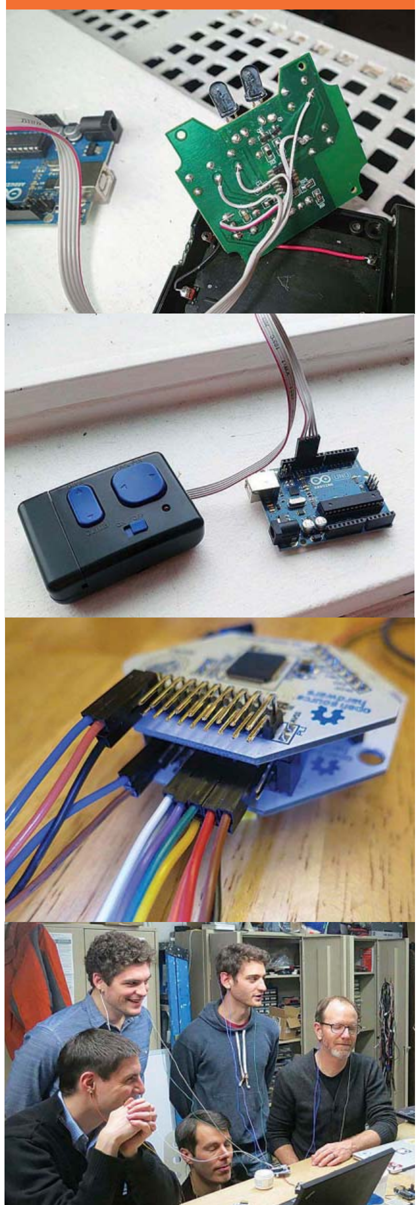
While this worked great for commanding a single action, the shark is capable of five different motions: forward, left, right, up, down. One way to take advantage of this might be to map five distinct brain signals to the five different shark actions. The brain is not so easily read, however. I could not find five distinct yet easy-to-detect signals. As before, the solution was to alter my expectations. Rather than control the shark by myself, I decided it would be more fun to control it as a group. So I enlisted four friends.

Connecting five people at once to a traditional EEG is not really possible: Traditional systems permit only a single reference electrode against which all other channels are measured. But OpenBCI is built to be flexible, and each of its eight EEG channels can have its own reference electrode. Connecting five people to one OpenBCI board is not a problem.

With all five people hooked up, the computer looked for eyes-closed alpha waves in each person's data stream. I modified the software to associate each data stream with one specific shark command. So, depending upon which shark motion we wanted, the correct person simply had to close his eyes.

As you can imagine, our coordination was poor. It was like those three-legged races, but with five people instead of two, and with our brains tied together instead of our legs. The outcome of this near-chaos was hilarity as the shark lurched through the air. But we did it. Five-person mind control! One heck of a parlor trick. **—CHIP AUDETTE**

SHARK CONTROL



CRACKING OPEN the floating shark's remote control [top] allowed us to issue commands via an Arduino [second from top]. I connected an Arduino to a PC that was also connected to an OpenBCI board [second from bottom]. I then hooked up myself and four volunteers [bottom] to the board with EEG electrodes, which let us direct the shark's movements.

CHIP AUDETTE (4)

RESOURCES_CAREERS

THE ICE STUFF

ANTARCTIC ENGINEERING REQUIRES RESOURCEFULNESS AND ENDURANCE

There is no visible horizon in the waters beneath the Ross Ice Shelf. So electrical engineer Jim O'Sullivan built an artificial one for the pilot of the submersible remotely operated vehicle (ROV) that he and a team of scientists were testing there in 2008. The team didn't lack for data: The ROV's orientation, speed, and depth were numerically displayed on the pilot's screen. But it is difficult to convert numbers into spatial awareness. The ROV was at risk of crashing into the delicate creatures, such as sea spiders, that it was supposed to be observing.

Fortunately, O'Sullivan had come across a similar problem in a different setting: aviation.

ENGINEERING FOR ANTARCTICA: Jim O'Sullivan [top] scouts for research sites near the Barne glacier; Julius Rix [bottom] works on systems that will be used to drill through ice to extract samples.

TOP: STACY KIM; BOTTOM: LUCAS LAURSEN

As a pilot, he had an instrument rating, "which was useful for understanding how to navigate without being able to see," he recalls. When flying blind, pilots use half a dozen different instruments to maintain their situational awareness, including an artificial horizon. O'Sullivan found open-source software that could convert the ROV's telemetry data to display an artificial, underwater horizon. This example of engineering on (and under) "the Ice,"—as Antarctica is known—demonstrates the need for ingenuity and improvisation beyond anything training can provide.

In fact, those characteristics are precisely how British Antarctic Survey (BAS) engineer Julius Rix got his job: "My boss told me I got my first job with him because of my hobby working on old cars," Rix says. Unlike O'Sullivan, who went to Antarctica as a contract engineer for a one-time gig and now advises startups in and around Palo Alto, Calif., Rix has grown increasingly involved in Antarctic engineering. Rix got that first job maintaining ionosphere-measuring equipment at Halley Research Station on the Brunt Ice Shelf in 2008 after doing a Ph.D. in vehicle dynamics. After two years, he took a medical-imaging job in the United Kingdom. But his old boss lured him back a few years later to move the equipment from the old Halley station to a new one. Now he is a staff engineer at the BAS Cambridge office and has returned to Antarctica twice with a scientific team searching for the world's oldest ice.

At Rix's Cambridge office, a tangle of hats, gloves, goggles, and giant fuzzy boots nearby attest to his frequent visits to a nearby walk-in freezer, with ice core samples and drilling equipment. In between visits to Antarctica, Rix must troubleshoot the drilling equipment and try to anticipate what might go wrong in the field, packing accordingly. Still, teams are unlikely to anticipate everything and must be prepared to adapt. "Learn as many skills as you can," he advises prospective Antarctic engineers.

Recent job ads for electrical or electronics engineering jobs in Antarctica confirm that while jobs are available for those seeking an unusual workplace, a diversity of experience and willingness to embrace difficult living conditions are prerequisites. Engineers on the Ice do everything from building new facilities to maintaining telescopes and tagging along with scientific teams for temporary projects, as O'Sullivan did. The diversity of roles means that many kinds of engineers can go, but be warned: The competition is stiff.

Several nations operate Antarctic research programs. Interested applicants should monitor these programs' websites and those of any private contractors supporting national programs. Hiring tends to be seasonal: Opportunities spike for the Antarctic summer. Another method is to seek out scientific research projects that may need an engineer and approach them directly. O'Sullivan got his field gig through an introduction from a mutual contact.

Both O'Sullivan and Rix emphasize the difficulties that come from Antarctica's remoteness. "Probably the isolation was the hardest part," O'Sullivan says. That goes for digital communication almost as much as physical isolation: Few satellites dip that far south, and visitors must be prepared for limited Internet bandwidth. Rix noted that his wife didn't like his being away so long and the uncertainty of when he would return.

Still, Rix is looking forward to going back and seeing new parts of the continent with the drilling team. And O'Sullivan says he's very glad he went. "I was surprised at how alive it is in the water down there," he says. "It looks very barren on the surface in Antarctica, but the oceanic life is quite vibrant."

—LUCAS LAURSEN

THE MAN BEHIND *THE MARTIAN*

A SOFTWARE ENGINEER TALKS ABOUT HIS HIT BOOK'S FUTURE TECH

CHLOE AFTEL/CONTOUR BY GETTY IMAGES

ANDY WEIR IS THE AUTHOR OF THE 2011 SCI-FI NOVEL *The Martian* (Crown Publishers), which became a best seller upon its rerelease in 2014. The book follows the exploits of Mark Watney, an astronaut accidentally left for dead on the surface of Mars; this month marks the release of a movie adaptation directed by Ridley Scott. Weir's shift to author came after a career in software engineering, which turned out to come in handy in crafting *The Martian*'s plot. *IEEE Spectrum* Senior Editor Stephen Cass talked to Weir about writing his novel and the technology of space exploration.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

Stephen Cass: Tell me about your engineering career.

Andy Weir: I really liked it. I was good at it—I did it for 25 years! When the time came to quit to go full time writing, it was bittersweet: I liked my job, I liked my boss, I liked my coworkers.

S.C.: What was your favorite project?

A.W.: The most famous thing I've ever worked on was *Warcraft II*. And there were a few really fun small projects, because I spent a lot of time working for mobile gaming companies. Mobile games, back in the days before smartphones, were very simple. One engineer per game. I made a Garfield-branded bowling game. That was pretty fun because the AI had to be good at bowling, but not *great*. But the thing I'm proudest of was mobile device management software for MobileIron, the last company I worked at. When I started on it, the code base was something that had kind of been thrown together and just kept having new stuff glued to it. I gambled my reputation at the company on this gigantic redesign. And it worked! That was probably my shining moment in software engineering.

S.C.: *The Martian* is packed with detailed and plausible aerospace technology. How did a software guy come to write about hardware?

A.W.: I've spent a lifetime being a huge space nerd. I'm less about astronomy than stuff like spacecraft: I've spent my whole life watching documentaries and [learning] anything I can find out about that.

S.C.: You wrote your own software to model the trajectory of the novel's *Hermes*, an ion-drive-propelled spaceship that shuttles astronauts between Earth and Mars. Why go to so much bother?

A.W.: I really wanted scientific accuracy. It was important for me, defining things like how long did it take them to get there, and so on. The math for calculating a constantly accelerating ship was just way beyond me—once I was in my 10th nested integral I went to see how real space agencies did this. As far as I can tell NASA does it through simulation, and I thought, "Well, *I* can do simulation!"

S.C.: The abilities and limits of space suits are critical to the plot. Did thinking about real suit tech inspire these plot points, or did you have a plot turn in mind and then worked out technology to match?

A.W.: It was based on real space suits. I would always start with the science and work forward to the plot. That's how, for example, I realized Watney wouldn't have enough water to grow potatoes [for food], by sitting down and going, "Wait a minute, how much water does it take to grow those? Oh, he doesn't have near enough." So that gave me the whole plotline of "How do you create water?" I was actually too pessimistic on space-suit technology. A few months ago I went to Johnson Space Center—it was the best week of my life. They showed a new [space-suit life-support system] that no longer needs filters for carbon dioxide; it can just filter carbon dioxide forever. That's one of several ways in which technology has been invented, or discoveries have been made, since the publication of *The Martian* that invalidate things in it. Another is that the Curiosity rover found a ridiculous amount of water stored in the soil of Mars. So all this dangerous stuff that Watney had to do to generate water—he could have just brought dirt in and heated it up!

S.C.: The protagonist has many near-death experiences, yet it never feels like you're invoking deus ex machinas to keep things rolling. How did you avoid that pitfall?

A.W.: The biggest challenge was making sure that each new problem was plausible. I tried to make each problem come from reasonable stuff, like equipment that was designed to last 31 days wearing out after 400 days. What I really liked was when a problem was caused by his solution to the previous problem.

S.C.: *The Martian* sometimes reads almost like a series of math word problems. Were you surprised it found such a wide audience?

MOVIE MARS: Matt Damon plays Mark Watney, an astronaut stranded on the Red Planet, in the Hollywood adaptation of the *The Martian*.

TWENTIETH CENTURY FOX

A.W.: When I was writing it, I was posting it a chapter at a time to my website. I had about 3,000 readers that I accumulated over 10 years of writing dorky stuff. These readers were all heavily science-minded people. So I made sure to show all my work, so that my readers could be like, "Yep, that checks out." It never occurred to me that anyone who wasn't a science geek would like it!

S.C.: How do you feel about the movie version?

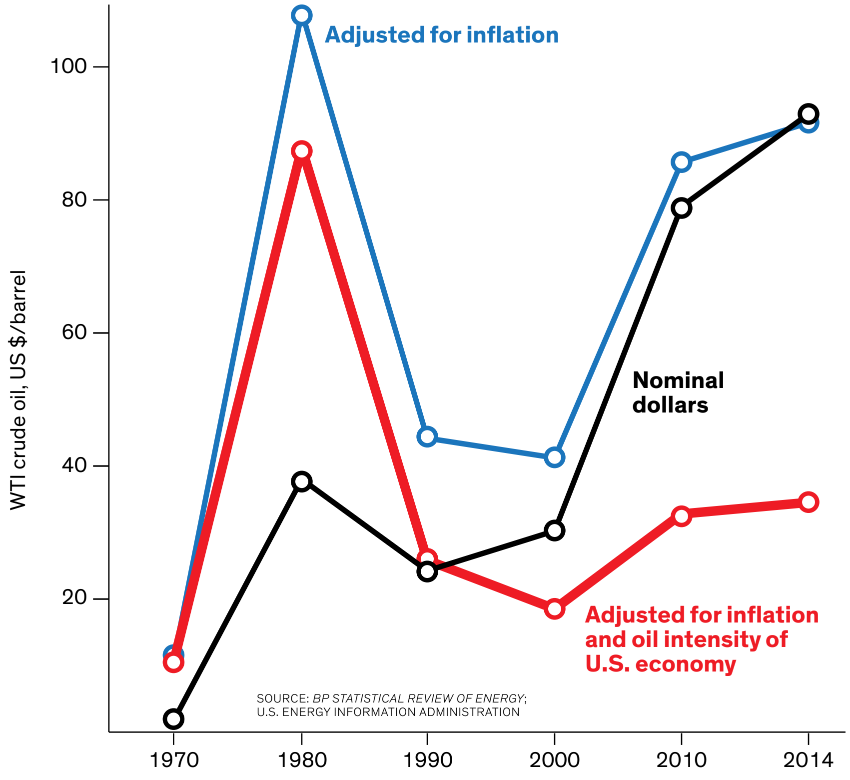
A.W.: I'm very happy with the adaptation. They definitely care a lot about scientific accuracy.

S.C.: What's next?

A.W.: I'm working on my next book now. It's more traditional sci-fi. It's got aliens and faster-than-light travel, but done my own way. I spent a month coming up with a physics model that allows FTL travel without conflicting with any established physics. [In Einstein's relativity theory, FTL travel implies the ability to travel back in time, but] I don't want any time travel in my story, so I came up with the mechanics for why it doesn't work. I try to start with the tiniest kernel of made-up BS that I can and then work everything out from there.

For more excerpts from this interview, visit http://spectrum.ieee.org

THE REAL PRICE OF OIL



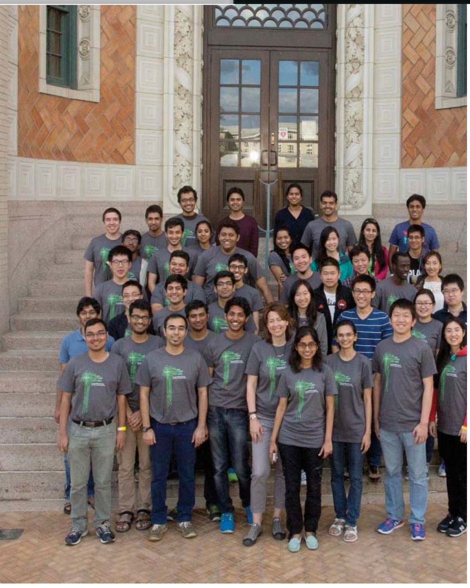
ON FRIDAY, 20 JUNE 2014, WEST TEXAS INTERMEDIATE (WTI) crude oil traded in Cushing, Okla., at US $107.95 a barrel; by the end of the year it was selling for $53.45, almost half the summer peak. For the first time, people wondered whether the price of oil might actually be *too* low. • Average prices of WTI rose roughly 52-fold between 1970 and 2014, in current dollars—an enormous jump. How could the economies of oil-importing countries have kept on growing? The answer is simple: That 52-fold multiple is based on a doubly misleading metric. Though prices did soar in the 1970s, their fluctuations have been relatively restrained since then. • The first adjustment we must make—for inflation—is trivially obvious, because currency values do not remain constant. Low inflation rates of recent years (and actual deflation in some countries) have resulted in only minor annual devaluations (or even in marginally higher value) of currencies, while back in the 1970s and 1980s, inflation rates were in the double digits. In 1970, a dollar was worth about $6 in today's money; in 1980, it was worth $2.87 and in 2000, $1.37. Expressed in today's dollars, average oil prices rose more than eightfold, from $10.90 in 1970 to $92.10 in 2014, virtually all of which took place between 1974 and 1980. In 1980, oil averaged $108.20 per barrel in 2015 monies, and its value has fluctuated ever since. • The next adjustment is more subtle and thus often neglected. We must account for crude oil's declining importance in all Western economies. This measure, usually called the oil intensity of the economy, traces oil used per unit of gross domestic product, and it is calculated by dividing the total national oil consumption by GDP expressed in constant monies. Before the first oil price rise of 1973-74, oil intensity had been diminishing rather slowly; afterward, its decline accelerated.

We have done many things to lower oil intensity. We've stopped burning liquid fuels to generate electricity, injected powdered coal instead of fuel oil into blast furnaces, raised the corporate average fuel efficiency (CAFE), lowered the kerosene consumption of jet engines, and improved the efficiency of thousands of industrial processes. The results have been impressive: By 1985 the U.S. economy needed 37 percent less oil to produce a dollar of GDP than it had in 1970. By 2000 the rate was down 53 percent, and by 2014 it was 62 percent lower.

If you doubly adjust the WTI oil price—once for inflation and a second time for the declining oil intensity of the economy—you'll find it rose from $10.90 per barrel in 1970 to about $88 per barrel in 1980, then dropped to just $19 per barrel in 2000. Then it rose again, hitting $33 per barrel in 2010 and $34.50 per barrel in 2014. The multiple for the entire 1970-2014 period is only 3.2-fold.

When seen in a proper perspective, there is no doubt that the 1970s and the early 1980s brought us a historically unprecedented price rise and widely felt economic consequences. But in the past 30 years, the doubly adjusted crude oil price fluctuations have been rather subdued. No wonder the United States has coped with those ups and downs surprisingly well—even if it did, unpardonably, halt the improvement of CAFE for the two decades ending in 2005.

That, however, is a matter for another column. ■






TINY HOUSES, BIG LEXICON

Small is the new big. —*Bob Wheeler, CEO of Airstream*

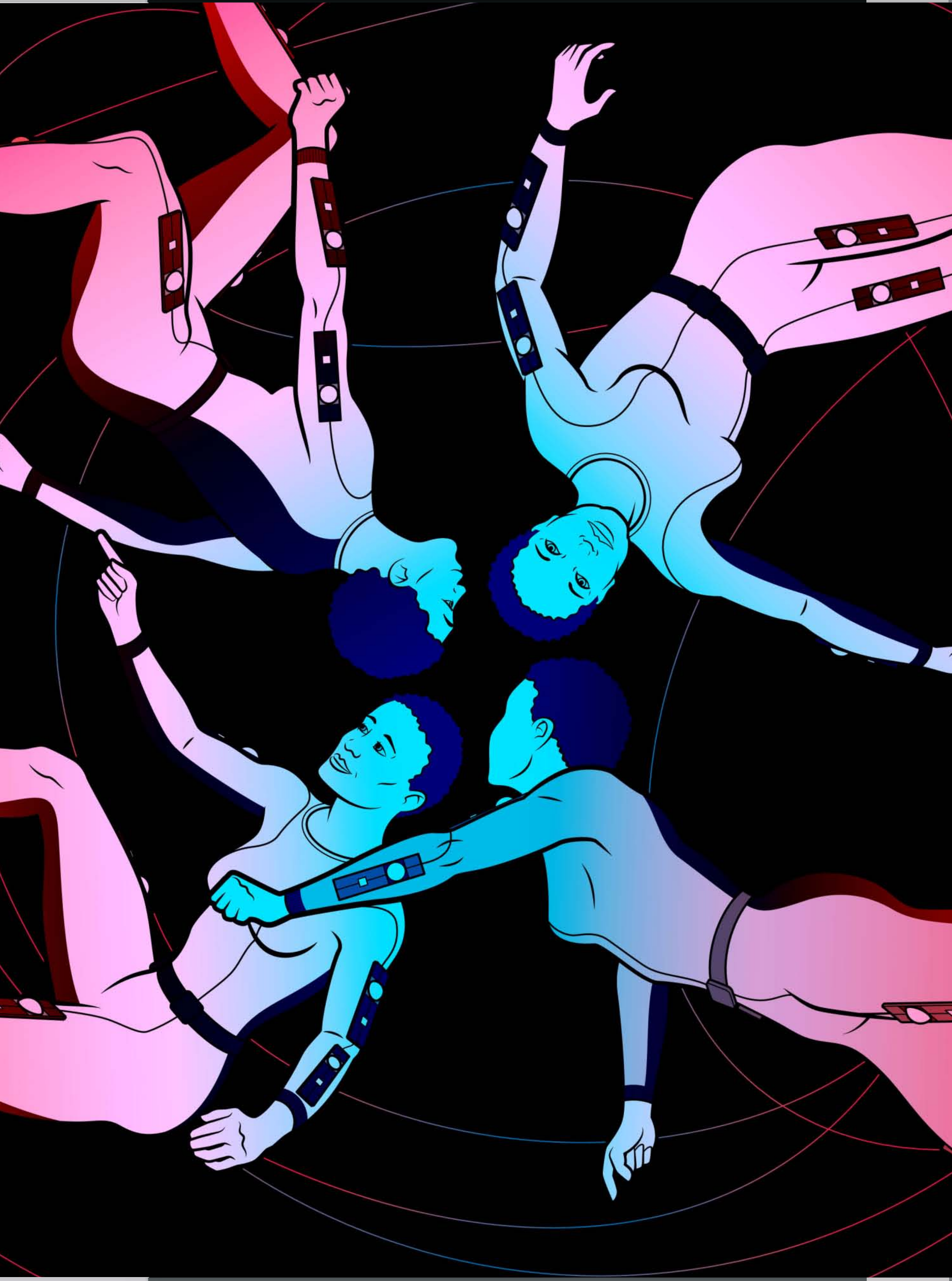
THE COMEDIAN STEVEN WRIGHT ONCE QUIPPED, "You can't have everything. Where would you put it?" Yet for many years now, it seems as though consumers *have* been determined to buy everything, and are purchasing ever-bigger houses in which to store all their knickknacks and doodads. Back in 1900, the average U.S. single-family house was 65 square meters (700 square feet). That jumped to 93 m² in 1949, 154 m² in 1973, and a whopping 234 m² in 2007 (according to the U.S. Census Bureau). This trend led to a raft of new words that reflect a world increasingly flabbergasted by house sizes: Really big houses became **monster homes** or **megahomes**; oversize houses that didn't fit the neighborhood were called **McMansions** or **Godzilla homes**; a massive house crammed into a small lot was a **bigfoot home**; garishly large dwellings were known as **starter castles**. • True, this **mansionization** trend did reverse itself for a few years as the housing market crashed—by 2010 the average size of a new house was down below 223 m²—but it soon continued its apparently unstoppable trend upward, cracking the 242 m² mark by 2014. • But in the same way that many people are replacing conspicuous consumption with **conspicuous austerity** and lavish lifestyles with **asset-lite lifestyles**, housing **downshifters** are replacing **trophy homes** with **tiny houses**. And when I say tiny, I mean *teensy tiny*: These **microhouses** are often under 19 m², with some **nanohouses** measuring less than 10 m². This is known as the **tiny-house movement**, and its adherents—called, with pleasing ambiguity, **tiny housers**—are advocates of **small-footprint living**. The "footprint" here refers both to the dimensions of the house and to its impact on the environment, with the vast majority of **small footprinters** being dedicated environmentalists. Their **eco homes** are designed not only to be small but to be green, as well. • Some denizens of **minihouses** are **solar guerrillas** who use alternative energy sources such as solar power to illegally direct electricity back to the grid. Why would they do that? Usually it's because they live in jurisdictions that don't have **net metering**, which allows a utility to track the net difference between the electricity consumed via the grid and that generated by alternative means. The **guerrilla solar movement** advocates installing inverters that enable generated power to be fed back to the grid and force the electricity meter to run in reverse.

Some owners of **pint-sized houses** go a step further and live completely **off the grid**, where "the grid" now refers not only to the electricity network but to all utilities, including the water and sewage systems. This often involves **stealth camping** (also called **boondocking**), where **tiny-house ninjas** secretly park their **wee homes** in remote, isolated locations. Some are even equipping cargo trailers with home amenities, resulting in **stealth tiny houses**.

The small-space trend is also trickling down to home workers' and telecommuters' office space. Many home offices are moving outside to the garden, where toolsheds and potting sheds are being renovated and reborn as **shedquarters**, and their inhabitants are calling themselves **shedworkers**. There's a thriving **shedworking** subculture online, where the **shed-based** lifestyle (the **shedlife**) is celebrated and refined.

The average size of a U.S. house has nearly quadrupled over the past 100 years. This has occurred despite Americans having smaller families and being only slightly taller on average than at the beginning of the 20th century (although, perhaps not coincidentally, they are *much* wider). The culprit is likely a version of the **expenditure cascade**, the increase in spending that results from consumption by the wealthy, which triggers emulative spending by the next lower class, which triggers spending by the class below that, and so on. Rich people have ever-bigger mansions, so the rest of us need ever-bigger houses, an unsustainable cascade. As the tiny housers and shedworkers are showing, small is indeed the new big. ■

ILLUSTRATION BY Elias Stein



A NEW SPIN ON SPACE SUITS

PERSONAL "GRAVITY PACKS" COULD HELP ASTRONAUTS LIVE AND WORK IN SPACE

By **MICHELE CARPENTER + KEVIN DUDA**

Illustrations by **MCKIBILLO**

Future Space Suits

AFTER EXITING THE AIR LOCK, an astronaut uses the thrusters on her space suit to propel herself toward a nearby asteroid. With great care, she gets as close and as steady as she can in preparation for knocking a few samples off the surface. But with very little gravity to anchor her, the strike of her hammer throws her backward in an uncontrolled tumble.

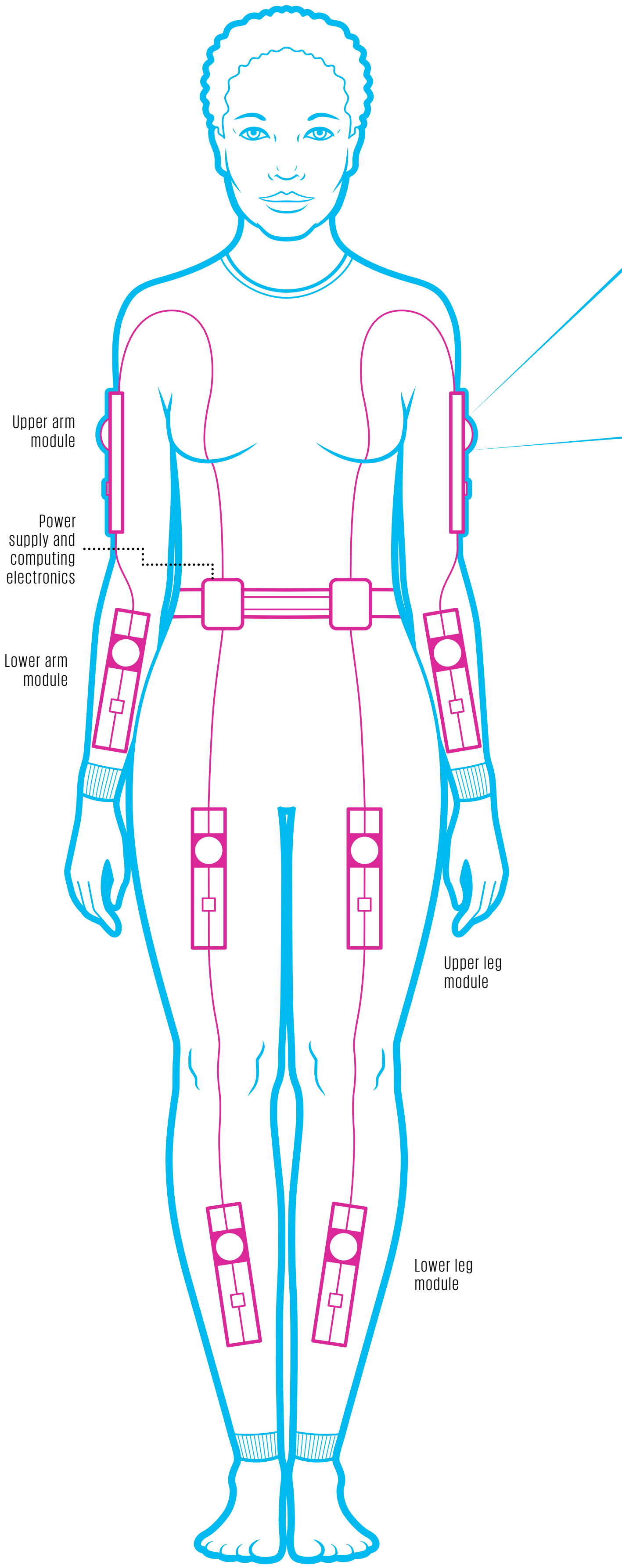
This scenario may sound a bit comic, but it's one that engineers will have to keep in mind as they design ways to once again send astronauts out beyond low earth orbit–to an asteroid brought close to the moon by a robotic spacecraft, according to NASA's current plans; to other small bodies in deep space; and on long missions to what could be our generation's ultimate destination–Mars.

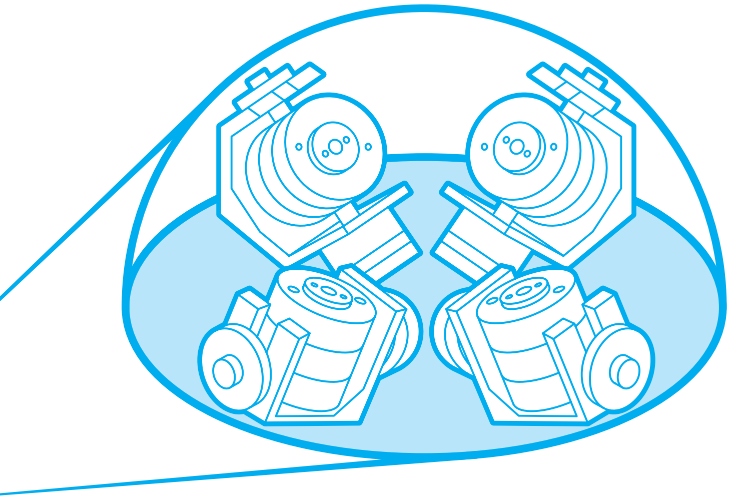
Of the myriad dangers and difficulties associated with space travel, weightlessness places some of the biggest demands on an astronaut's body. The absence of gravity can wreak havoc on an astronaut's physiology, causing muscles to atrophy, weakening bones, and producing disorientation and unsteadiness that can persist even after the return home.

The lack of gravity also turns each space walk into a precise dance. Even the slightest nudge against a surface will push an astronaut off in the opposite direction. This challenge will only become greater once people start exploring environments where they don't have the benefit of handholds and robotic arms, which astronauts now use to move around the exterior of the International Space Station (ISS).

Fortunately, there is a technology that could help address these sorts of difficulties: the control moment gyroscope, or CMG. Unlike the sensor-type gyroscopes found in smartphones and other gadgets, the CMG is an actuation device. It uses a spinning mass to rotate an object or resist such movement, in the same way that changing the rotation axis of a spinning bicycle wheel while you're seated in a chair can cause you to turn.

Today, CMGs are employed to steady a range of spacecraft, including Earth-observation satellites and the ISS. At Draper Laboratory, in Cambridge, Mass., we're working to make this technology compact enough for astronauts to wear and yet powerful enough to restore some of gravity's greatest advantages. Placed on a flight suit, our CMGs could be used to resist an astronaut's movement, helping to mitigate some of the effects of long-term weightlessness. Similar modules could be





GYRO POWER

Modules mounted on the upper and lower arms and the upper and lower legs could be used to resist limb movement in space. A single module might contain four control moment gyroscopes, mounted in a pyramidal configuration. These gyroscopes can be programmed to work in concert to provide torque in a particular direction, providing a feeling of resistance similar to that of gravity.

placed alongside thrusters on astronauts' manuevering units to help improve their stability when performing repairs and exploring low-gravity environments. With any luck, when humans put the first footprints on the Red Planet, they'll find the adjustment won't be nearly as abrupt as they expected.

OUR WORK ADAPTING CMGs for use on space suits began when we started considering astronauts' experiences inside their spacecraft. Astronauts en route to Mars will experience half a year or more of weightlessness, and like any good system, the human body will react by adapting to its new environment: The cardiovascular system will become deconditioned, muscles will shrink and weaken, and bone mineral density will decrease.

The lack of gravity also affects sensorimotor functions and the vestibular system, the inner-ear sensory organs that control our sense of balance. Astronauts have reported spatial disorientation, motion sickness, balance instability, and difficulty maintaining coordination when walking or performing tasks that require fine motor skills. Many of these symptoms manifest themselves during gravitational transitions, such as after launch or landing. Unfortunately, these transitions occur during critical times when astronauts' physical and cognitive performance is crucial for their own safety and their mission's success.

Because NASA currently has no plans to build a giant spinning centrifuge ship à la *2001: A Space Odyssey* to create artificial gravity for Mars-bound astronauts, we decided to explore an alternative: a personal resistance suit that could mimic some of gravity's effects.

In collaboration with researchers at MIT and at the David Clark Co., in Worcester, Mass., we designed the Variable Vector Countermeasure Suit, or V2Suit, with initial support from the NASA Innovative Advanced Concepts program. It would look much like an ordinary flight jumpsuit. The main difference is that it would be equipped with small modules to be worn on the arms and legs, one for the upper and one for the lower section of each limb. Each module contains a sensor system to measure the limb's orientation and its linear and rotational motion, and four CMGs to resist that rotational motion. A module on a belt would contain the system's power and the processor needed to compute how the CMGs should react.

The CMGs we chose for the task each contain a cylindrical mass that spins at constant speed. This rotor is itself mounted on a gimbal. When the gimbal rotates, it changes the orientation of the rotor's axis. When the rotor is spinning–which it can easily do at 15,000 or so revolutions per minute–the change in the orientation of its spin axis imparts a rotational push, or torque.

The modules can be programmed to recognize an arbitrary direction as representing "down." The CMGs will then move to create resistance with the appropriate strength and direction whenever the astronaut moves against the "down" direction. If an astronaut programs "down" to mean the floor of the spacecraft, then raises an arm in the direction of the corresponding ceiling, the CMGs on that arm can orient themselves to oppose that motion, resulting in a feeling of resistance, as if the astronaut were moving her arm through a vat of molasses.

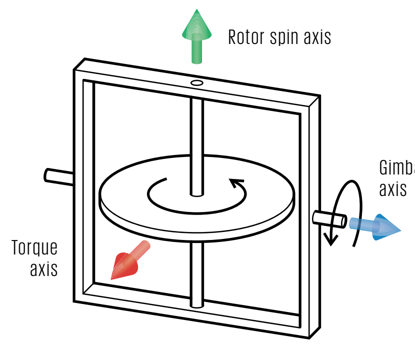
That's not the same thing as creating artificial gravity, of course. An astronaut's inner ear won't operate any differently, for example, and she might still experience motion sickness. And while the suit might help astronauts get a more robust workout, other measures will likely be needed to counteract the depletion of bone mass and muscle strength. Those strategies could include exercise, perhaps inside a one-person centrifuge, and tight-fitting suits like the "penguin suits" developed by the Russian space program, which use elastic to put pressure and tension on muscles.

But CMGs could really help in improving eye-hand coordination. When we move our arms and legs, our brains take gravity into account. Making the switch to zero gravity can cause an astronaut to miss her target by failing to compensate for the sudden absence of pull when she tries to move a limb. The opposite effect can occur when returning to Earth. The resistance offered by CMGs could help astronauts acclimate to the gravitational environment of their destination, enabling them to practice how to move and work smoothly months in advance of their arrival.

The trick will be making sufficiently powerful CMGs that can fit in a small, wearable package. It's not yet clear how much resistance we need to offer astronauts, but when we set out to make our prototype CMG array we aimed to have it provide as much as 1 newton meter of torque. That's about what you'd feel at your shoulder if you were holding a full soda can with your arm straight out to the side.

This level of torque is easy to achieve with a larger CMG. It can also be made with a tiny one that spins very fast, although a smaller CMG has less of a range of angular momentum to work with. It also won't be able to operate as long as a larger CMG without having to be reset, by unwinding each of the gimbals.

Thankfully, CMG design has improved considerably in the last few decades, and we were able to use commercial parts to build relatively compact and inexpensive prototypes. Our current model, which was completed last year, is about 20 centimeters on a side and 10 cm high. This is still larger than we'd like for astronauts to wear, but the module is not optimized for size. It contains, for example, a fairly large safety enclosure to make sure the spinning parts stay contained and can't injure anyone experimenting with it. Our next step is to begin testing the module on people on the ground to see how they perceive different magnitudes of resistance. From there, we plan to transition to tests aboard airplanes flown in parabolic arcs, which offer their passengers brief periods of weightlessness.



A CONTROL MOMENT gyroscope, such as the single-gimbal variety here, uses the angular momentum of a spinning mass [center] to create torque. Rotating the spin axis of this mass using a gimbal [blue arrow] generates a torque in the direction of the red arrow. A body attached to the CMG will rotate around this red axis (clockwise from this perspective).

NOT LONG AFTER WE BEGAN working on the V2Suit, we started exploring how CMGs might also help astronauts moving around outside a space vehicle to perform repairs, for instance, or to propel themselves to an object of interest.

Today, astronauts generally navigate in the vacuum of space using safety tethers, robotic arms, and handholds attached to their vehicles. In the past, maneuvering units–backpacks equipped with jetlike thrusters–were used to perform space walks without an attachment to a vehicle. Today, astronauts on the ISS wear such jet packs, but they're designed to be used only in case of emergency.

As planners contemplate missions beyond low earth orbit, they'll want thruster systems that can be used more routinely, so that astronauts can propel themselves across empty space to explore new objects and maneuver with as much freedom as possible outside their spacecraft in case emergency repairs are needed.

But thrusters by themselves are a brute-force solution, especially when you consider the possibility of visiting low-gravity objects, such as asteroids and Martian moons. Because they're essentially miniature rockets, thrusters are great for moving in a line from one point to another. But they're not as effective at maintaining a constant attitude–the rotational orientation of a body.

Imagine that an astronaut's suit has two thrusters attached behind the shoulders, one pointed to the left and the other to the right. One thruster is designed to rotate the astronaut clockwise and the other counterclockwise. The control system can command the thrusters to fire whenever the astronaut rotates away from the target attitude.

It's a simple approach, but it's imprecise. The astronaut will never sit exactly at the commanded attitude; she'll be pushed in one direction and then the other when she overshoots, bouncing back and forth around the desired orientation. The process eats fuel, limiting the amount of time that can be spent performing extravehicular activities. And if the astronaut happens to be near the surface of an asteroid, she'd risk kicking up dust clouds, potentially contaminating the area she's trying to sample.

CMGs could offer better control. And it turns out that CMGs have actually been used before. Astronauts flying on NASA's Skylab space station in the 1970s experimented with an early mobility unit that contained both thrusters and CMGs, but those CMGs were quite massive and power hungry. Later, when the agency's Manned Maneuvering Unit was being developed, CMGs were found not to be necessary. NASA determined that astronauts could perform extravehicular activities, such as spacecraft maintenance and satellite retrieval, by maneuvering at the end of a robotic arm or with thruster-only jet packs.

After several decades of advances in manufacturing and with NASA's new low-gravity mission objectives in mind, our team at Draper, along with researchers from MIT and NASA Johnson Space Center, decided to revisit the Skylab idea.

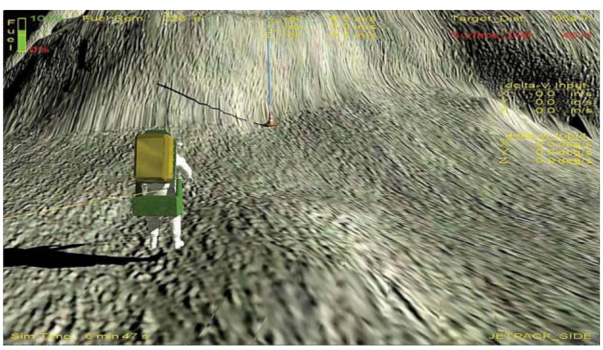
The CMG module design we settled on for the jet pack looks quite similar to the one we used in the V2Suit; it too is made up of an arrangement of four individual CMGs. The jet-pack CMGs are a bit larger, though, each about the size of a baseball, and are designed to produce as much as several newton

ILLUSTRATION BY James Provost

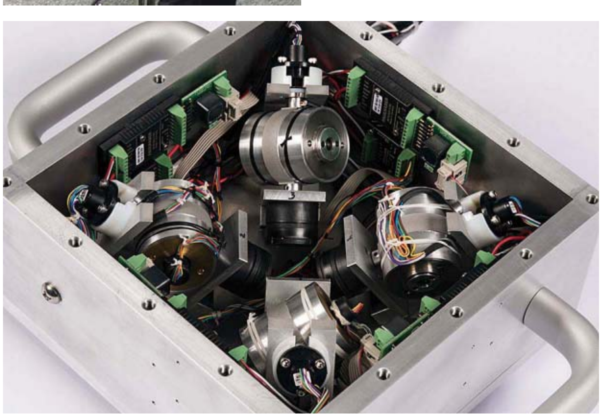
meters of torque, which should be enough to prevent astronauts from pushing themselves into uncontrolled spins if they need to sample the surface of a low-gravity body.

Picture our astronaut floating in the vacuum of space. If she dips to her side into a sideways cartwheel, she is spinning about her roll axis; leaning forward or backward in space, she is rotating about her pitch axis. When she twirls around to change the direction she's facing, she is moving about her yaw axis. So to fully control an astronaut's attitude, we needed at least three CMGs–one to control pitch, one for roll, and one for yaw.

In practice, we used four. That's partly so there's a backup in case one fails. It's also to help the gimbals avoid what's called a singular configuration, which can occur when two or more of the CMGs cancel one another out or when the gimbals can't be moved any farther in a particular direction to provide additional torque. Well-designed control software, which would operate all four CMGs at once, can recognize when one of these problems threatens system controllability. It will then either steer the CMGs away from a singular configuration or apply torque using thrusters so that the gimbals can be oriented away from their extreme positions, giving the CMGs some breathing room.



KEEPING STEADY: Virtual-reality simulations [above and left] were used to test whether a CMG-equipped jet pack could better enable an astronaut to control his or her attitude on an approach to an asteroid's surface and while performing basic tasks. Prototypes [bottom image] of the CMG modules that astronauts might one day wear on their arms and legs have been tested in the lab.



DRAPER LABORATORY (3)

Last year, we used a computer-simulated mission to an asteroid to test three different jet-pack schemes: one with only jets and two with a combination of jets and different sizes of CMGs. Our experimenters tried to navigate a virtual asteroid while maintaining a certain attitude, by using a video-game controller and virtual-reality goggles. We also performed computations to simulate the physics involved in an astronaut removing a tool from her belt and performing reaching motions with the tool in hand.

When carrying tools, our test subjects preferred to work with the jet pack containing thrusters and the larger CMGs. It's harder to get these CMGs into a singular configuration because they can store more angular momentum. We found that the gyroscopes not only improved stability, they also cut fuel consumption by two-thirds. Of course, there are trade-offs to adding CMGs. The most important is that gyroscopes need electricity to function. Adding CMGs to a mobility unit as well as a battery to power them could add a fair amount of mass, thus increasing launch costs. But we expect that over their lifetime, CMGs will come out ahead in the cost-benefit equation.

Of course there are still open questions. Although we tested a mock asteroid encounter using VR goggles, we won't know how an astronaut feels using our equipment until someone tries it in a weightless environment.

We recently took a step in that direction, by testing a combined CMG and thruster system on a free-floating satellite experimentation platform during a series of parabolic flights. The flights were our first opportunity to see how well our combined CMG-thruster system could maintain a stable attitude in a microgravity environment. In the future, we hope to test a scaled-up CMG system in similar flights with human subjects.

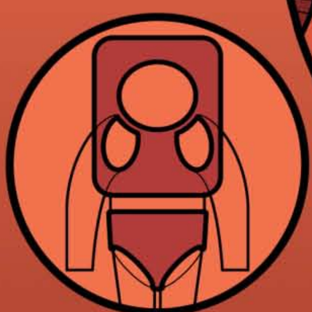
A key consideration will be how easy the system is to use. Today, astronauts command maneuvering-unit thrusters with a hand controller through their bulky gloves. A hands-free interface, perhaps controlled using foot pedals or voice commands, might ultimately prove simpler.

We're still in the early days of figuring out how to make long-duration flights safer and finding ways for astronauts to perform well outside their craft without having to rely on handholds and tethers. The gyroscope systems we're working on should indeed help combat some of the problematic effects of weightlessness. A decade from now, space might feel a little less ethereal for astronauts than it does now. And that will be a good thing. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/cmg1015

A. Free breathing

The carbon dioxide scrubbing canisters on today's space suits are good for one use only or else must be recharged for hours. A dual system, which uses amine beds to remove carbon dioxide from astronauts' exhalations, could be used continuously and repeatedly. While one filter releases the carbon dioxide it collected, the other can continue to absorb the gas.



B. Body armor

The suit will likely rely on a mix of hard and soft parts to keep its shape against the air pressure inside. The materials should also help protect against falls: Mars's gravity is more than twice that of the moon. A mix of hard components and flexible but sturdy outer layers could prevent punctures while being lightweight enough for walking.

C. Boots made for walking

Apollo boots won't cut it on Mars. Astronauts will need something rugged, comfortable, and durable enough to last for weeks or months. Chances are Mars footwear will be custom molded to an astronaut's foot, says ILC Dover engineer Jinny Ferl. The soles will likely be flexible, but they could also be rounded, allowing astronauts to walk in part by rolling their feet.

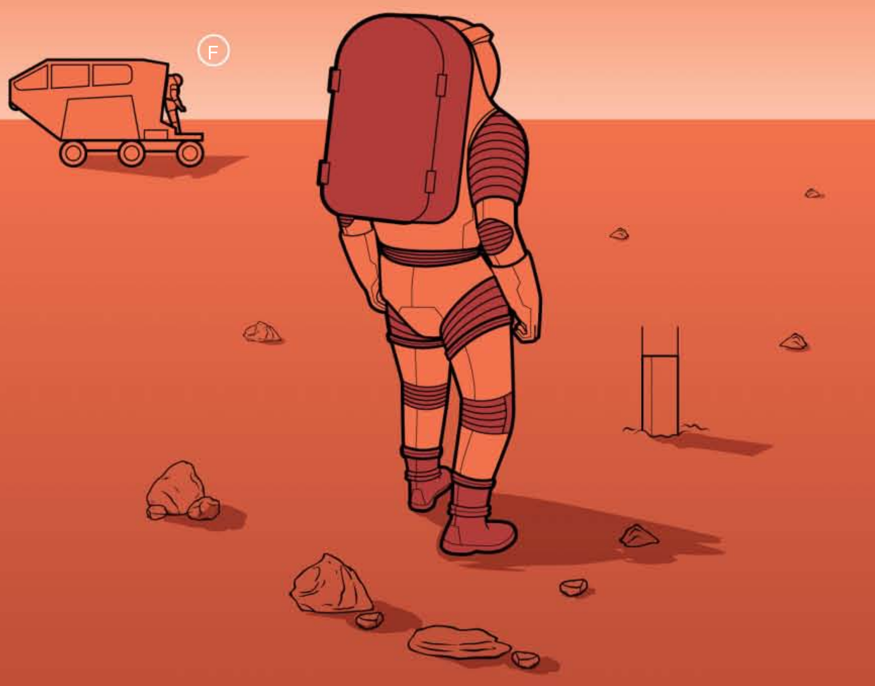
D. Knees that can kneel

Spacewalkers on the International Space Station use handholds to get around. On Mars, astronauts will need to walk and even kneel. Getting this mobility from a gas-filled, pressurized suit will be a challenge, but bendable knees, along with bearings and accordion-like joints at the hip, should allow greater freedom of movement.

G. Show me the map, Siri
Basic life-support controls will likely still be mounted on the exterior of the suit (shown here on chest), but head-up displays—and potentially voice-command capability—could help astronauts monitor the condition of their suits, communicate with others, run through checklists, take pictures, control lights, and navigate the Martian surface.

F. Slide in, suit up
Mars is covered with potentially toxic dust. To protect interior spaces, suits could be hung outside a landing craft or rover. To perform a Mars walk, an astronaut could slip into the suit through a port at the back. A backpack containing the suit's life-support equipment would close behind the wearer. Latches would then release to pop the suit off the vehicle.

E. Fresh fabrics
Today's space suits use the vacuum of space to provide thermal insulation between outer and inner suit layers. The Martian atmosphere may be thin, but it's thick enough that engineers will likely have to develop new materials to regulate the temperature of the suit. Polymers that can offer some radiation protection will also be in demand.



SUITING UP FOR THE RED PLANET

Engineers fashion ways to survive on Mars

By RACHEL COURTLAND

WE'RE LIKELY STILL at least a couple of decades away from landing people on Mars, but the space suits that will protect those astronauts are very much in development. • Last year, NASA made headlines when it invited the public to choose the design that would decorate the exterior of the Z-2, a new suit designed to be mobile enough to explore the Red Planet. And its manufacturer, longtime space-suit maker ILC Dover, based in Frederica, Del., has now put the finishing touches on that suit, which is set for a public unveiling in a few months. • Some would argue that we can't get started on Mars suits soon enough. Today's space suits are designed for delicate work in zero gravity, not the rigors of a months-long trek around the base of Olympus Mons. • So what will that first Martian space suit look like? Will it be similar to today's suits—a rigid, human-shaped balloon inflated with gas? Or will we wind up with something sleek, like MIT's BioSuit concept, which would use form-fitting elastic materials to apply pressure directly, by squeezing the body? • Chances are we'll see an evolution in design, says David Klaus, a professor of aerospace engineering sciences at the University of Colorado Boulder. "The first suits on Mars will probably be like the Z-2," he says. "They may not be perfect, but they'll get the job done." • The Z-2 isn't yet a complete suit, but discussions with its engineers and other space-suit experts provide a sketch of what the first people to land on Mars might wear.

ILLUSTRATION BY MCKIBILLO

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

The most important requirement, of course, is that the suit offer future Martian explorers adequate protection. By physiological standards, conditions on the surface of Mars are effectively equivalent to those of a vacuum, the atmosphere having less than 1 percent of the surface pressure of Earth's. As a result, future Martian explorers will face the same basic danger that spacewalking astronauts do today: A large breach in their space suits would quickly turn the liquid water in their tissues and veins into vapor. The body would swell drastically, and blood would stop circulating within about a minute.

But Mars poses new challenges. The weak magnetic field of that planet offers little protection from solar-wind particles and cosmic radiation. And the thin atmosphere complicates suit design. The space suits worn outside the International Space Station (ISS) use vacuum to their advantage–that vacuum provides thermal insulation between outer layers of the suit. Transport such a suit down to the surface of Mars and gas molecules will slip between those layers and carry heat away from the astronaut's body.

Astronauts will also have to contend with something that they haven't had to tackle since the days of the Apollo moon missions: dust. Whipped by wind and once shaped by water, Martian dust is likely less sharp than moon dust, but the Martian variety is readily lofted into the air. The dust can scratch up visors, bind up bearings, and coat space suits, altering their reflective properties. Should it get into a rover or habitat, scientists say it could pose a significant health hazard.

Even if today's suits could perfectly protect Martian explorers, they'd be quite difficult to work in. They'd be a lot to lug around, for one thing: Mars has 38 percent of the gravity of Earth. The current suits are also optimized for moving about in zero gravity using handholds, so their hip, waist, and knee joints aren't particularly flexible. "The suits that are up there are not designed for walking around," says former astronaut Jeffrey Hoffman, now director of MIT's Man Vehicle Laboratory. "I had to take [one] on a treadmill once. You sort of turn your body and throw one foot in front of the other. It's very awkward."

NASA's Z-2 is designed to tackle this mobility problem. "Our current goal is to work toward a suit that we could fly on the space station as a demonstration," says Amy Ross, who heads the advanced space-suit engineering team at NASA Johnson Space Center, in Houston. "But it is a planetary-surface walking suit."

Like its predecessors, the Z-2 is filled with gas and consists of three basic layers: a restraint layer to hold in the air, a structural layer that helps shape the suit and allows joints to move, and a set of environmental layers that provide thermal insulation and protect the suit from punctures. Where the Z-2 diverges most is in how it bends and flexes. The suit comes with improved joints and bearings, particularly at the shoulder, hip, and waist.

As with the suits used by today's Russian cosmonauts, astronauts enter at the back. The idea is that, to avoid contact with dust, explorers could hang the suits outside their vehicles or habitats. The suits would be part of a compact air-lock system; a Mars walker would enter his or her suit through a combination hatch-backpack containing the suit's life-support equipment. When open, the suit hatch would nestle inside the vehicle's inner hatch. After the astronaut enters the suit, both hatches would close and the astronaut could release the latches holding the suit to the vehicle.

In theory, an astronaut could get in the suit and go fairly quickly. To improve their flexibility, existing Russian and American suits are kept at a relatively low pressure. Astronauts must go through a lengthy "prebreathe," in which the air is slowly depressurized to lower the risk of developing the bends. This is the same hazard scuba divers face upon returning to the surface from deep water–dangerous bubbles that are created when the lower pressure causes dissolved gases in the body to come out of solution.

The Z-2 is designed to operate at 8.3 pounds per square inch (about 57,000 pascals). Although still just over half the pressure at sea level and inside the ISS, the level is high enough for astronauts to forgo the prebreathe procedure. To resist the higher pressure, some of the widest parts of the suit, namely the chest and pelvic area, employ rigid components made from a composite of fiber and resin. These rigid parts could also help protect the astronaut against falls, says Jinny Ferl, a space-suit engineering manager at ILC Dover.

But the Z-2 isn't quite ready for a Mars debut. The suit's environmental garment doesn't yet have any layers to help protect against extreme temperatures and radiation, says Ferl.

What's more, there's the pesky matter of overall heft. The Z-2 is being developed in tandem with an improved life-support system that can better remove carbon dioxide. Together, the mass of the pair comes to roughly 140 kg, says NASA's Ross, on par with the mass of the U.S. suits currently used on the ISS, if you don't include their emergency thrusters. But, she adds, the new system does more with that mass: The Z-2 suit has better mobility, and the new life-support technology is more reliable and can operate longer.

In the future, we could see sleeker, more-capable suits emerge. MIT's BioSuit project is blazing that trail, although it is still in its earliest stages, Hoffman explains. The approach presents some significant challenges, including finding a way to provide pressure in concave areas, such as behind the knees and between the knuckles. At present, the MIT team has not developed a prototype that can provide enough pressure to protect against vacuum. But they are working on it.

In parallel, UC Boulder's Klaus and others are exploring additional ways to make suits more capable. Earlier this year, for example, he and graduate student Christopher Massina reported that it should be possible to save on the water now used to help keep temperatures steady by transforming the space suit into a dynamic, full-body radiator. The approach uses materials that change their surface properties–and thus how strongly they reflect or absorb light–in response to an applied voltage.

"That's definitely next-generation stuff," Klaus acknowledges. But when it comes to Mars, it's good to plan ahead. ■

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IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

INTRODUCING THE MICRO-SUPER-CAPACITOR

LASER-ETCHED GRAPHENE BRINGS MOORE'S LAW TO ENERGY STORAGE

By Maher F. El-Kady & Richard B. Kaner

ILLUSTRATION BY Greg Mably

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page Qmags THE WORLD'S NEWSSTAND®

Capacitors. Open up your computer and they stick out like rocks on a sandy beach. They're the one kind of electronic device that never made it to Lilliput. If they finally obeyed Moore's Law by squeezing themselves down to the microscale, it would make life a lot easier for electronics engineers.

With tiny but powerful capacitors you could make cheaper, even tinier cardiac pacemakers and computers. They'd be great in nonvolatile memory, microsensors and actuators, RFID tags, and microelectromechanical systems, applications in which the power supplies can weigh up to 10 times as much as the other parts combined. And because, like all capacitors, such devices would be able to release their charge very rapidly, they could be coupled with high-energy batteries to provide periodic surges, as conventional capacitors do to power the flash in smartphone cameras. (Miniaturized supercapacitors could thus lead to even thinner smartphones.)

TILING A DISC WITH SCORES OF SUPERCAPACITORS

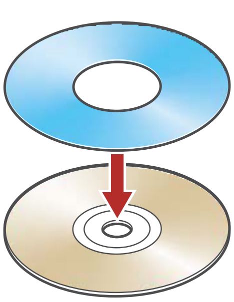
The authors produce many supercapacitors at a time with nothing fancier than a LightScribe laser etcher, available for the price of a good men's blazer. Each device consists of graphene electrodes separated by graphite oxide dielectric, topped with a drop of electrolyte.

Our group at the University of California, Los Angeles, has created such microsupercapacitors using a simple DVD burner to forge the one-atom-thick sheets known as graphene on which these devices are formed, in arrays. Together with a battery, such supercapacitors could run a cellphone for days. And because an array is less than 10 micrometers thick—far finer than a human hair—it is completely flexible. Build these arrays on flexible substrates and they could power a roll-up display.

All these things can be done at low cost. Our fabrication method can easily be scaled up, and our microsupercapacitors can be readily integrated onto silicon chips. In many cases they can make up for the inherent weaknesses of batteries, such as relatively slow power delivery and long recharge times. So even in those applications where these devices cannot replace batteries, they will augment them enormously.

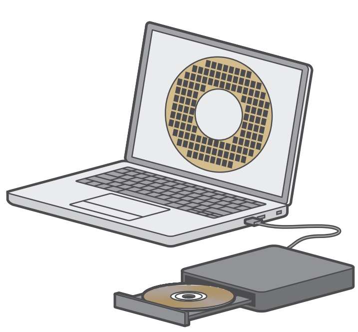
Consider the lead-acid battery. If Moore's Law had applied to it for as long as the law has applied to semiconductors, a fully functional car battery would now be the size of a red blood cell. But this technology, invented in 1859, matured long ago. Nickel-cadmium and nickel-metal-hydride battery technology matured more recently, but they, too, are close to their theoretical limits for power and energy density. Even lithium-ion batteries—which have tripled in energy density since the early 1990s—are near the end of their technological growth spurt.

Batteries can't follow Moore's Law because no known material can pack an immense charge into a small volume. And the microbatteries that we do have are expensive because they are made using complicated and time-consuming processes. Nor are we likely to find salvation in the various energy-harvesting schemes that have been suggested; they just don't give product designers the necessary performance and reliability.

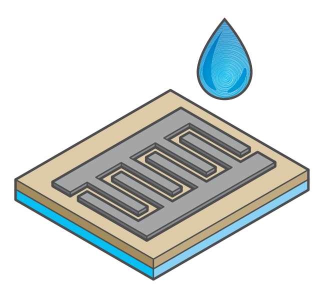


First the authors glued a plastic substrate onto a standard DVD.

Next they coated the plastic with graphite oxide, which conducts ions but not electrons. That makes it an excellent dielectric between the electrodes of a capacitor.



Then they inserted the disc into a LightScribe, whose laser normally etches labels onto DVDs. Here it etches some of the graphite oxide into graphene electrodes.



The interlaced electrode design maximizes the interface and hence the capacitance. A drop of electrolyte turns it into a supercapacitor.

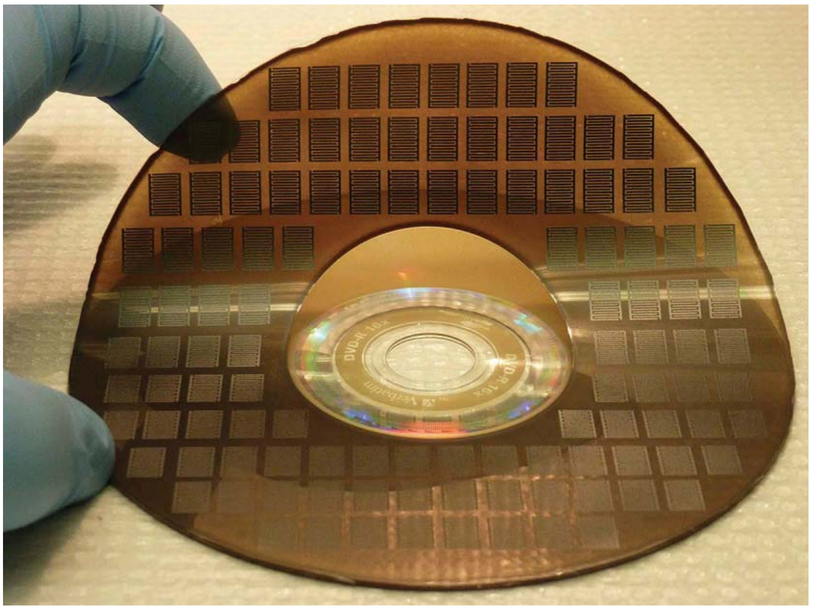
ILLUSTRATION BY James Provost

But capacitors offer another form of storage. And we have found a way for them to hitch a ride on Moore's Law.

A traditional capacitor is made of two metal plates separated by a thin insulating layer. It stores charge electrostatically, in an electric field created by the two oppositely charged plates. How much charge can be stored is determined by the capacitance of the device. It is a function of the area of one of the metal plates—typically less than a square meter—divided by the spacing between them, which is typically about a micrometer or less. Therefore, to increase the charge you must maximize the area and minimize the distance.

Supercapacitors minimize the distance by borrowing a bit of battery technology—the electrolyte. A supercapacitor is defined as an electric double-layer capacitor. It consists of two electrodes impregnated with a liquid electrolyte and separated by an ion-permeable layer to prevent short circuits between the electrodes. As voltage is applied, ions from the electrolyte move onto the surfaces of the electrode of the opposite charge. Charge accumulates at the interface between the electrodes and the electrolyte, forming two charged layers, or electric double layers, that are separated by only a nanometer or so.

Our form of supercapacitor also improves area, the other variable. Graphene's atom-thick sheet has the highest possible ratio of surface to volume: A gram of it could pave 2,630 square meters—nearly two-thirds of an acre. Together with the 1-nanometer separation of charge, this yields a capacitance a million times that of a garden-variety ceramic capacitor and about 10,000 times that of a typical electrolytic capacitor.



A FLEXIBLE SUBSTRATE: These flat supercapacitors can fit directly onto microcircuitry, and if need be, they can even bend.

MAHER EL-KADY/UCLA

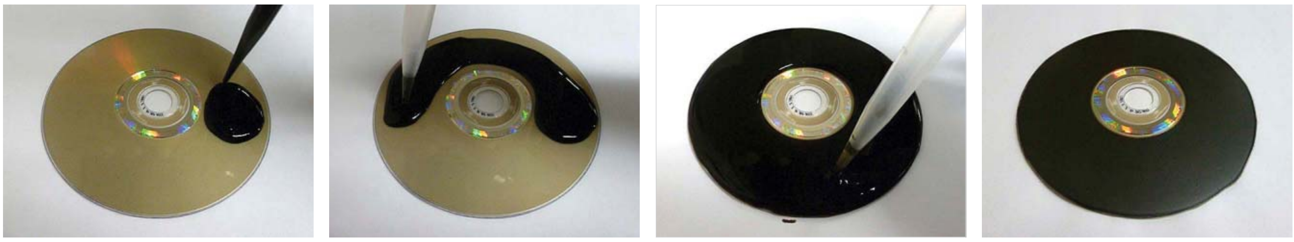
Our interest in energy storage goes back to the early 1980s in Neil Bartlett's lab at the University of California, Berkeley, where one of us (Kaner) was a postdoctoral scholar, working on new forms of graphite. This type of carbon is widely used in lithium-ion batteries today because it is inexpensive, highly conductive, and able to store lithium ions efficiently. However, its low surface-area-to-mass ratio limits its ability to store charge. But it gave Bartlett an idea: to fabricate a "holey" graphite with the surface area needed to store plenty of charge. Unfortunately, his Berkeley team couldn't then realize this top-down idea of drilling 3-D holes at the atomic scale.

It took 30 years, but we finally did solve this problem in our lab at UCLA, with a bottom-up approach. We started from individual sheets of graphite oxide—a 150-year-old material that is hydrophilic and therefore easily processed in water into films or coated onto virtually any substrate. A few years ago, we found that by shining intense laser light on graphite oxide we could boil off the oxygen in the form of carbon dioxide, leaving behind a 3-D form of graphene—holey graphite. Essentially, we are assembling 2-D graphene sheets into a macroscopic 3-D network that looks like corrugated cardboard.

This corrugated carbon has extraordinary properties. We found that electrons moved 100 times as fast in our 3-D graphene as in the graphite used in batteries and 10 times as fast as in state-of-the-art carbon nanotubes. That speediness meant that supercapacitors could be an excellent application.

We had one more technical problem to overcome: geometry. Traditional supercapacitors consist of pairs of electrodes stacked vertically, like the stories of a high-rise building, but most integrated systems are laid out flat and thus can accommodate only single-story structures. We needed a planar geometry that could be fabricated in a way that would be compatible with modern microelectronics.

We found the solution in LightScribe, an inexpensive, off-the-shelf laser technology that millions of people have used to etch labels and designs



onto compact discs. However, instead of using a disc coated with a reactive dye that changes color on exposure to laser light, we use a very thin coat of graphite oxide. The laser heats the oxide, transforming it into graphene in precisely defined tracks, one micrometer apart. These are the electrodes. In between we leave untreated graphite oxide, which conducts ions but not electrons and so can serve as an excellent dielectric between the positive and negative graphene electrodes. To complete the cell, we top off the pattern with a droplet of gel electrolyte to provide a bit of battery-like storage—the same technique that's used in conventional supercapacitors.

By "interdigitating" the electrodes to resemble interlaced fingers, we greatly extend the interface, which increases the surface area to which electric charge can cling. At the same time, we shorten the path over which ions in the electrolyte need to diffuse. That's important because supercapacitors store charge via the adsorption of ions on the surface of graphene, and therefore the ion diffusion rate controls the rate of charge and discharge of the supercapacitor. Faster ion diffusion means faster charge and discharge capabilities. As a result, the new interdigitated supercapacitors demonstrate greater charge storage capacity than their stacked counterparts.

EASY TO APPLY: No ion-deposition machines are needed to coat a disc with graphite oxide—just a hand-operated pipette.

No photomasks or expensive clean rooms are required for the processing of these microsupercapacitors. This single-step laser-writing method can produce devices at a fraction of the cost of conventional microfabrication techniques. In our lab we can now produce 100 of the devices on a disc in less than 30 minutes, and there is plenty of room for improvement. Of course, a manufacturer could speed things up by simply running a roomful of DVD burners in parallel. It would be even better to optimize a burner for mass production with industrial-

MAHER EL-KADY/UCLA (4)

IONS GO UP & DOWN, ELECTRONS GO BACK & FORTH

Electrodes [gray] consist of stacks of chicken-wire-shaped graphene, which conducts electrons. Positive [red] and negative [blue] ions flow between and through the electrodes, completing the circuit of the battery-like element of the supercapacitor.

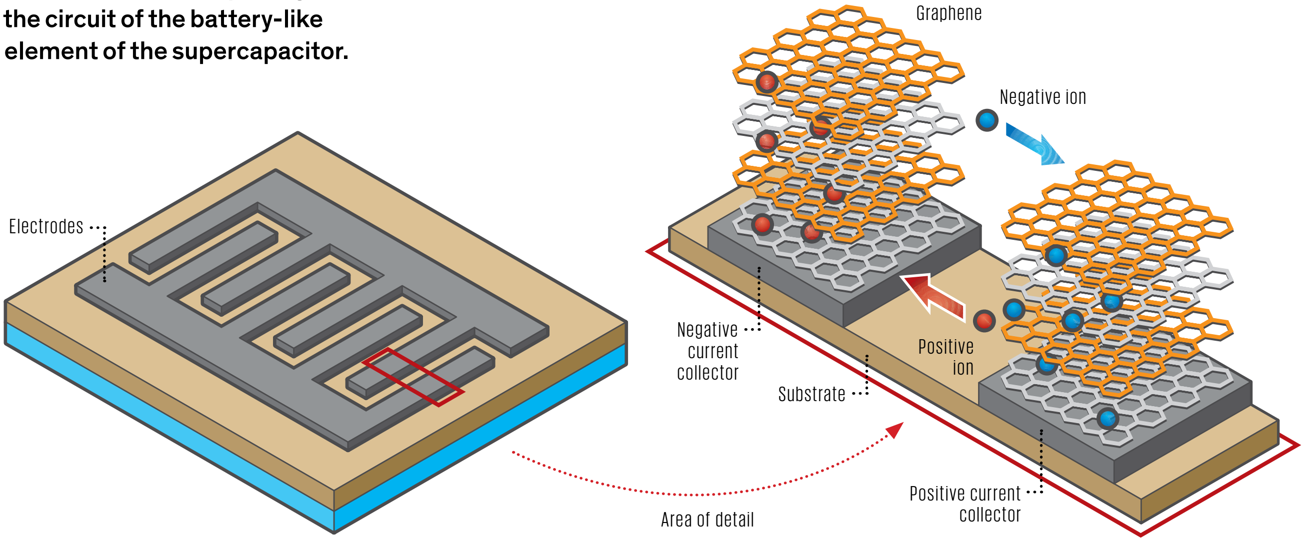
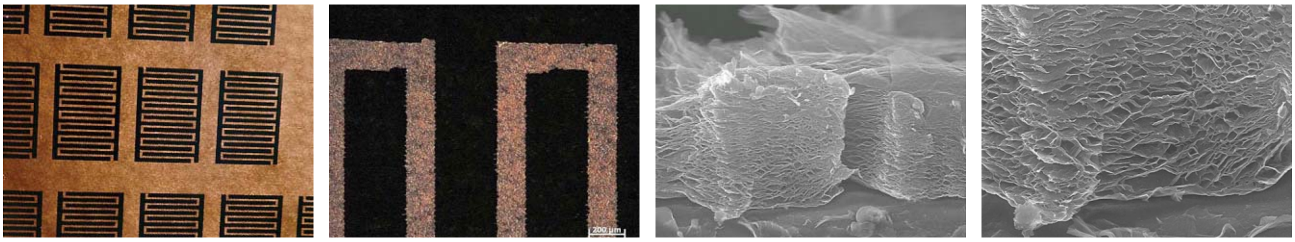


ILLUSTRATION BY James Provost



scale laser engravers, which are now widely used in industry to mark products so that they can be tracked later on. The laser engraving machines can be constructed on a conveyor-belt system using long rolls of graphite oxide.

The result is a marvelously compact, two-dimensional device that can be integrated directly with silicon circuitry. By contrast, today's computer motherboards require complex interconnects between the electronics and the backup power supply, typically a coin-size lithium battery that keeps memory alive when system power is off. And because they can be integrated on-chip, these microsupercapacitors could make it easier to extract energy from mechanical, thermal, and solar sources. For instance, they could be fabricated on the backs—literally—of solar cells to store power generated during the day for use after sundown. Typical practice today is to use batteries for this application, but supercapacitors would be better because they can extract charge much more efficiently and with minimal losses. In addition, integrated supercapacitors can simplify the external wiring used in conventional energy harvesting and storage systems.

Our design also sidesteps one of the main challenges in today's power supplies: leaking electrolyte. Both batteries and conventional supercapacitors use highly corrosive liquid for this function, and as the devices age, this liquid sometimes escapes to eat away at circuits and surrounding components. The result is failure and sometimes even fire. Our microsupercapacitors employ an all-solid-state electrolyte, which we apply directly onto the interdigitated pattern.

For this solid electrolyte, we have plenty of choices. We can use gelled polymer electrolytes, made by swelling a polymer matrix with an electrolyte solution, or we can solidify ionic liquids by adding polymers or silica nanopowder. This nonleaking design, together with a virtually unlimited number of charge and discharge cycles, means that our supermicrocapacitors will likely outlast all other electronic devices on the chip. Such long life will be particularly useful whenever it is inconvenient or dangerous to open things up to replace a power source, as in pacemakers, defibrillators, and other medical implants.

Another interesting feature of our direct laser-writing technique is the ability to link any number of microsupercapacitors together to produce modules with both high voltage and high current output. That beats yoking many cells together with clumsy wiring. More important, we can pack far more high-voltage supercapacitors into a very small volume than any scheme could accomplish today.

Recently, our team has produced a hybrid that combines the best features of capacitors and batteries. We fabricate this hybrid device by growing manganese dioxide—a battery-like material—inside the corrugated graphene structure of our supercapacitors. The hybrid can be recharged in minutes, yet it has an energy density up to 10 times that of commercially available microbatteries. The hybrid device is only one-fifth the thickness of a sheet of paper; its footprint can vary from a few square micrometers up to the centimeter scale. The centimeter-scale devices would have capacitances in the range of 400 to 1,000 millifarads—easily enough to power an LED flashlight for an hour.

Because of their power and compactness, our microsupercapacitors will open up new opportunities. You could knit them right into the fabric of an adhesive bandage so that it could put out a bit of electrical current to stimulate the slow, steady release of a drug. Or you could integrate them onto smart cards to provide an independent, onboard source of energy that could be tapped to erase stored data in case of fraudulent use.

Commercial applications of our devices are now being explored by Nanotech Energy, a Los Angeles-based startup. As mass production expands, unit costs should plummet until microsupercapacitors find their way into camera phones, RFID tags, and solar cells. And as Moore's Law begins to apply in full force, supercapacitors will begin to shrink right out of sight. As electronics engineers well know, there's plenty of room at the bottom. ■

GERM'S EYE VIEW: From left, increasingly magnified views of the electrodes show the 3-D graphene network [second from right] and finally the interconnected pores.

FROM LEFT: MAHER EL-KADY/UCLA (2); VERONICA STRONG/UCLA (2)

POST YOUR COMMENTS at http://spectrum.ieee.org/supercapacitors1015

Building a Better Disease Detective

MACHINE-LEARNING ALGORITHMS CAN IDENTIFY THE WILD SPECIES RESPONSIBLE FOR OUTBREAKS BY BARBARA HAN

In April 2014, just after world health officials identified a series of suspicious deaths in Guinea as an outbreak of Ebola, 10 ecologists, 4 veterinarians, and an anthropologist traveled to a Guinean village named Meliandou. Theirs was a detective mission to determine how this outbreak began. How had "patient zero," a 2-year-old boy named Emile, contracted the Ebola virus?

JOE MCDONALD/GETTY IMAGES

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

Because we believe people catch Ebola through contact with infected animals, ecologists have long sought the animal "reservoirs" that harbor the virus and pass it along (often without getting sick themselves). With every new outbreak of a zoonotic disease like Ebola, scientists race to identify the reservoirs so that public health officials can determine the method of transmission and perhaps prevent more "spillover events," in which the disease flows from animal reservoirs to people. Such is today's post hoc, reactive model of dealing with outbreaks. In Meliandou, the Ebola detectives interviewed villagers, studied primate populations in nearby forests, and collected bats in nets. In December 2014, they published a paper hypothesizing that little Emile had contracted Ebola from a colony of insect-eating bats that lived in a hollow tree, near where the local children often played. But the tree had caught fire before the team arrived in the village and the bats were gone, so the investigators couldn't say for sure.

As most previous research on Ebola reservoirs has focused on fruit bats, the team's findings may prompt scientists to study this insectivorous bat species, and may cause health officials to stay alert in areas where these bats live in close proximity to people. But these are rearguard maneuvers against a brutal opponent: The current Ebola epidemic has killed more than 11,200 people in West Africa to date, and health officials are still fighting to end it. Is there a way to go on the offense against Ebola and other zoonotic diseases? Can we predict outbreaks before they occur?

In my research as a disease ecologist at the Cary Institute of Ecosystem Studies, in Millbrook, N.Y., I use computer modeling and machine learning to predict which wild species are capable of causing future outbreaks. My models create "caricatures" of likely reservoirs, revealing the suite of features that distinguish the unusual species that can harbor »

CULPRIT CREATURE: Humans catch zoonotic diseases through contact with infected animals. This fruit bat is a known carrier of Nipah virus, a potentially deadly disease first identified in Malaysia in 1999.

microbes dangerous to humans. I then use algorithms to sort through hundreds or thousands of species that have never been checked for zoonotic diseases, and calculate the probability that any given species is a disease reservoir based on its similarity to that caricature. The models give us a list of suspects.

My colleagues and I do this work in the spirit of scientific inquiry, and also with an urgent sense of purpose. Infectious diseases are on the rise around the world, and the U.S. Agency for International Development reckons that about 75 percent of new diseases are zoonotic. If we can predict which species may carry infections capable of jumping to humans, we can monitor the potential hot spots where people interact with these creatures. One day, I hope that biologists will forecast disease outbreaks in the same way meteorologists forecast the weather. With one major difference: A meteorologist can't stop a storm front, but we may be able to prevent outbreaks.

To understand why the reactive approach to outbreaks has prevailed thus far, just look at Ebola. Imagine you're a wildlife biologist trying to find this virus's reservoirs where it first emerged, in the Congo rain forest. You're standing in front of a forest roughly the size of Alaska that's home to more than 1,400 species of mammals and birds, as well as countless insect species. If you have the resources, you might try to sample every animal you can catch: many representatives of common species and occasional solitary specimens from rare species.

Even then, you probably won't succeed in your goal. Only a fraction of a reservoir species' population will be infected—and given the intermittent nature of Ebola outbreaks, the prevalence of the virus in its animal host populations is thought to be very low. Also, there may be multiple reservoir species—and you're trying to identify them all in a dynamic environment, where animals migrate with the seasons and relocate due to habitat destruction. Even if you get your hands on an infected animal, the Ebola virus may be hard to spot: The amount of virus in the animal's body may vary seasonally or according to the animal's stress levels.

During previous surveys seeking Ebola's wild reservoirs, biologists have collected more than 30,000 individuals from hundreds of species. While traces of prior infections (that is, antibodies) have been detected in the blood of a number of animals, we have yet to isolate the live virus in the body of a living animal. Biologists won't give up the search, but clearly an additional approach would be welcome.

In my work, I use machine-learning algorithms that take in vast amounts of unstructured data about wildlife and identify the key traits that are most helpful in predicting a reservoir species. The algorithms I apply are an extension of tools called classification and regression trees, which have been around for decades. The novelty of my work is the application of these techniques to a massive challenge of ecology and global health.

How a Machine Learns

This very simplified diagram shows how our algorithm creates classification trees, which it can then use to predict which rodent species carry zoonotic diseases.

The algorithm learns how to classify species as "zoonotic" (represented here as "Y") or "not known to be zoonotic" (represented as "N") using a training data set. To create an initial classification tree, it repeatedly splits the data set of rodent species into two groups, using a randomly selected feature (such as body size under or over 1 kilogram) for each split. Its goal is to separate the Ys from the Ns at the terminal "leaves" of the tree.

This first tree may produce lots of classification errors, so the algorithm builds a second tree that prioritizes the misclassified species, aiming to sort them correctly. The second tree's misclassified species are prioritized as the algorithm builds its third tree, and so on.

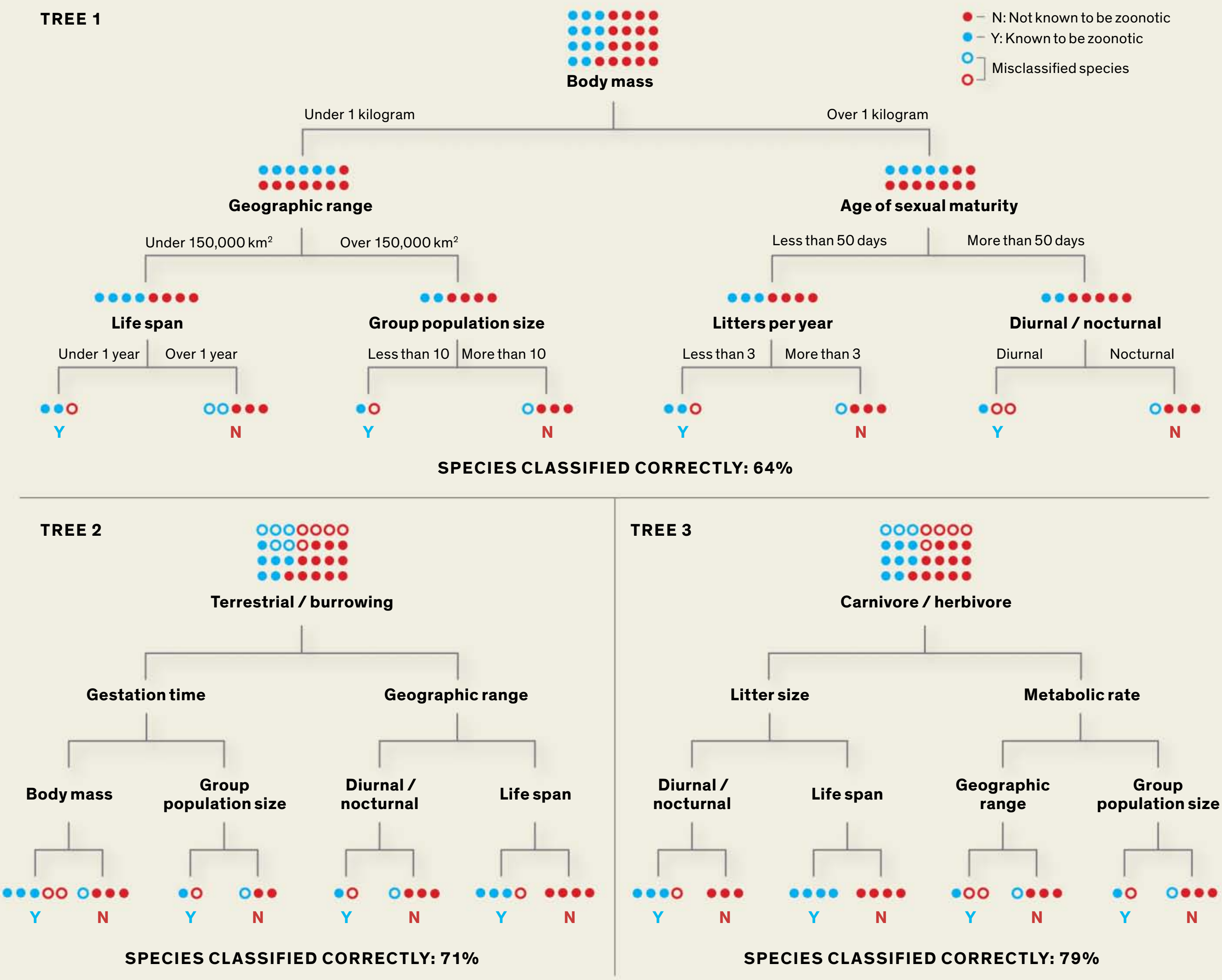
In this iterative fashion, the algorithm generates thousands of trees. When data is filtered through all these trees as an ensemble, the classification accuracy goes way up. Once the model performs well on the training data, we use it to make predictions with the rest of the data set.

MY RECENT STUDY of rodents, conducted with colleagues at the University of Georgia, gives an example of how this approach works. The order Rodentia includes more than 2,200 species, more than any other group of mammals. Rodents are also prolific with their pathogens: In our conservative estimate, we counted about 200 rodent species that are already known to transmit between 1 and 11 different zoonotic diseases. Among their contributions to human suffering are hantaviruses that can cause fatal pulmonary disease and the bacterium responsible for bubonic plague.

To train our algorithm to find more of these carriers, we fed in data for 80 percent of all rodent species, leaving the remainder to serve later on as a test bed. We gave each species a binary label: a "1" indicating that it's known to carry a zoonotic disease, or a "0" indicating that its reservoir status is unknown. We also fed in information from sources such as the massive PanTHERIA database of mammals, which collates data from thousands of field studies regarding rodent species' physiology, behavior, geographic range, social structure, and so forth.

The algorithm creates a classification tree by taking the training data and identifying split points: values of particular variables that lead to two classes that are the most different from each other. It does this again and again, creating fork-

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page



ing branches until all the data is sorted into a series of bins—the leaves of the classification tree. It can also create a regression tree, which is slightly fancier. Its final leaves don't simply show binary responses to the split points (such as "one litter per year" versus "more than one litter per year"); instead, its leaves show a continuum of values (such as one, two, three, four litters per year).

In our study, the algorithm generated a tree by randomly selecting a feature to split the group of rodent species into two homogeneous subgroups consisting of "1s" and "0s." It did this as best it could—inevitably, there were classification errors. It then selected a second feature, then a third, and so on until all the rodents had been separated into leaves of the tree. These features included resting metabolic rate, adult body size, age of sexual maturity, number of offspring per litter, number of litters per year, group population size, and more than 50 other such characteristics.

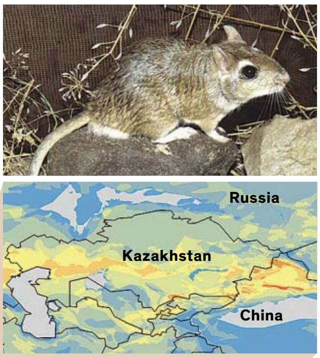
This method has a major weakness: It's very sensitive to which feature is selected first. Depending on whether the algorithm selects, say, "group population size" or "metabolic rate" as the first feature, it will produce very different trees. Using any one tree, we won't have great success in correctly predicting whether a new rodent is a zoonotic suspect or not; its prediction accuracy may be little better than a coin toss. To overcome this fault, we apply an iterative process called "boosting." Here, the algorithm focuses on the errors it made in any given tree, and prioritizes that data as it creates new trees. This method generates hundreds or thousands of weakly predictive trees that, when employed as an ensemble, produce a powerfully accurate predictive model.

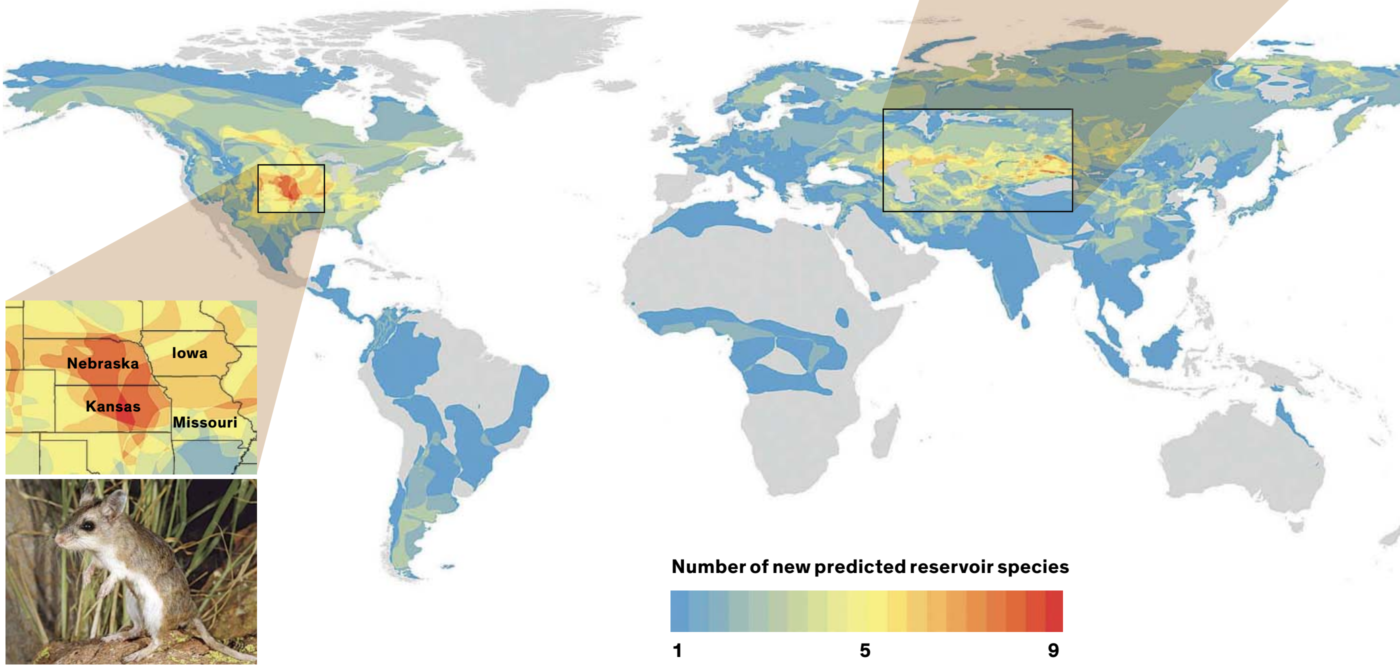
When we tested our rodent-sorting algorithm on the 20 percent of rodents that hadn't been included in the training data set, it predicted species' reservoir status with about 90 percent accuracy. And when we pulled back the curtain

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

Where to Look for Trouble

Our computer model identified 58 rodents that had never before been associated with a zoonotic disease as likely "reservoirs" of pathogens that could infect humans. The maps of those rodents' ranges revealed two potential hot spots where we predict disease outbreaks are likely to occur: the American Midwest and a band across central Asia and the Middle East. Armed with these predictions, field biologists can canvass these areas and study species from our list of suspects, such as the northern grasshopper mouse [left] and the tamarisk jird [right].





to see which features the algorithm had used to make its accurate predictions, we saw that it identified zoonotic reservoirs based on a unique trait profile. It had not, as you might expect, picked out species that were closely related to each other. Instead, it found that reservoir species were distinguished by their "fast" life cycles—with rapid growth rates, early sexual maturity, and frequent litters. This finding fits nicely with in-depth studies of individual rodents, which have suggested that reservoir species may have less sensitive immune systems. These animals may tolerate pathogens because they have a "live fast, die young" strategy: Their immune systems aren't their top priority because they need to stay healthy just long enough to reproduce. The profile also showed that reservoir species tend to have large geographic ranges. These animals may thrive in diverse ecological habitats or may adapt well to the fragmented and heterogeneous landscapes created by humans.

Our study yielded more than scientific insights: It also provided actionable intelligence. As the algorithm sorted through the 2,200 rodent species, it provided a list of new suspects. Some species that had previously been given a "0" for unknown reservoir status fit more neatly in the "1" category of known disease carriers. We didn't have to wait long for validation. While we were getting our results to press, two of those suspect species were indeed recognized as novel reservoirs for human diseases. One species, a red-backed vole (*Myodes gapperi*) native to Canada and the northern United States, was found to carry the parasite that causes echinococcosis, a nasty ailment in which cysts grow in multiple organs. And researchers identified a vole (*Microtus guentheri*) native to Asia Minor as a newfound reservoir for leishmaniasis, which causes skin ulcers.

Our list of suspects presents an opportunity for biologists: They can go out into the field and try to "ground-truth" our results. And those field studies will, in turn, inform our work. As surveillance continues and biologists make new discoveries of disease carriers, our databases will grow richer and our model's predictions will become more accurate. The algorithm will continue to evolve, continue to learn.

We're now applying our methods to help combat other devastating diseases. We're currently trying to determine which additional bat species may be reservoirs for the filoviruses that cause hemorrhagic fevers such as Ebola and Marburg virus disease. We hope our results will help explain how certain

LEFT: RICK & NORA BOWERS/ALAMY; RIGHT: KLAUS RUDLOFF/MOSCOW ZOO bats can live with an infection that's so deadly to great apes, including humans.

Already our model has identified a cluster of bat species that belong on a watch list. To our surprise, some of the species that seem capable of carrying Ebola-like viruses live outside of Africa, in countries where human outbreaks of hemorrhagic fevers have never been officially reported. The results raise a question for biologists: If outbreaks truly haven't occurred in these places, why not? They also raise a question for public health officials: Should they be worried?

Machine-learning methods have a few key advantages for ecology, a discipline that seeks to understand the complex and ever-shifting interplay between the billions of living beings jockeying for position on Earth.

For instance, our algorithm can deal with our incomplete data sets. Biologists simply can't learn everything about the 1.6 million species we've cataloged thus far, let alone the many millions we haven't. But the algorithm considers the presence or absence of any particular piece of data as just another variable that can be used as a split point in its classification trees.

Moreover, our approach counteracts the sampling bias that can skew the study of infectious diseases: Extensive wildlife surveys in wealthy regions like the United States and Europe have resulted in higher-quality data regarding American and European species. Biologists can also fall afoul of vigilance bias when they study individual host species: The more they look for something, the more likely they will find it. Thus, if they find that the Norwegian rat carries disease X, they are likely to also sample it for Y and Z, with the result that a few species may appear downright plague-ridden, while others have yet to be checked for any pathogen.

As our method focuses on intrinsic properties of species, we minimize the effects of such biases. For example, if the algorithm zeros in on rodent species with small bodies, it will draw species from all over the world (because small-bodied rodents are just as likely to live in poor countries as rich ones). By using species' intrinsic biology to predict reservoir status, we avoid falling into the vigilance bias trap: making predictions that center on places that can afford surveillance to begin with. On the other hand, there isn't much to be done about serious data deficiency. If we have no data on a species, there's simply no possibility of predicting its reservoir probability. Our work shows that cutting basic science funding has significant ripple effects: It really is worth knowing the life history of that obscure mouse in Papua New Guinea.

Machine learning also deals well with complexity. Ecological analyses can easily include dozens of variables, but it's often not clear how those variables interact. For instance, although there's good evidence that an animal's body size and metabolic rate scale according to a particular mathematical relationship, it's less clear how the size of a newborn relates to metabolic rate. The more variables there are, the harder it is to understand their complex and hidden interactions.

But our algorithm doesn't require us to set any rules for these interactions. Instead, our method allows the data to speak for itself. If a particular combination of variables leads to great predictive accuracy, the model identifies those variables and presents them to the researcher for further interpretation. The algorithm doesn't care how the variables are interacting; its only goal is to maximize predictive performance. Then we human scientists can step up. Our job is to look at the variables that are most important for prediction and figure out what they reveal about the biology of zoonotic disease reservoirs.

To make progress toward the ambitious goal of forecasting and even preempting zoonotic disease outbreaks, it's not enough to learn which disease arises from contact with which reservoir. Biologists need to understand: Why is that particular species special? Our approach gives us a clue about the "why"—the biological mechanisms that allow some animals to be carriers and transmitters of deadly infections.

Of course, human beings play a role in the emergence of disease, often by coming directly into contact with wild animals or by bringing domestic animals into contact with them. For example, Nipah virus emerged in Malaysia from human contact with infected pigs, which had picked up the virus from fruit bats. Those bats had begun foraging in orchards and swine farms because people had chopped down their forest habitats.

Some of the species that seem capable of carrying Ebola-like viruses live outside of Africa, in countries where outbreaks have never been reported

Urbanization, deforestation, and hunting will continue to bring humans into contact with wild species potentially bearing wild new diseases. We're all part of the same system of life, and diseases emerge from this complex system. We're only beginning to understand these ecological dynamics. Predicting reservoir species is quite a challenge, but I see it as part of an even greater challenge: figuring out how to live harmoniously with the wild creatures with which we share this planet. ■

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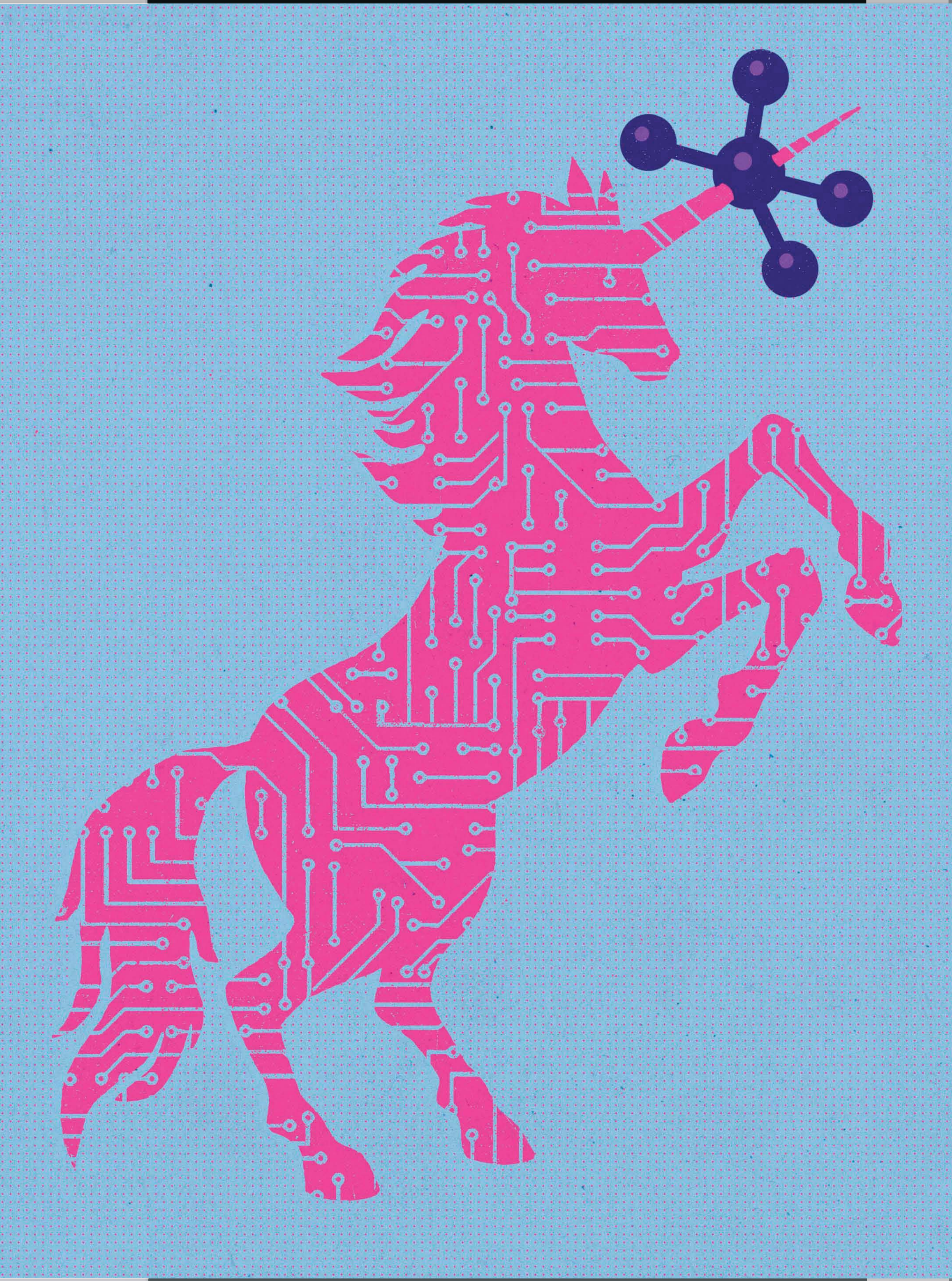


THE BOOMS AND BUSTS OF MOLECULAR ELECTRONICS

WHY THE TANTALIZING PROMISE OF REPLACING TRANSISTORS WITH SINGLE MOLECULES HAS YET TO BE FULFILLED

By **Kevin F. Kelly & Cyrus C.M. Mody**

FORTY YEARS AGO, a New York University graduate student named Arieh Aviram opened his Ph.D. dissertation with a bold suggestion: "Taking a clue from nature, [which] utilizes molecules for the carrying out of many physical phenomena, it may be possible to miniaturize electronic components down to molecular size." What Aviram was proposing was revolutionary: leapfrogging the ongoing miniaturization trend of Moore's Law by substituting single organic molecules for silicon transistors and diodes.

In a paper written with his thesis advisor, Mark Ratner, Aviram even described a theoretical starting point for such a revolution—a "molecular rectifier," for converting alternating current to direct current.

Aviram and Ratner's bold idea sank into obscurity. Little wonder: Aviram was still a student, while Ratner was just a few years into his academic career. But in the late 1980s, their paper resurfaced and was taken up by a small and determined band of researchers. It has since been cited more than 3,000 times and today is celebrated as giving birth to the field of molecular electronics, which now seems closer than ever to realizing the vision that Aviram put forward four decades ago.

Bulk ensembles of molecular electronics have made their way into commercial displays, and recent high-profile break-

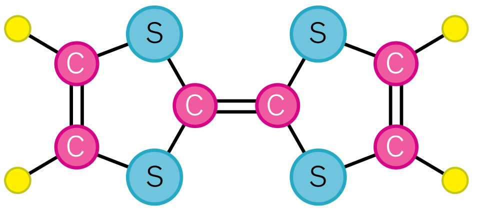
ILLUSTRATION BY Dan Page

throughs include single-molecule light-emitting diodes and carbon nanotube transistors coupled to silicon in a monolithic integrated circuit. Other, less flashy but more technically relevant results have come, for example, from Danny Porath and his colleagues at Hebrew University in Jerusalem, who have measured electrical transport in wires made of DNA; such wires are a self-assembled alternative to copper interconnects. Latha Venkataraman's group at Columbia University has measured single-molecule diodes to a rectification ratio of more than 200 times–a critical step for maintaining a high signal gain as devices shrink. And Christian Nijhuis and his coworkers at the National University of Singapore were able to measure the rectification changes that occurred when they replaced an individual functional group–just a handful of atoms–in a nanometer-size molecule. This is exactly the type of control dreamed of by Aviram and Ratner.

Meanwhile, chip designers face ever steeper hurdles in keeping pace with Moore's Law. With Intel's recent announcement that it would delay the launch of its 10-nanometer node–the next milestone along the semiconductor road map–to 2017, the recent successes in molecular electronics look especially timely. After decades of effort, could molecular electronics finally be ready to replace silicon? It's a tantalizing possibility.

And yet researchers have thought they were on the verge of such a breakthrough before. Indeed, it's happened three times: in the early 1960s (well before Aviram and Ratner's paper), in the mid-1980s, and again in the early 2000s. Each heady boom was followed by a disappointing bust during which the field had to retreat from its promises in the face of poor results–and, in one case, egregious fraud. Fads in research aren't unusual, to be sure: Many disciplines have been captivated by a big idea only to retreat from it later. But the story of molecular electronics is special for what it says about the nature of research and progress, and about the human capacity for optimism and hubris.

The two of us view this colorful history from our own perspectives: One of us (Kelly) is a physicist who has done research in molecular electronics; the other (Mody) is a historian who has studied the field as a cultural phenomenon. Our collaboration on this article and on other projects has taught us to celebrate the progress that has been made in the pursuit of molecular electronics but also to approach the field with a healthy amount of skepticism.



ORGANIC CONDUCTORS known as organic charge-transfer salts were explored as a possible replacement for silicon electronics in the 1970s.

SINCE THE LATE 1950s, circuits for computers and other devices have been made by etching complicated patterns into a semiconductor crystal (usually silicon) in an elaborate and precise process involving dozens of steps. But early on, some people wondered whether a better approach to miniaturization might be to "grow" single molecules that functioned as electronic circuits or components. Such molecules might be faster and smaller than silicon integrated circuits, and they might also be easier to make. Arthur R. von Hippel and his research group at MIT were the first to explore this concept. In 1959, the U.S. Air Force began funding Texas Instruments, Westinghouse, and a few other firms to develop solid-state "molecular" circuits from doped inorganic crystals. While these crystals weren't molecules per se, they were allegedly designed from the molecular scale up, rather than carved from the macroscale down, like conventional integrated circuits.

Researchers at Westinghouse in particular promised they would soon be able to grow a crystal of germanium that would behave like a complex circuit, but without the need for failure-prone connections between components. (Fashioning the connections between components in silicon ICs was at that time a great technical challenge.) The company's complete failure to deliver such a molecular circuit–and, in stark contrast, the continuing success of silicon ICs–led to the disappearance of this first wave of molecular electronics by the mid-1960s.

A decade later, Aviram and Ratner initiated a new era of molecular electronics based on organic molecules rather than inorganic crystals. Circuits made from a class of organic conductors known as organic charge-transfer salts seemed amenable to far greater miniaturization than either inorganic crystals or silicon devices.

Aviram and Ratner envisioned their molecule working very much like a semiconductor diode, where one part of the molecule would be an electron donor (analogous to the *n*-doped region of a semiconductor diode) and the other an electron acceptor (analogous to a diode's *p*-doped region). As with a diode, when you put a voltage across the molecule, the bands of the two regions would bend until electrons moved freely from one region to the other; a voltage with the opposite sign, on the other hand, would prevent the electrons from flowing. What's more, such a molecular diode could potentially be mass-produced with the proven tools of synthetic organic chemistry. As a proof of concept, Aviram and Ratner designed a molecular rectifier–a single molecule into which an alternating current would flow at one end, with a direct current coming out the other. Although their proposal was briefly mentioned in *Time* magazine, the scientific community showed little interest–that is, until their ideas were taken up in the late 1970s by a chemist at the U.S. Naval Research Laboratory named Forrest Carter.

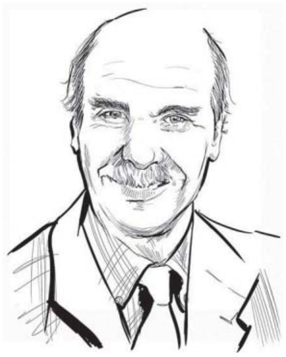
With his giant beard, booming bass voice, and outsize passion for fast cars and ballroom dancing, Carter was the pied piper who brought together a diverse set of polymer chemists, device physicists, electrical engineers, biotech researchers, futurists, and defense policymakers. He generated publicity with promises of the revolutionary potential of molecular electronics for computing and, in particular, for artificial neural networks that could recognize patterns almost as deftly as the human brain could. The community that formed around Carter's grand vision didn't gain much in the way of federal funding, but his followers exchanged ideas more rapidly than they would have in isolation. Meanwhile, well-funded if less ambitious national programs in molecular electronics started to appear in Japan, the Soviet Union, and the United Kingdom.

Despite Carter's overly optimistic promises, no one managed to synthesize even a single molecular diode or transistor, much less dozens (and certainly not thousands) of them wired together to form a complex circuit. And even as Carter's detailed descriptions of molecular computers inspired some researchers, they alienated others who wanted tangible evidence for the feasibility of his molecular-electronic visions. As a 1983 report in *Chemical & Engineering News* put it, "hype seems inevitable for so-called molecular computers. There are claims for the miraculous things they will be able to do...[that] are barely a step removed from science fiction." By the time Carter died in 1987 at the age of 57, the U.S. molecular-electronics community had gained, in the words of the British physicist Richard A.L. Jones, a "louche reputation."

Meanwhile, Aviram had quietly continued his research and started organizing a series of conferences on molecular electronics with support from the Engineering Foundation. Though Aviram himself avoided the hype surrounding Carter, his gatherings helped catalyze the next boom in molecular electronics.

The Many Characters of Molecular Electronics

ARIEH AVIRAM
His 1975 Ph.D. thesis proposed substituting silicon transistors with single organic molecules.



MARK RATNER
With Aviram, he described a "molecular rectifier" made from organic charge-transfer salts.

FORREST CARTER
Taking up Aviram and Ratner's ideas, he became the field's charismatic leader in the late '70s.

MARK REED
With Tour, he proposed a way to fabricate single-molecule switching devices.

JAMES TOUR
He and Reed patented a molecular computer and cofounded Molecular Electronics Corp.

JANE "XAN" ALEXANDER
She oversaw DARPA funding for molecular electronics, which grew to US $15 million per year.

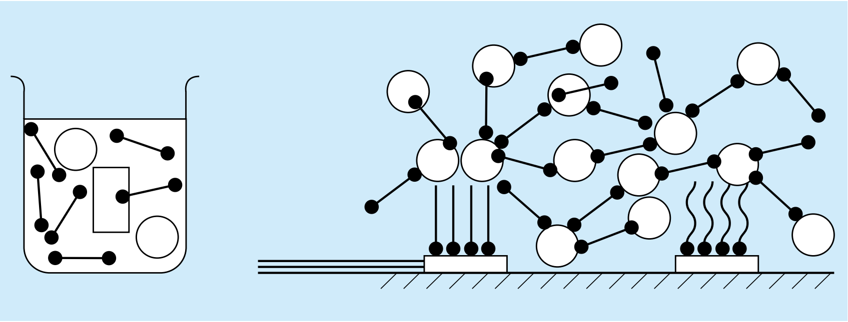
JAN HENDRIK SCHÖN
In 2002, his remarkable claims, including a single-molecule transistor, proved false.

PAUL WEISS
A collaborator of Tour's, in 2003 he questioned some of Reed and Tour's earlier results.

R. STANLEY WILLIAMS
His group's discovery of the memristor in 2008 grew out of their study of molecular devices.

Mark Reed, a specialist in microfabrication from Yale, attended one of these conferences in 1991, which that year was being held in the Virgin Islands. Drawn largely by the opportunity to scuba dive, Reed met a synthetic chemist named James Tour (then at the University of South Carolina and now at Rice University), who had come up with a way to synthesize organic molecules that could, at least in theory, func-

PORTRAIT ILLUSTRATIONS BY Miss Led



ELECTRONICS FROM A BEAKER: In a 2002 U.S. patent application, James Tour and his colleagues described a method for accelerating the "self-assembly of molecular devices."

tion as "molecular switching devices." But Tour hadn't yet figured out how to wire his molecules into a circuit to see whether they could indeed switch. Reed proposed a solution: He would use microfabrication techniques to create electrodes separated by a tiny gap, onto which he could pour Tour's molecules. If just one molecule bridged the gap, any current flowing through the circuit would be measurable.

Reed and Tour's research proposal landed on the desk of Jane "Xan" Alexander, a grant officer (and later deputy director) at the Defense Advanced Research Projects Agency. The agency soon funded this work and then in 1998 expanded its patronage through its Moletronics program. Eventually, DARPA's support of Reed and Tour and their collaborators, and of similarly directed groups at Hewlett-Packard, IBM, Northwestern, Penn State, and elsewhere, grew to about US $15 million per year. Once again, the field was swept up in heady visions of single-molecule devices with complex electronic behaviors. And progress was indeed made in characterizing the electronic properties of single-molecule "components." Reed and Tour were even optimistic enough to cofound a startup, Molecular Electronics Corp., with several colleagues. In 2000 they filed a patent for a "molecular computer" that would provide a way past the "lithography driven...diminishing returns" of traditional silicon.

But as before, the sweeping promises outran the actual achievements. In 2003, one of Tour's Penn State collaborators, Paul Weiss, told the journal *Science* that some of Reed and Tour's earlier results on molecular-electrical properties, such as negative differential resistance, were not as solid as a 1999 article had implied. Another prominent collaboration–between Hewlett-Packard's R. Stanley Williams and James Heath and Fraser Stoddart, who were both at the University of California, Los Angeles–also faced criticism for claims about the switching behavior of a device made with a layer of rotaxane molecules. Such revelations undermined the field's credibility to the point that the news story in *Science* asked whether the field was undergoing a "midlife crisis."

These missteps were trivial, however, compared with the outright fraud that Jan Hendrik Schön committed at Bell Laboratories. In 2001, Schön had burst onto the scene with a series of high-profile discoveries in molecular electronics, including the field's holy grail: a single-molecule transistor. Just one year later, that transistor–and almost everything else Schön had claimed to have done–proved utterly false.

Schön's fraud was disastrous to many in the field. Prominent scientists who had spoken glowingly of the physicist's results now looked gullible or careless–a damning mark on their reputations. As investors retreated, startups like Molecular Electronics were forced to close their doors. And the field's leaders either dialed back their rhetoric or abandoned molecular electronics altogether, choosing to transfer their expertise to related but unsullied areas such as designing molecules for drug delivery.

OF COURSE, scientific fraud is not unique to Schön, and so it's worth looking at the circumstances that facilitated his deception. One obvious problem in hindsight was that the field had not placed a high value on the repeatability of results. Many teams were working with unique molecules that others didn't have access to and were thus unable to study. As a result, Schön's spectacular findings went unchallenged for too long. The sole reward for those who did try to chase his phantom discoveries was a loss of their valuable time.

The Schön affair also revealed a failure by too many to heed the old adage "Don't fool yourself." Perhaps because of the high commercial stakes or because the field seemed to be moving so quickly during the years of DARPA funding, researchers had no time to dwell on disconfirming evidence. Too many articles presented results in the best light while overlooking observations that didn't support the authors' pet hypotheses. For example, some early reports on nanojunctions described astounding device yields of 80 percent. But this figure turned out to be based on the number of nanojunctions that had passed an initial measurement, not on the total number that had been fabricated. The true yield was more like 1 to 2 percent.

Even before Schön's fabrications came to light, plenty of researchers had agitated for a more cautious approach and shown a willingness to revisit and revise their own results. His defrocking spurred such people to start to change the culture of their field. For instance, researchers finally began running control experiments where they inserted both active and insulating molecules into the inorganic nanojunctions in their devices; that way, they could separate the properties of the nanojunctions from the properties of the active molecules.

At first, such ad hoc changes occurred in an informal way. But true reforms gained more structure and momentum with the creation of the National Nanotechnology Initiative in the United States (and similar programs in other countries) right around the time of the Schön scandal. A multibillion-dollar, multiagency effort, the NNI was created to foster nanoscale research and development. Its members have since provided more than $20 billion in funding. For those in molecular electronics, the program not only offered monetary support at a time when other private and government sources had dried up but also gave access to expensive, specialized equipment and to new collaborators from a wide variety of disciplines.

The NNI's other gift to molecular electronics was its increased oversight of the research, which put a much-needed check on the field's tendency to overheat and overpromise. Member agencies of the NNI that run their own laboratories—namely, the Department of Defense, the Department of Energy, the National Institutes of Health, and the National Institute of Standards and Technology (NIST)—now coordinate their results with academic researchers receiving NNI support through the National Science Foundation.

The Naval Research Lab and NIST, in particular, have for more than a decade rigorously attempted to replicate the findings of researchers in molecular electronics, issuing notices when any discrepancies appear. Even as the Schön scandal was unfolding, articles by James Kushmerick and Roger van Zee (both now at NIST) and their coworkers began to clarify and quantify the discrepancies between measurement techniques and between disparate molecular systems. An important lesson from this work was the recognition that results had to describe the synthesis of the active molecule as well as characterize both the inorganic nanodevice architecture surrounding the active molecule and the interaction between molecule and architecture.

In the wake of these reforms have come a series of scientific and engineering successes. Though less heralded—and less expected—than the big promises of the past, these results can be viewed as a quieter fourth boom in molecular electronics.

The effect of NNI's cross-disciplinary approach is clearly seen in the rapid progress in creating and characterizing devices made from graphene. Such work lies at the intersection of chemistry, device physics, electrical engineering, and surface science. A little over a decade ago, graphene didn't exist; yet less than six years after it was first isolated, it was the basis for the Nobel Prize in Physics. Whereas in the past molecular electronics meant devices made from crystalline ribbons of germanium, charge-transfer salts, conducting polymers, or carbon nanotubes, today the most promising substance appears to be graphene.

Perhaps the most tangible results from this latest wave of research are new, potentially commercializable devices, such as the memristor crossbar memory, a device inspired by molecular electronics. First developed by Williams's group at HP and also being pursued at Hynix Semiconductor and Knowm, the memristor owes its "memory" to the generation and erasure of filamentary connections in titanium dioxide and other compounds. (All three of these companies seem to have been leapfrogged by Intel and Micron, which recently announced their similar but nonmemristor 3-D XPoint crossbar memory.) That these traditional materials could be fashioned for such an end was a direct offshoot from their use as the electrical contacts in "molecular" devices—devices that themselves never materialized.

In other areas, better understanding of the chemistry of a "molecular transistor" has translated into innovations in organic light-emitting diode displays. Efforts to fabricate the inorganic components of a "molecular circuit" have led to novel architectures for traditional silicon microelectronics. Investigations of how to marry the organic and inorganic parts of a molecular circuit have spurred advances in "neuronano" research and human-machine interfaces. And because their participation in nanotechnology has brought them in contact with researchers in the life sciences, some people studying molecular electronics have become involved with the Obama administration's new BRAIN Initiative, which aims to revolutionize the science of the human brain.

BUT WHAT OF the grand vision of a molecular computer? In our view, the field is still not much closer to pouring a Pentium chip out of a beaker than it was when Tour and his colleagues envisioned this possibility a quarter century ago. And the attempt to reach this far-out goal has come at a significant cost: a half century of boom-and-bust cycles, with premature announcements of breakthroughs attracting money and attention but then slowing the field down when those results and promises had to be walked back.

Hoping for molecular electronics to catch up with the fast-moving advances of silicon has repeatedly led to disappointment. In the four decades since Aviram and Ratner's paper, processors have gone from having about 250 transistors per square millimeter to roughly 10,000,000 in that same area.

Silicon ICs can now be patterned with features that are tens of atoms in length and a single atom in thickness. Although the average transistor is still more than 100 nm on a side, the dream that molecular components would be smaller than silicon ones may now be unattainable. But the convergence in size of silicon and organic-molecule components may actually make it easier to marry the two.

On the plus side, the history of molecular electronics demonstrates that the pursuit of even impossible dreams can spur important discoveries. And when daydreaming gets out of hand, the field has shown that deliberate reforms can shift research toward a more sustainable path. Since the Schön debacle, structured government programs have not only funded, conducted, and coordinated research but also policed the quality of the results, thereby enabling molecular electronics to proceed more steadily, over a wider front of materials, disciplines, and research topics, and with less breathless talk of molecular computers. Ironically, today's slow-but-steady approach may ultimately bring that mythical beast closer to reality. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/molecularelectronics1015

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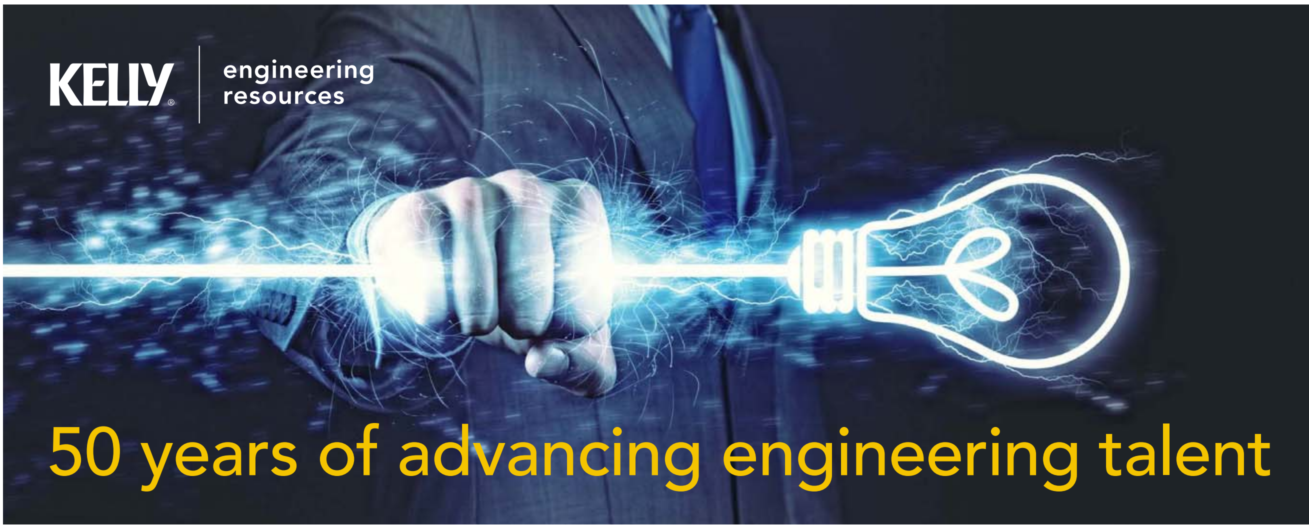

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Making a smooth transition to a new job

Growing demand for engineers brings new career opportunities and career moves. Though exciting, it can feel overwhelming. A career move involves many steps—from resigning at your current job to integrating properly into a new company. Here are some pointers to help you make informed decisions and take appropriate actions:

Motivators for making a move. Before looking for another job, spend time reviewing why you want to move from your current position. Determine your precise pain points. By analyzing the reasons you want to leave, you'll be better equipped to accept a new position that doesn't have the same drawbacks and meets your requirements.

Making a better move. Once you've decided to make a move, it's crucial that you don't just take the first opportunity that comes up simply because you need a change. Make sure you're making a better move that will advance your personal and professional goals. Make a wish list that considers compensation, company culture, growth potential, work-life balance, and opportunities to work internationally or in cutting-edge fields. Decide which points are non-negotiable, and use this list to evaluate potential positions.

The resignation process. This is one of the most sensitive aspects of transitioning to a new job. Even if you've already accepted a new position, it's crucial that you handle your exit from your current organization professionally. You don't know when you'll need a reference from your current boss or colleague, so do everything you can to ensure an amicable resignation process.

Counteroffers. When you announce your resignation, your employer could make you a counteroffer in an attempt to get you to stay. However enticing the offer may be, it's rarely a good idea to accept it. Statistics show that the majority of workers who accept a counteroffer find themselves back on the job market within a year—typically because they're let go by their employer or they resign due to pain points that haven't been addressed.

Make the most of the on-boarding process. Your first months at your new company lay the foundation for the rest of your career with your new employer. The sooner you become productive, and the more relationships you build, the higher your chances of success.

Integrate into your new company. According to recent studies, 89 percent of hiring failures are due to a poor cultural fit. It's imperative that you discard entrenched beliefs and methods, and adapt to those of your new company. Observe, ask questions, and do your best to fit in.

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City University of Hong Kong is a dynamic, fast-growing university that is pursuing excellence in research and professional education. As a publicly-funded institution, the University is committed to nurturing and developing students' talents and creating applicable knowledge to support social and economic advancement. The University has seven Colleges/Schools. As part of its pursuit of excellence, the University aims to recruit **outstanding scholars** from all over the world in various disciplines, including **business**, **creative media**, **energy**, **engineering**, **environment**, **humanities**, **law**, **science**, **social sciences**, **veterinary sciences** and other strategic growth areas.

Applications and nominations are invited for :

Head *[Ref. A/182/36]*
Department of Electronic Engineering

The Position
Reporting to the Provost through the Dean of College of Science and Engineering, the Head of Department will provide leadership and strategic direction in research and professional education for the Department. The Head will encourage and promote academic excellence, and steer the Department to enhance the mission and vision of the University in alignment with the University's Strategic Plan.

The Person
A doctorate degree with strong academic and professional qualifications, a distinguished record of teaching, research and scholarship, and substantial relevant experience in tertiary education; outstanding management effectiveness; commitment to teamwork; and strong communication and networking skills to build and nurture internal and external contacts to the benefit of the Department.

Salary and Conditions of Service
The appointee will be offered appointment to an academic rank commensurate with qualifications and experience. The headship appointment will be on a concurrent basis for an initial period of three years. Remuneration package will be attractive and driven by market competitiveness and individual performance. Excellent fringe benefits include gratuity, leave, medical and dental schemes, and relocation assistance (where applicable).

Information and Application
Further information on the post and the University is available at http://www.cityu.edu.hk, or from the Human Resources Office, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong [Email : eesearch@cityu.edu.hk/Fax : (852) 2788 1154 or (852) 3442 0311].

To apply, please submit an online application at http://jobs.cityu.edu.hk, and include a current curriculum vitae. Nominations can be sent directly to the Human Resources Office, or email to "eesearch@cityu.edu.hk". **Applications and nominations received before 30 November 2015 will receive full consideration.** The University's privacy policy is available on the homepage.

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Worldwide recognition ranking 5th among top 50 universities under age 50 (QS survey 2014); 1st in Engineering/Technology/Computer Sciences in Hong Kong (Shanghai Jiao Tong University survey 2014); and 2nd Business School in Asia-Pacific region (UT Dallas survey 2014).

Washington University in St. Louis
School of Engineering & Applied Science

Preston M. Green Department of Electrical and Systems Engineering
Tenured/Tenure-Track Faculty

The Preston M. Green Department of Electrical & Systems Engineering at Washington University in St. Louis invites applications for faculty positions at all levels, for fall 2016. The Electrical & Systems Engineering department moved to a new building, Preston M. Green Hall, with state-of-the-art facilities. Candidates should be exceptionally strong, possess novel and creative visions of research, and commit gladly to teaching at both the undergraduate and graduate levels. They should have an earned doctorate in Electrical Engineering, Computer Engineering, Computer Science, Applied Physics, Systems Engineering, Mathematics, Statistics, Operations Research or related fields.

Technical areas of interest include, but are not limited to, signal processing, machine learning, imaging, information theory, network science, applied physics, control systems, operations research, optimization, applied mathematics, and applied statistics. Applications include biomedicine, energy, the environment, robotics, financial engineering, and modeling of physical and complex systems. Successful candidates are expected to conduct high-quality research and teaching, publish in peer-reviewed journals, and participate in department and university service.

Applications will be accepted immediately, and interviews will begin after January 1, 2016. Applications received by **December 1, 2015**, will receive full consideration. The details of the application process and necessary documents are found at **http://ese.wustl.edu/aboutthedepartment/Pages/faculty-openings.aspx**.

Washington University in St. Louis is a medium-size private university, which is 14th in U.S. News & World Report's national university ranking.

Washington University in St. Louis is an Equal Opportunity and Affirmative Action employer, and invites applications from all qualified candidates. Employment eligibility verification required upon employment.

COLLEGE OF ENGINEERING
ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

The Electrical and Computer Engineering (ECE) Division of the Electrical Engineering and Computer Science Department at the University of Michigan, Ann Arbor invites applications for junior or senior faculty positions, especially from women and underrepresented minorities. Successful candidates will have a relevant doctorate or equivalent experience and an outstanding record of achievement and impactful research in academics, industry and/or at national laboratories. They will have a strong record or commitment to teaching at undergraduate and graduate levels, to providing service to the university and profession and to broadening the intellectual diversity of the ECE Division. The division invites candidates across all research areas relevant to ECE to apply.

The highly ranked ECE Division (**www.ece.umich.edu**) prides itself on the mentoring of junior faculty toward successful careers. Ann Arbor is often rated as a family friendly best-place-to-live.

Please see application instructions at **www.eecs.umich.edu/eecs/jobs**

Applications will be considered as they are received. However, for full consideration applications must be received by **December 7, 2015.**

The University of Michigan is an Affirmative Action, Equal Opportunity Employer with an Active Dual-Career Assistance Program. The College of Engineering is especially interested in candidates who contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community.

IEEE SPECTRUM Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page

Joint Institute of Engineering

Faculty Positions available in Electrical and Computer Engineering

Sun Yat-sen University and **Carnegie Mellon University** have established the **SYSU-CMU Joint Institute of Engineering (JIE)** as a conduit for innovative engineering education and research. Our mission is to nurture a passionate and collaborative global community and network of students, faculty and professionals advancing the field of engineering through education and research.

The JIE enrolled its first cohort of dual-degree M.S. and Ph.D. students in Electrical and Computer Engineering in fall 2014. All current JIE faculty members have been recruited worldwide and we continue to seek **full-time tenure-track faculty** in all areas of electrical and computer engineering. Candidates should have a doctoral degree in electrical and computer engineering, computer science or related areas, with a demonstrated record of or potential for research, teaching and leadership. The position includes an initial year at Carnegie Mellon University in Pittsburgh to establish educational and research collaborations before relocating to Guangzhou, China.

This is a worldwide search open to qualified candidates of all nationalities. We offer an internationally competitive compensation package.

Please visit jie.cmu.edu for details and to apply online.

SHUNDE INTERNATIONAL

Joint Research Institute

Research positions available in Electrical and Computer Engineering

SYSU-CMU Shunde International Joint Research Institute (JRI) is located in Shunde, China. Supported by the provincial government and industry, JRI aims to form high-level teams of innovation, research and development, transfer research outcomes into products, develop advanced technology, promote industrial development and facilitate China's transition from labor-intensive industries to technology-intensive and creative industries.

JRI is seeking **full-time research faculty and research staff** who have an interest in the industrialization of science research, targeting electrical and computer engineering or related areas.

Candidates with industrial experiences are preferred. Application review will continue until the position is filled.

Applicants should include a full CV, three to five professional references, a statement of research and teaching interests and copies of up to five research papers.

Email applications or questions to sdjri@mail.sysu.edu.cn.

SUN YAT-SEN UNIVERSITY Carnegie Mellon University

BAYLOR UNIVERSITY

Faculty Position

The Electrical and Computer Engineering Department of Baylor University seeks faculty applicants for a tenured/tenure-track Faculty Position at any level. Any area of expertise will be considered but applicants in computer engineering will be given special consideration. Applicants for assistant professor must demonstrate potential for sustained, funded scholarship and excellent teaching; applicants for associate or full professor must present evidence of achievement in research and teaching commensurate with the desired rank. The ECE department offers B.S., M.S., M.E. and Ph.D. degrees and is rapidly expanding its faculty size. Facilities include the Baylor Research and Innovation Collaborative (BRIC), a newly-established research park minutes from the main campus.

Chartered in 1845 by the Republic of Texas, Baylor University is the oldest university in Texas. Baylor has an enrollment of over 15,000 students and is a member of the Big XII Conference. Baylor's mission is to educate men and women for worldwide leadership and service by integrating academic excellence and Christian commitment within a caring community. The department seeks to hire faculty with an active Christian faith; applicants are encouraged to read about Baylor's vision for the integration of faith and learning at **www.baylor.edu/profuturis/**.

Applications will be considered on a rolling basis until the **January 1, 2016** deadline. Applications must include:

1) a letter of interest that identifies the applicant's anticipated rank,

2) a complete CV,

3) a concise statement of teaching and research interests,

4) the names and contact information for at least four professional references.

Additional information is available at **www.ecs.baylor.edu**. Send materials via email to Dr. Keith Schubert at keith_schubert@baylor.edu. Please combine all submitted material into a single pdf file.

Baylor University is affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Employment Opportunity employer, Baylor encourages candidates of the Christian faith who are minorities, women, veterans, and persons with disabilities to apply.

KANSAS STATE UNIVERSITY

Department of Electrical and Computer Engineering
Kansas State University
www.ece.ksu.edu

The Department of Electrical and Computer Engineering (ECE) at Kansas State University seeks outstanding individuals for multiple tenure-track faculty positions at all ranks. Applications are invited for all areas of computer engineering and electrical engineering, but the department is particularly interested in the smart grid and microelectronics areas. Outstanding candidates at higher ranks will be considered for several open endowed positions.

The successful candidate will be expected to develop an internationally recognized research program, attract external funding, participate in collaborative and interdisciplinary research, engage in scholarly publication, and foster a strong commitment to graduate and undergraduate teaching. Applicants are expected to have an earned doctorate, ABD, or equivalent in electrical engineering, computer engineering, or computer science at the time of appointment. Other qualifications include: the ability to think creatively, exceptional interpersonal skills, excellent written and oral communication skills, and a history of academic proficiency.

Kansas State University, with its enrollment of approximately 25,000 students, is designated a Carnegie Doctoral/Research-Extensive Institution and has declared its goal to be a top-50 public research university by 2025. The K-State College of Engineering is the largest and most comprehensive engineering college in Kansas, with an enrollment of over 3500 undergraduate and 550 graduate students. The college is undergoing rapid expansion and will be hiring 35 additional faculty over the next five years. ECE, one of eight departments within the K-State College of Engineering, comprises over 400 undergraduate students, 80 graduate students, and 20 faculty members. The department offers a hands-on, learning-centered environment for a community of outstanding students pursuing B.S., M.S., and Ph.D. degrees, and it has garnered significant increases in competitive research funding in recent years. The vibrant research environment is fueled by multidisciplinary, collaborative projects supported by federal agencies, national labs and industrial partners.

Applicants should submit the following, in PDF form, to search@ece.ksu.edu: (1) a cover letter, (2) a curriculum vitae, (3) a statement of research vision, (4) a statement of teaching interests and philosophy, and (5) contact-information for five references.

Review of applications will begin **December 1, 2015**, and will continue until the position are filled. A background check is a prerequisite to an employment offer. K-State is an equal-opportunity employer, and it actively seeks diversity among its employees.

UTSA

Open Faculty Positions in Electrical and Computer Engineering

The Department of Electrical and Computer Engineering at **the University of Texas, San Antonio (UTSA)** invites applications for multiple faculty positions starting Fall 2016 at the Assistant, Associate, or Full Professor ranks in: (1) VLSI Design and FPGA Systems, (2) Microelectronic, Mixed Signals and Advanced Materials, (3) Smart Grid, Power and Energy Systems, and (4) Computational Biology, Neuroscience, and Medical-Health Informatics. Outstanding candidates from all research areas will be considered, but preference will be given to candidates with primary research interest in VLSI design, FPGA systems, mixed signal integrated circuits, solid state devices and materials, power and energy systems, neuroscience, or big data applications. Please read the entire advertisement on the Department website at **http://ece.utsa.edu/about/faculty-openings.html**. The search committee will begin review of applications immediately and will continue until the positions are filled.

The UTSA is an Affirmative Action/Equal Employment Opportunity Employer, committed to diversity in its faculty and its educational programs. Women, minorities, veterans, and individuals with disabilities are encouraged to apply.

Faculty Positions in Robotics and Mechatronics

NAZARBAYEV UNIVERSITY

Nazarbayev University is seeking highly qualified full-time faculty members at the Assistant, Associate and Full Professor levels to join its rapidly growing program in Robotics and Mechatronics in the School of Science and Technology. Successful candidates must have a Ph.D. degree from a reputed research university, a demonstrated ability for research, excellent English-language communication skills and a commitment to graduate and undergraduate teaching and program development.

Launched in 2010 as the premier national university of Kazakhstan, NU's mandate is to promote the emergence of Astana as the research and educational center of Eurasia. The strategic development of this English-language university is based on the Western model via partnerships with top ranking world universities. The university is committed to be a world-class research university and has made significant investments in research infrastructure, equipment and personnel.

Applications are particularly encouraged from candidates with expertise and research interests in the areas of medical robotics, unmanned aerial vehicles, sensor fusion, and mechanical systems design and control. Exceptional candidates with research interests in the broader field of Robotics and Mechatronics are also encouraged to apply.

Benefits include an internationally competitive salary, international health care coverage, free housing (based on family size and rank), child educational allowance, and home-leave travel twice per year.

Applicants should send a detailed CV, teaching and research statements, and list of publications to sst@nu.edu.kz. Review of applications will begin immediately but full consideration will be given to applications submitted no later than September 1st, 2015. Successful appointments are expected to begin on January 4th, 2016. For more information please visit http://sst.nu.edu.kz.

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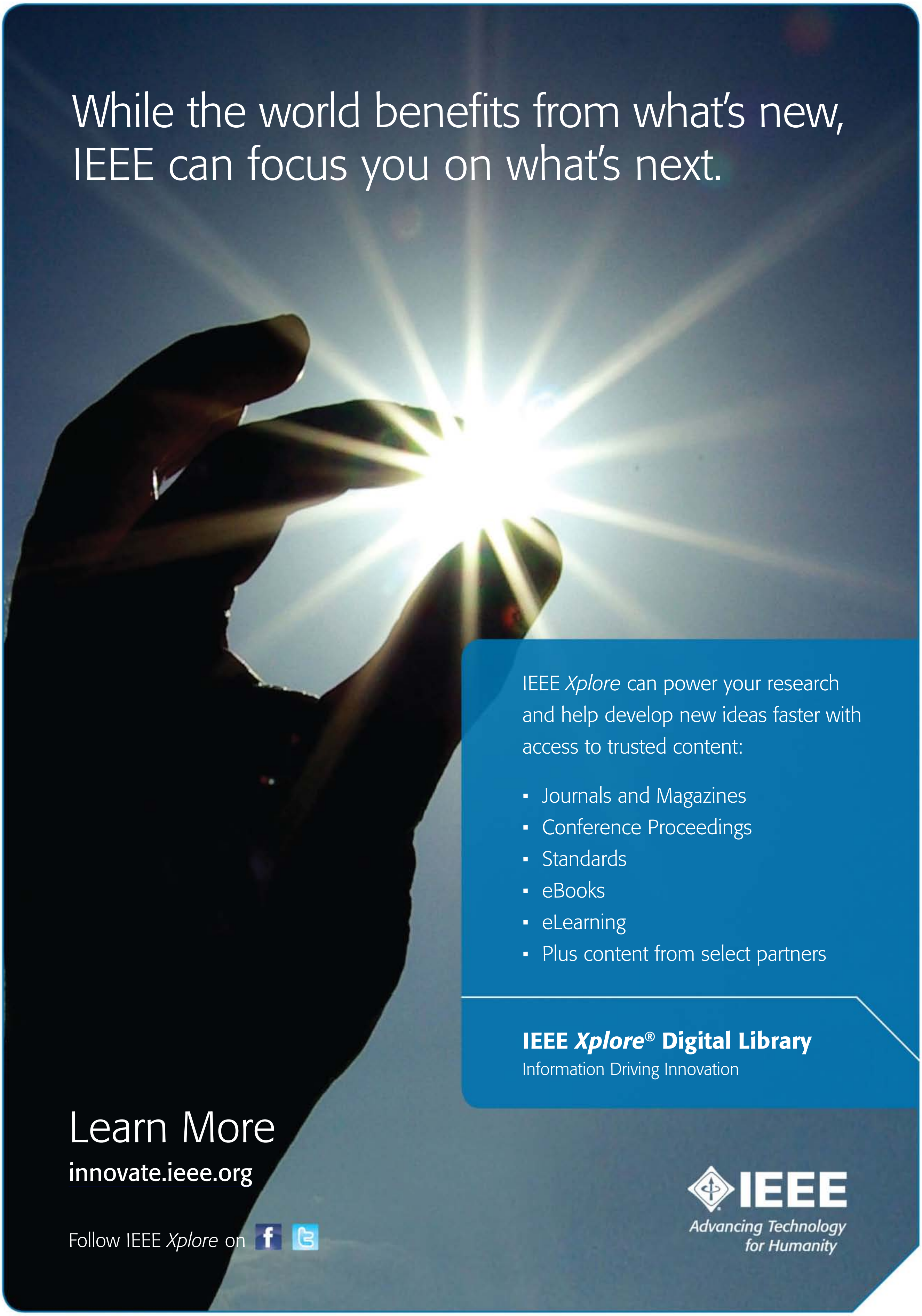
WHEN ENGINEERS HAD THE STARS IN THEIR SIGHTS

This 1964 ad attests to the enduring lure of the final frontier

At the height of the space race in the 1960s, Hughes Aircraft Co. was one of many companies that recruited engineers by boasting of its involvement with space projects—even when that involvement was peripheral or the company was looking to fill unrelated positions. But Hughes was the real deal: This ad, from *IEEE Spectrum*'s January 1964 issue, features Hughes's Syncom, the world's first geosynchronous communications satellite. Even after the space race wound down and the industry endured downturns and consolidation, Hughes continued to put hardware into orbit. Now part of Boeing, the descendant of Hughes's aerospace divisions still builds satellites for a variety of commercial and government customers. Going forward, though, it will likely face growing competition from the likes of OneWeb, SpaceX, and O3b Networks, which all aim to send aloft entire constellations of communications satellites. As these startups reinvigorate the industry, landing a job in aerospace may once again be perceived as "cool."

ATHAN BREWER, IEEE History Center

PHOTOGRAPH BY Randi Klett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