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On the cover and above **Illustration for *IEEE Spectrum* by Tavis Coburn**

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Right around the corner from the illuminated marquee of the Ed Sullivan Theater, a behemoth rotary converter from the heroic age of power engineering stirs to life in the New York City subway's Substation 13. Watch the 45-metric-ton relic spin into near-deafening, hypnotic action: https://spectrum.ieee.org/rotaryconverter0418

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- **FUTURE OF FARMING** This month we feature some of the latest in agricultural tech, including a "plant tattoo" that can estimate how well crops can survive a drought, and the Internet of Agricultural Things, which is expected to make farming more efficient.

- **LIGHTING UP HAWAII** An IEEE Milestone honors Honolulu's first installation of electric lights, in 1886 at Iolani Palace.

- **SOUND EFFECTS PIONEER** We interview IEEE Member James Agnello, who received a Grammy Lifetime Achievement award for his impact on the recording industry.

FROM LEFT: NASA; GRACE SCHNEIDER; CELIA GORMAN

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LAWRENCE ULRICH

POWER TO THE PEOPLE

HERE'S ONE OF THE LITTLE IRONIES of our times. Just as some pundits have begun predicting the coming twilight of cars driven by people, the cars themselves have become so supremely capable–and so much fun to drive–that to truly feel what they can do you have to drive them on a test track.

"Without the track, you can't test these cars anymore," says our auto tech contributor, Lawrence Ulrich. "Even a $70,000 Audi Coupe has so much brake, grip, and power, it can't even approach its limits on the street." Ulrich is especially impressed with the Honda Civic Type R, the world's fastest front-wheel-drive car, which goes for just US $30,000.

"Take most of the Ferraris and Porsches from the early '80s and this Honda would kick the s--t out of them on the race track," Ulrich declares. "Absolute supercar performance." Today's auto tech impresses not just with its energy efficiency and its increasing autonomy but also with old-fashioned brawn.

Ulrich drives about 100 new cars a year, many of them on a track. Here you see him with a McLaren 720S, which, at $288,000, is the costliest entry in our annual Top 10 Tech Cars package.

So, if you can tear up the track with a Honda, why shell out the cost of a small airplane for a McLaren? People crave the design touches, the last 10 percent increment in acceleration, the rumble of the engine, whatever. "It's bragging rights," Ulrich says. "Even if these owners are never going to experience it on the track, they can trot out the statistics at a cocktail party."

Ulrich does experience it. "Being a speed junkie, the track time is the best part of my job," he says. ■

CONTRIBUTORS_

Lee Gomes

Gomes, a freelancer who wrote “Quantum Computing: Both Here and Not Here” [p. 42], spent a dozen years covering technology for *The Wall Street Journal*. He first learned about quantum mechanics from *The Tao of Physics*, but he makes no apologies for that informal–and distinctly metaphysical–introduction. “Many physicists deride the book as pure woo-woo,” he says. “But some respectable quantum theorists seem just as far out there with their own ideas.”

Jeff Hecht

Hecht has been writing about lasers since before U.S. President Ronald Reagan announced the “Star Wars” antiballistic missile program in 1983. “Orbital battle stations with monster chemical lasers were fantastic in both senses of the word,” Hecht says. But the fiber-laser weapons he describes in this issue [p. 24] are practical and proven. His book *Lasers, Deathrays, and the Long Strange Quest for the Ultimate Weapon* (Prometheus Books) is due out in early 2019.

Stacey Higginbotham

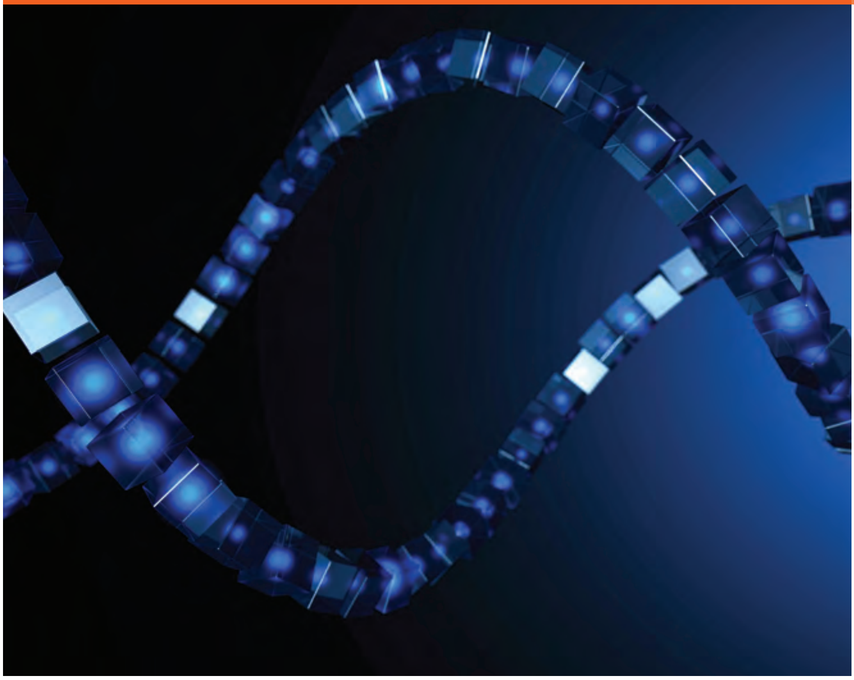
Higginbotham enjoys covering the Internet of Things because the topic encompasses semiconductors, wireless networks, and computing hardware. In addition to writing *IEEE Spectrum*’s Internet of Everything column [p. 22], she publishes a newsletter called *Stacey Knows Things* and hosts The Internet of Things Podcast. Higginbotham figures she has at least 60 IoT gadgets in her Austin, Texas, home. “Frankly, I hate keeping it all up and running,” she says.

Vaclav Smil

Smil, a Distinguished Professor Emeritus at the University of Manitoba, wrote *Energy and Civilization: A History* (MIT Press, 2017) and 39 other books. Smil calls himself a “lifelong interdisciplinarian,” with specialties that include energy, manufacturing, and demographics. That background gives him plenty of fodder for *Spectrum*’s Numbers Don’t Lie column, a data-centric look at technological trends. This month Smil takes on transatlantic travel [p. 23].

Tracy Staedter

Staedter fell in love with science journalism 29 years ago while working as a secretary for *Astronomy* magazine. For this issue, she writes about a massive sensor network that’s monitoring a huge new canal in China [p. 10]. “I was shocked by how much water the project is diverting,” she says. Equally surprising was the massive scale of the sensor network: “That’s a huge undertaking–in and of itself, it’s incredibly impressive.”



Get Paid for Your Genetic Data

A startup bets on the blockchain to get people to sequence and share their genomes

As the cost of DNA sequencing continues to drop, academics and biotech companies have been waiting for more individuals to sequence and share their full genomes. But so far, that isn't happening. ¶ Personal genomics companies, such as 23andMe and Ancestry.com, perform consumer genotyping, a relatively inexpensive process that identifies single DNA letters at regular intervals across the genome. While such genotyping has become popular, academics, medical researchers, and pharmaceutical companies want something different. They want whole genome sequences–every single one of the roughly 6.4 billion letters in the human genome–to do research, develop drugs, and more. But they're not getting them: Consumers have been loath to pay up to US $1,000 for full genome sequencing, and they are even more wary of sharing that detailed, private data. ¶ Nebula Genomics, a new startup cofounded by Harvard biologist and sequencing pioneer George Church, says it can solve both problems using the blockchain, the decentralized technology that enables cryptocurrencies like Bitcoin. In a 28-page white paper published quietly in February, the company's founders describe their aims: to use the blockchain to reduce the costs of personal genome sequencing, to cut out the middlemen, and to make it easy for individuals to share full genome sequences. ¶ "Who knows what will be possible to do with your genome a decade or two from now? People are concerned about giving up ownership to someone else," says Kamal Obbad, an ex-Googler and Harvard graduate who will lead Nebula as CEO. "We're working to address those pain points." ¶ Users who opt to have their genomes sequenced and stored with Nebula (the actual DNA sequencing would be done by another of Church's companies, Veritas Genetics) would continue to own and control access to their personal DNA sequences. Sounds logical, but that has not been the norm in the consumer genomics field: Many leading genotyping companies require users to relinquish ownership of their genetic data and then in turn sell it to others. Nebula will do none of that, says Obbad: Consumers will choose where to store their data and who gets access to it.

The Nebula network, built on the Blockstack platform and an Ethereum-derived blockchain, will allow consumers to remain anonymous, although data purchasers, such as pharmaceutical companies, will be required to be fully transparent. All transactions between consumers and purchasers will be private, stored in the blockchain, and powered by a cryptocurrency called Nebula tokens.

Here's a rough idea of how it will work: Nebula will ask consumers to participate in detailed health surveys; then, companies interested in particular traits or diseases will pay consumers with those characteristics Nebula tokens to access their genetic data. Consumers can use those tokens to pay for their own genetic sequencing. Thus companies will subsidize the cost of consumer sequencing for access to the data they want.

It is unclear how valuable the Nebula tokens will be to users after their sequencing is complete, but Obbad suggests people might eventually use tokens to pay for third-party apps that interpret genetic data, such as a cosmetics line matched to one's genetic profile.

To make all this happen, Nebula is banking on the continued decrease of sequencing costs. The first human genome, sequenced in 2001, racked up an estimated $2.7 billion. Today, the sequencing giant Illumina is working on a platform expected to enable a $100 genome.

Nebula has received $600,000 in funding from an angel investor, and it expects to make another funding announcement soon, says Obbad. The company is hoping to have a first version of the Nebula network ready for users in six months.
—MEGAN SCUDELLARI

A version of this article appears in our Human OS blog.

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ISTOCKPHOTO

NEWS

2.3 MILLION: LINES OF CODE REQUIRED TO OPERATE THE INTERNATIONAL SPACE STATION

NASA

ROBONAUT RETURNS FOR REPAIRS

A mysterious hardware problem has kept NASA's ISS robot out of action

In February of 2011, NASA launched Robonaut 2 to the International Space Station (ISS). It was a huge achievement for the robotics team at NASA's Johnson Space Center (JSC), in Texas. There had been other robots in space, but Robonaut was the first advanced humanoid ever to go on a long-term mission to orbit. On board the space station, the robot was intended to work alongside astronauts, helping with maintenance tasks and scientific experiments.

For a while, things went well. Robonaut was powered up for the first time that August, and by 2012 astronauts were using it in research tasks for several hours at a time. Then, two years later, NASA decided to perform a complex and risky upgrade. At the time, Robonaut was just a torso with a pair of arms and a head, and NASA wanted to add legs to help it move around the space station.

But the upgrade didn't go according to plan, and instead created a persistent problem that astronauts have been unable to fix. For the »

SPACE AIDE: Robonaut 2 poses on the International Space Station in 2014.

last several years, Robonaut has been almost entirely disabled. Publicly available ISS status reports show that the robot last completed a full research task in December of 2013.

Now, Robonaut is coming home. This month, a SpaceX resupply mission to the ISS is expected to bring the robot back to Earth to be fixed.

The decision to give Robonaut mobility had always been part of NASA's long-term plan for the robot. "If we were able to move around, we could do logistics management, we could possibly clean filters, or do repairs," Julia Badger, Robonaut project manager at JSC, told *IEEE Spectrum*.

But adding legs was much more involved than simply shipping them up to the space station and bolting them onto Robonaut's torso. The procedure required upgrading a significant amount of Robonaut's core hardware, including new computers and new wiring to interface the legs to the robot's main processor, along with a complex mechanical assembly process.

NASA expected the upgrade would take astronauts 20 hours to complete. It ended up taking about 40. And almost immediately, the JSC team realized something was wrong. On 29 August 2014, they partially powered up the robot, but the ground crew wasn't able to receive any telemetry data. On 17 December—the first time they applied motor power to Robonaut after the upgrade—its legs wouldn't move.

In the months that followed, astronauts and ground teams recorded a series of erratic robot behaviors, including sensor failures, communication errors, and repeated processor lockups. Sometimes they'd be able to power up Robonaut and use it for a while, but sometimes it would just fail right away. "It was very confusing," Badger said.

David Wettergreen, a roboticist at Carnegie Mellon University, in Pittsburgh, who specializes in autonomous robots for planetary exploration, explained that the complexity of robotics systems makes error detection and prevention a massive task, especially in hardware that you're not able to access directly. "Robonaut must be both robust and safe," he said, "so the systems engineering required is at the cutting edge of technology."

It may seem surprising that NASA's robotics experts weren't able to diagnose and fix the problem more quickly, since hardware is painstakingly tested before being sent into space. But the ISS Robonaut that the astronauts were working on is slightly different from the version used as a reference model back at JSC.

"It took us a really long time to figure it out, but what ended up being the case was that the [ISS] robot was missing its ground path from its computer chassis to the ground," Badger said. "The current was finding another path through, and it was slowly degrading the robot."

And that's why Robonaut is returning home. Depending on how much damage the JSC team finds, the plan is to either repair it and send it back up to the station, or swap it for the unit at the lab and ship that one up instead—possibly with the legs preattached this time.

"I think [Robonaut] has given us a lot of knowledge on what the requirements for humanoid robots in space will be in the future," Badger said. "We're bringing it home, repairing it, and in the near future, we're hoping to fly it up there again to proceed with our original goals of advancing new technology."

—EVAN ACKERMAN & ERICO GUIZZO

An extended version of this article appears in our Automaton blog.

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NASA (2)

REMOTE CONTROL: NASA astronaut Karen Nyberg [left] tests Robonaut's ability to receive signals from Earth. The robot's legs [right] were supposed to help it move in zero gravity.

THE NEXT-GEN DISPLAY: MICROLEDs

Bright and efficient, they could extend the life of your smart-watch battery

The race for the next great display technology may be nearing the finish line. British chipmaker Plessey Semiconductors claims it will be the first to market with a microLED display—a screen in which each pixel is made from bright, efficient gallium nitride–based LEDs. The company plans to begin selling a monochrome display in the first half of 2018. But Plessey is, in fact, a latecomer to a crowded field that includes big names like Apple, Facebook, and cash-caffeinated startups around the world.

They're all chasing a display that offers orders of magnitude more brightness and double or triple the efficiency of today's technologies. Though it's difficult to see microLEDs being practical for screens much bigger than smartphones, there are plenty of smaller displays that desperately need brightness and efficiency, especially for smart watches and augmented-reality systems.

"This is going to be a generational shift in technology," says Giorgio Anania, CEO of Aledia, a French startup, based in Grenoble, that's developing a nanowire-based microLED display. Investors seem to agree. In January, Aledia took in US $37 million, adding Intel Capital to its investors. Its Swedish nanowire competitor, Glo, got $15 million, with Google leading the investment in August.

But it was Apple that saw the value of this technology early on. It acquired microLED display startup LuxVue back in 2014. Judging by its patent portfolio, Apple has been growing its investment, according to Eric Virey, an analyst at Yole Développement. Facebook, through its Oculus VR division, is also among the early spenders, having acquired InfiniLED, of Cork, Ireland, in 2016.

PLESSEY

BRIGHT LIGHT: This transparent microLED display from Plessey Semiconductors appears bright even against ambient light.

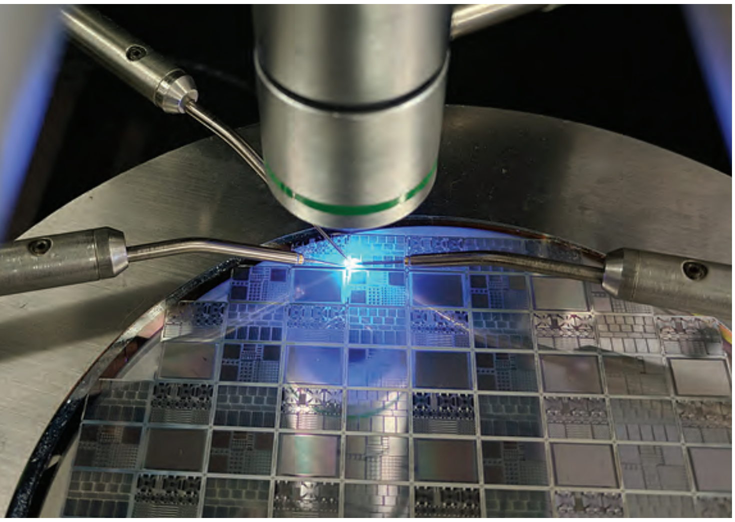
The main advantages of using gallium nitride LEDs as pixels are brightness and efficiency. OLED displays, such as what you find on Samsung smartphones, typically throw off about 1,000 candelas per square meter, or nits, Virey explains. MicroLEDs should give you 100,000 nits or even 1 million. "Clearly that's overkill for a smartphone," he says, "but it's valuable for augmented reality and head-up displays," where the image is competing with the brightness of daylight.

Indeed, text was nearly invisible against anything but a black tablecloth when I tried a 1,000-nit LCD-based head-up display kit at the New York City offices of the startup Lumiode. But replacing the LCD with the company's 100,000-nit microLED unit produced clear-blue lettering even against the blue sky.

The other draw, efficiency, is no less impressive. LCDs and OLED displays are only around 5 to 7 percent efficient. But the efficiency of gallium nitride LEDs for lighting is closer to 70 percent. Efficiency degrades as you make the LEDs tinier and tinier, Anania points out, but even a 15-percent-efficient display "would be a revolution" because it would free VR systems from power cords and hugely extend smart-watch and smartphone battery life.

Right now, the revolution seems to be coming in two general flavors. Plessey and startups such as Lumiode and JB Displays are chasing what are called monolithic displays. In these, the gallium nitride LED pixels are produced in place on a chip and then connected as a unit to an array of silicon transistors that switch them on and off. The problem here is that it doesn't make

NEWS



CLOSE UP: Lumiode employees examine a wafer containing microLEDs and thin-film transistors.

sense to build displays much bigger than a centimeter or two. It'd be a waste of silicon, which is expensive, and of gallium nitride, which is even more expensive.

So these firms are targeting the high-density displays needed for things like AR. Each has its own take on the technology, and much of that uniqueness has to do with dodging the fundamental thermal and crystalline mismatch between the silicon control matrix and the gallium nitride LEDs. This mismatch can cause stress-related dislocations in the LED crystal that can kill such a tiny device. Plessey's claim that it will be first is backed up by its considerable commercial experience growing gallium nitride LEDs on silicon substrate and making silicon backplanes, according to Myles Blake, marketing director at Plessey.

The second approach to microLED displays seems absurd on the face of it, yet it has the potential to work in smart-watch screens and larger displays. It involves dicing up wafers into individual microLEDs, making sure they're all working perfectly, and transferring each one to its proper place on the display (not necessarily in that order). A 42-mm Apple Watch has roughly 120,000 pixels, each one of three colors, so that might mean some 360,000 microLEDs. "You need a technology that can transfer 30,000 LEDs per second for a consumer application," says Virey.

Yet that's exactly the technology Apple is pursuing, and the company is thought to be nearing its goal. Apple did not respond to requests for comment. Virey estimates that Apple's and possibly other microLED displays will debut in products in 2019. Watch for signals in the supply chain about six months prior, he says. –SAMUEL K. MOORE

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SENSOR NETWORK MONITORS 1,400-KM CANAL

100,000 sensors keep watch over China's huge water diversion project

As an engineering feat, China's massive South-to-North Water Diversion Project is a stunner. Three artificial canals in various stages of completion are being designed to reroute water from the country's rainy south to more than 200 million people a day in its parched north.

The massive Internet of things (IoT) network that quietly monitors the completed middle route is impressive in its own right. More than 100,000 individual sensors stud the 1,400-kilometer waterway, which connects the Danjiangkou reservoir to Beijing and Tianjin. For the past year, those sensors have been scanning for structural damage, tracking water quality and flow rates, and watching for intruders.

"The IoT monitoring system has detected and tracked 10-plus intruders and immediately reported all evidence to the local police," says Yang Yang, the technical lead for the IoT network and a professor at the Shanghai Institute of Microsystem and Information Technology (SIMIT), part of the Chinese Academy of Sciences. He says the system has even saved several people from drowning. His team will apply lessons learned from this network to other massive infrastructure projects, such as the eastern and western routes.

Yang and his team, including Zhang Wuxiong, an associate professor at SIMIT, began to plan the central canal's IoT network back in 2012 after spending two weeks traveling the length of the canal and assessing its needs.

They saw many challenges. The waterway traversed regions prone to earthquakes. The water's flow had to be controlled so that none of it was wasted. Water quality also needed to be checked periodically for pollutants or toxins. In some places, local villagers scaled the fence along the canal in order to fish or swim, creating safety risks.

LEFT: LUMIODE; RIGHT: CONSTRUCTION AND ADMINISTRATION BUREAU/SOUTH-TO-NORTH WATER DIVERSION MIDDLE ROUTE PROJECT (5)

EYES ON YOU: This canal in Hebei province carries water to dry northern communities from China's rainy south [top]. Sensors fixed to floodgates [center] measure the flow rate and depth of water. Video cameras [bottom left] monitor the perimeter, and other sensors attached to fences [center right] alert authorities to intruders. Still more sensors monitor water levels along the entire route [bottom right].

Yang and his team grouped these challenges into three broad categories–infrastructure, water, and security–and settled on more than 130 types of Internet-connected sensors to install along the canal and within its 120 tunnels.

Technicians embedded sensors to measure stress, strain, vibration, displacement, and water seepage in the ground, in concrete banks and bridges, and on 50 dams that control the water's flow. They also attached probes that measure water quality and flow rate to the steel support columns of bridges. And they installed video cameras every 500 meters along the entire canal.

With all these sensors in place, the team puzzled over how to send data back to a control room. Some sections of the canal had access to a fiber-optic Internet connection, but others had no such access and passed through remote areas with spotty or nonexistent cellular network service.

To solve this problem, Yang and his team developed the Smart Gateway, a custom-built wireless device that would receive data continuously from local sensors and then transmit it periodically to a cloud server using whatever method was available at the moment: fiber, Ethernet, 2G, 3G, 4G, Wi-Fi, or Zigbee.

"The Smart Gateway can learn the availability of the connection to the cloud. After a successful transmission, it will follow that network next time. Otherwise, it will try another one," says Zhang.

The Smart Gateway transmits data to the nearest server, which may be any one of 47 regional branch servers. Under normal circumstances, it transmits every 5 minutes, every 30 minutes, or once a day, depending on advice from authorities at branch locations. (If an earthquake or a chemical spill were to happen, the device would continuously send data to the cloud.)

From there, the data is stored or forwarded to any of five administrative servers in provincial cities between the Danjiangkou reservoir and Beijing, until it reaches the main server center in Beijing.

Separately, Yang and his team designed a platform and interface to allow people working at the server stations to respond to any alerts via a website. This platform also helps the central management team in Beijing stay apprised of developments at remote sites and make decisions in real time. Because the network is isolated from the Internet, says Zhang, the data has a lower risk of being hacked.

"To me, this is a good example of IoT applied to critical infrastructure," says Adam Drobot, chair of the IEEE IoT Activities Board and chairman of the board of Open TechWorks, an Internet security and IT consultancy firm. "You build it so it's protected to begin with and not as an afterthought."

Yang says that one remaining challenge to monitoring the South-to-North Water Diversion Project is capturing sensor data from a monstrous, 4-km-long tunnel that runs beneath the Yellow River. From such a depth, wireless signals are very weak. Eventually, he wants to develop aquatic robots that serve as mobile relays to transmit data up to the surface.
–TRACY STAEDTER

An extended version of this article appears in our Tech Talk blog.

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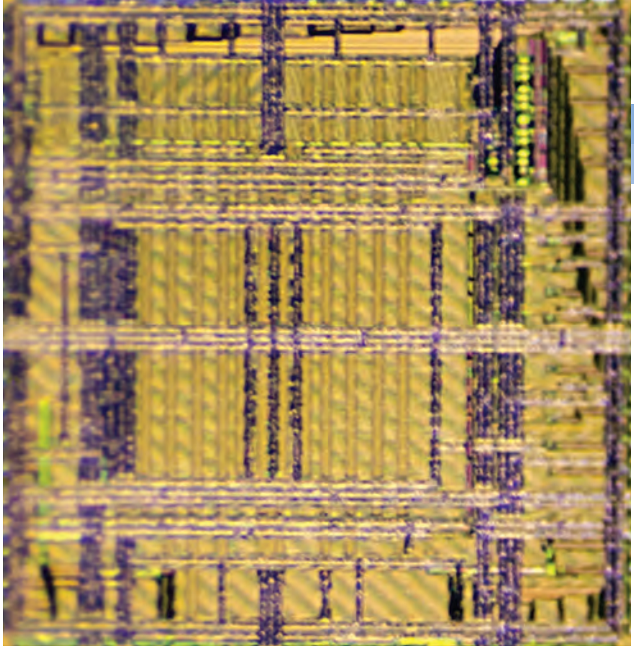

TEARING DOWN WALLS: This prototype features a new chip design called deep in-memory architecture.

SUJAN GONUGONDLA

FOR FASTER AI, MIX MEMORY AND PROCESSING

New computing architectures aim to bring machine learning to more devices

If John von Neumann were designing a computer today, there's no way he would build a thick wall between processing and memory. At least, that's what computer engineer Naresh Shanbhag of the University of Illinois at Urbana-Champaign believes. The eponymous von Neumann architecture was published in 1945. It enabled the first stored-memory, reprogrammable computers–and it's been the backbone of the industry ever since.

Now, Shanbhag thinks it's time to switch to a design that's better suited for today's data-intensive tasks. In February, at the International Solid-State Circuits Conference (ISSCC), in San Francisco, he and others made their case for a new architecture that brings computing and memory closer together. The idea is not to replace the processor altogether but to add new functions to the memory that will make devices smarter without requiring more power.

Industry must adopt such designs, these engineers believe, in order to bring artificial intelligence out of the cloud and into consumer electronics. Consider a simple problem like determining whether or not your grandma is in a photo. Artificial intelligence built with deep neural networks excels at such tasks: A computer compares her photo with the image in question and determines whether they are similar–usually by performing some simple arithmetic. So simple, in fact, that moving the image data from stored memory to the processor takes 10 to 100 times as much energy as running the computation.

That's the case for most artificial intelligence that runs on von Neumann architecture today. As a result, artificial intelligence is power hungry, neural networks are stuck in data centers, and computing is a major drain for new technologies such as self-driving cars.

"The world is gradually realizing it needs to get out of this mess," says Subhasish Mitra, an electrical engineer at Stanford University. "Compute has to come close to memory. The question is, how close?"

Mitra's group uses an unusual architecture and new materials, layering carbon-nanotube integrated circuits on top of resistive RAM–much closer than when they're built on separate chips. In a demo at ISSCC, their system could efficiently classify the language of a sentence.

Shanbhag's group and others at ISSCC stuck with existing materials, using the analog control circuits that surround arrays of memory cells in new ways. Instead of sending data out to the processor, they program these analog circuits to run simple artificial intelligence algorithms. They call this design "deep in-memory architecture."

Shanbhag doesn't want to break up memory subarrays with processing circuits, because that would reduce storage density. He thinks that doing processing at the edges of subarrays is deep enough to get an energy and speed advantage without losing storage. Shanbhag's group found a tenfold improvement in energy efficiency and a fivefold improvement in speed when using analog circuits to detect faces in images stored in static RAM.

Mitra says it's still unclear whether in-memory computing can provide a large enough benefit to topple existing architectures. He thinks its energy and speed must improve by 1,000 times to convince semiconductor companies, circuit designers, and programmers to make big changes.

Startups could lead the charge, says Meng-Fan Chang, an electrical engineer at the National Tsing Hua University, in Taiwan. A handful of startups, including Texas-based Mythic, are developing a similar technology to build dedicated AI circuits. "There is an opportunity to tap into smaller markets," says Chang.
—KATHERINE BOURZAC

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PHOTOGRAPH BY 116 Cameras/Birdling Films

NEVER FORGET

SURVIVOR... living memory... reminder of the depths of evil to which humans can sink... and now, the star of *116 Cameras*, a critically acclaimed documentary: That's Eva Schloss, the Austrian-born woman who, by her midteens, had survived being a refugee, living in hiding in Amsterdam (like her friend Anne Frank), and the horrors of the Auschwitz-Birkenau concentration camp. Here she is, pictured inside the high-tech recording setup from which the film takes its name. USC Shoah Foundation historians used the light- and camera-studded dome to create an interactive digital hologram of Schloss telling her story. She answered more than a thousand questions about her life for posterity.

RESOURCES

45,000: NUMBER OF CYCLISTS INJURED IN TRAFFIC ACCIDENTS IN 2015, ACCORDING TO THE NHTSA

HACK A SAFER BIKE LIGHT

PROJECTING LIGHT ONTO THE GROUND MAKES A BICYCLIST EASY TO SPOT

I'M CYCLING HERE: Drivers find it hard to spot bikes at night. *IEEE Spectrum* senior editor David Schneider built a flashing lighting rig to clearly mark his lane.

RESOURCES_HANDS ON

I live less than a mile from the campus of the University of North Carolina, in Chapel Hill. Not surprisingly, many of the nearly 30,000 students enrolled there get around town on bicycles, day and night. I bike, too, but seldom do I go out after dark: I fear it's just too dangerous.

This feeling about the perils of nighttime cycling are shaped by my experiences as a driver. I often find myself approaching cyclists at night and hardly noticing them. Perhaps they have no rear light. Or maybe they've got a small red one blinking away, but it somehow doesn't draw my attention the way the lights from other automobiles do.

My feelings about the risks of cycling in the dark align with what others have been saying. The U.S. National Highway Traffic Safety Administration notes that bicyclist deaths occur "most often between 6 p.m. and 9 p.m."

PHOTOGRAPH BY Grace Schneider

And in the most recently released edition of the administration's *Countermeasures That Work* report, it is recommended that cyclists make themselves more visible in the dark because "a common contributing factor for crashes involving bicyclists in the roadway is the failure of the driver to notice the bicyclist, particularly at night."

People have been making this point for some time. In an extended 1996 essay on bicycle safety, Jeffrey Hiles noted that "just a small red light, and in some places just a small red reflector, can satisfy the law without making a bicyclist all that conspicuous on the roadway." He went on to write: "It would be great if every bicyclist who rode at night looked like a rolling Christmas tree."

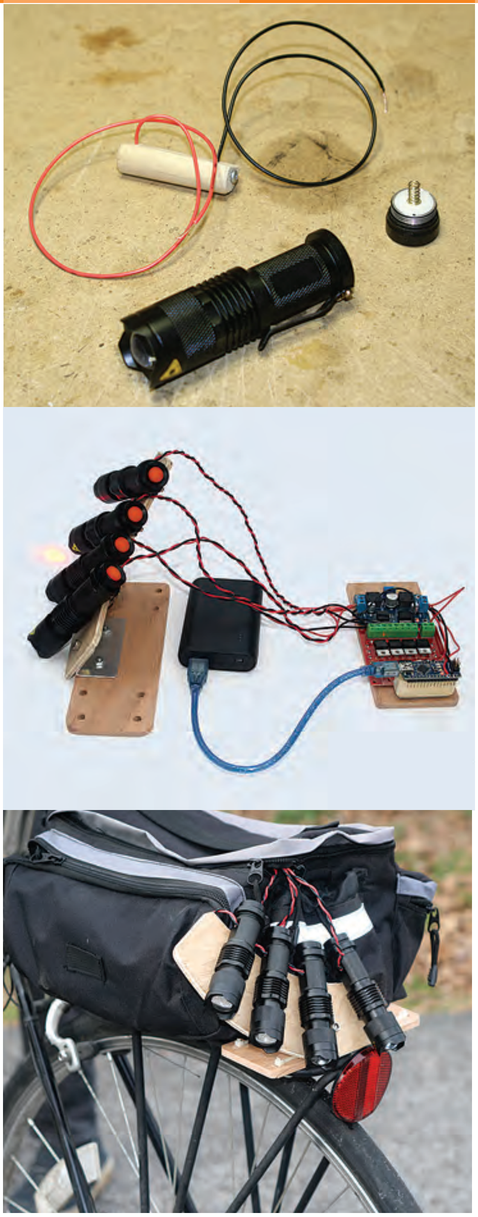
Challenge accepted.

As I contemplated the issue, I realized that it's not just a matter of putting out as many lumens as possible. A large part of the problem is that even a brightly blinking red light at the side of the road may not really register with drivers, who are looking ahead in their lane for the taillights of cars and trucks.

I surveyed various kinds of bike lights, including those that take advantage of a phenomenon called persistence of vision (POV). These units affix lights to wheel spokes, which rotate rapidly enough to give the impression that the entire wheel is alight. They look cool, and can be made to create patterns that catch the eye when viewed from the side. The problem is that they don't address the main issue—visibility from behind.

While examining a video of a commercial POV bike light, however, I noticed that it did provide some visibility from the rear—by virtue of the light that was cast on the ground. I figured I could take advantage of that effect.

Of course, the light had to be red. And I wanted to be able to project it well into the driving lane, not just illuminate the ground under the bike. A little browsing on Amazon.com turned up lots of candidates



LIGHT IT UP: Wooden "dummy" cells connect to each flashlight's battery terminals [top]; power comes from an Arduino-controlled external source [center]. The flashlights [bottom] are arranged to project light onto the ground.

DAVID SCHNEIDER (3)

to use for that purpose. I settled on a small flashlight that contains a red LED and an adjustable focusing lens. Actually, I bought four of them.

To control these lights, I use an Arduino Nano. The Nano is unable to channel enough current to power the flashlights directly, so I paired it with an inexpensive four-channel MOSFET-based switching module. The only other components of my novel bike light are a lithium-ion battery pack (the kind often used to run or recharge a phone) and a DC-to-DC converter, used to step down the voltage from the 5-volt battery pack to something more suitable for the flashlights.

The flashlights are meant to run on either a 1.5-V AA battery or a 3.7-V lithium-ion 14500 cell. The manufacturer warns that the lifetime of the LED may be shortened at 3.7 V. So I set my DC-to-DC converter to output 2 V.

To alter the flashlights so they could run on an external power source, I made four wooden plugs that resemble AA batteries in their dimensions, one for each flashlight. Screws on either end of those plugs provide a point of contact between the flashlight's battery terminals and power-carrying wires, which I route out of the flashlights through small holes.

I mounted the four flashlights to a small frame that allows me to adjust the lights so that they project back behind the bike at various distances to the left. I programmed the Arduino to flash each light in turn so that a spot of red light appears first directly behind the bike and then increasingly far into the driving lane. This, I figured, would draw a driver's attention without being overwhelming, just as a motor vehicle's directional indicators or emergency flashers do. For good measure, I use a traditional red light under the bike seat as well.

My trial runs were not without sweaty palms, given my general fear of riding at night. But I felt that much more confident knowing that I was indeed lit up like a Christmas tree. All this new bike light needs, I suppose, is a little tinsel. **—DAVID SCHNEIDER**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/bikelight0418

DIRAC: HIGH-FIDELITY AUDIO FOR YOUR SMARTPHONE

THIS SOFTWARE TRIES TO OVERCOME THE LIMITS OF SMALL SPEAKERS

ISTOCKPHOTO

In the years since the iPhone was launched, in 2007, smartphone manufacturers have competed primarily on the size and resolution of their screens, touting display capabilities sometimes to the exclusion of anything else. But as mobile display technology matures, manufacturers are looking to other areas to distinguish themselves, such as sound.

This is good news for a company like Dirac, which provides algorithmic audio-optimization tools. A few of the bigger brands around the world that already include Dirac's optimizations are Alcatel, Huawei, Infinix, Motorola, and Tecno. So when Dirac offered *IEEE Spectrum* a chance to try out its demo suite, I took it. I wanted to see if these tools really made a noticeable difference.

First, I am not someone who could be considered, under any reasonable definition of the term, an audiophile. If anyone tries to talk to me about high fidelity, I'm likely to just tune out. That's why I was so surprised when testing Dirac's tools. Not only was the audio difference arresting, but it was so superior that I was moderately bummed about going back to my own smartphone and earbuds.

The problem with acoustic drivers—the components that actually vibrate in speakers and headphones to produce sound—is that as a general rule, going smaller results in compromising sound quality, particularly for lower tones like bass notes. Dirac has created optimizations for small drivers that improve audio quality, both for built-in smartphone speakers and external speakers.

These optimizations come in two flavors. Dirac claims to be able to provide a surround sound–like experience with its Panorama Sound tuning, using just your phone's speakers. Meanwhile, its Power Sound tuning is supposed to improve clarity, especially by bringing out lower bass registers that are often lost with built-in smartphone speakers.

Both settings do improve sound quality. Without Dirac's tuning, listening to the provided clips of rain-forest and city noises on a Huawei Nexus 6p smartphone was underwhelming, to say the least. An audio clip of a lion growling and roaring was tinny and weak. In fact, without knowing that the file in question was named "Water Rain Lion Roar.wav," I would have assumed I was listening to a pig snorting during a light afternoon shower. With Dirac's Panorama Sound, the lower tones of the lion's roar came out much clearer and stronger.

Of course, clever software alone can't provide a true panoramic sound. After all, you're still limited to the smartphone's speakers. But it does widen the effect, making it seem as though the sound is originating from outside the speakers. It also makes the different tracks in a song's mix more discernible. It becomes clear how jumbled Madonna's recording of "Hey Mr. D.J." sounds without the tuning activated, once you've heard it with the tuning on. Without it, everything other than Madonna's vocals falls into the background and is nearly lost.

Unlike the Panorama Sound tuning, Dirac's Power Sound tuning emphasizes loudness without distortion, especially for bass-heavy songs. It handles songs like Daft Punk's hit "Get Lucky" better even than Panorama Sound, where the bass is still slightly washed out compared with the guitar and vocals. But with Power Sound, the bass comes through clearly without being overwhelming.

The last trick Dirac has up its sleeve is for headphones and earbuds. Dirac's filters for specific headphones and earbuds try to compensate for the particular foibles of specific models. A pair of Marshall Monitor headphones were provided, and without any of Dirac's filters activated, "Get Lucky" boomed and echoed in a way that was dissatisfying after I listened to it with the Dirac filter designed for the Marshalls. Testing other filters, such as the Apple EarPods filter, with the same headphones made the song more unpleasant to listen to than with no filter at all. The EarPods filter in particular gave "Get Lucky" an actively unpleasant amount of bass reverb in the Marshall headphones that drowned out the lead guitar, suggesting that each filter does indeed adjust the sound to correct for the specific shortcomings of different earbuds. **—MICHAEL KOZIOL**

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MILITARY MANGA
REALISTIC SCI-FI ILLUSTRATES U.S. VULNERABILITIES TO CYBERWARFARE

SELF-PREVENTING PROPHECIES: The U.S. Army Cyber Institute's graphic novels are aimed at making soldiers think about future threats.

At first glance, *Dark Hammer* looks a lot like any other science fiction comic book: On the front cover, a drone flies over a river dividing a city with damaged and burning buildings. But this short story in graphic form comes from the Army Cyber Institute at West Point, in New York. The ACI was set up to research cyber challenges, and it acts as a bridge between different defense and intelligence agencies and academic and industry circles.

"Our mission is to prevent strategic surprise for the army…to really help the army see what's coming next," explains Lt. Col. Natalie Vanetta, the ACI's deputy chief of research. *Dark Hammer* is the first of four recently released comic books set in the near future that depict some of the emerging threats identified by the ACI. The books are free and downloadable by all, but they are primarily intended for "junior soldiers and young officers to get them to think about—well, what if the next 10 years doesn't look like the last 80?" says Vanetta. The choice of format is unusual but far from unprecedented, she adds. "The army really has a large history of using graphic novels or fiction to help our workforce understand somewhat intangible concepts."

The books grew out of the ACI's collaboration with the Threatcasting Lab at Arizona State University, in Tempe. Brian David Johnson is the director of the Threatcasting Lab and Intel's former in-house futurist. He wrote the books—*Dark Hammer*, *Silent Ruin*, *Engineering a Traitor*, and *11/28/27*—with Sandy Winkelman as creative director.

"We do two-day threatcasting events where we…model possible threats 10 years in the future," Johnson says. "Threats to national security, threats to the economy, threats to civilization. And once we've established those, then we look backward and say, 'How do we disrupt and mitigate those threats?' " he says.

The ACI decided they wanted more than just the lab's traditional reports, Johnson says. "They wanted something that was much more visceral, that could be put in front of an 18-year-old cadet and also in front of a three-star general. They chose a process of mine called science fiction prototyping. You write science fiction stories based on science facts to explore possible futures. We used the threatcasting reports as the science facts, and we developed these four comic books as a way to illustrate these possible threats."

Johnson explains the difference between science fiction prototyping and just science fiction: In the latter the primary purpose is entertainment, and authors are allowed dramatic license, but in prototyping "we are held rigorously to the facts. It uses a narrative and it uses story as a way to get across the facts. We worked very closely with subject-matter experts and made sure that everything from the way the tanks looked to the insignia to even how the attacks might happen and what their effects might be [was right]."

In the series, U.S. forces don't end up scoring neat victories, and sometimes they suffer significant losses. In *Dark Hammer*, for example, U.S. forces hold an invading North Korean army to the north side of the Han River long enough to evacuate trapped civilians from Seoul. In *Silent Ruin*, U.S. tanks in Eastern Europe are devastated by a Russian hack delivered via battlefield drones.

Depicting such setbacks was a deliberate ploy to counteract complacency in U.S. forces, says Vanetta. "We have always been the victor. What happens if this does not continue in the future? What if cyber is potentially a game changer because there is a lower bar to entry for some of our adversaries to get in? If the game doesn't drastically change, okay, we're golden. But what if it does? How do we prepare ourselves for that?" —**STEPHEN CASS**

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TOP: MATT HALEY/ARMY CYBER INSTITUTE; BOTTOM: DON HUDSON AND KINSUN LO/ARMY CYBER INSTITUTE

"SWARM ELECTRIFICATION" POWERS VILLAGES

ME SOLSHARE LINKS ISOLATED PV SYSTEMS

POP-UP SOLAR: Photovoltaic systems are common in Bangladesh. ME SOLshare wants to link them to tap their unused potential.

ME SOLSHARE

Bangladesh hosts the world's largest collection of off-grid solar energy systems. Rooftop panels and batteries electrify over 4 million households and businesses there. The Dhaka-based startup ME SOLshare believes it has the technology to link these systems and foster a solar energy-sharing economy. If the company succeeds, home systems will morph into village minigrids, offering wider access to more power at lower cost.

SOLshare's European founders—Sebastian Groh, Hannes Kirchhoff, and Daniel Ciganovic—conceived their "swarm electrification" power-sharing platform during grad-school brainstorming sessions in Germany and California. The three moved to Dhaka to define, engineer, and launch their product, starting with power measurements in off-grid solar homes.

What Groh and his cofounders discovered upon arrival in 2015 was plenty of spare power going to waste. Typically, the batteries in home systems are sized to capture the power generated during the relatively dim monsoon season. As a result, during much of the year there is extra power available that isn't captured. On average, about 30 percent of each system's potential output is lost.

SOLshare's technology is designed to share this extra power. A smart power controller, called a SOLbox, is installed in each home or business and linked with cables to other local SOLboxes to form a DC distribution grid. The SOLbox enables users to set how much power they want to share with or draw from the network, and at what price.

The SOLbox handles the accounting, too, reconciling power purchases and sales—as well as SOLshare's brokerage fee—via each user's mobile money wallet. Wireless communications allow SOLshare to optimize power flows over the meshed DC grids to minimize bottlenecks and line losses.

All the equipment is engineered and assembled in Dhaka. Marketing, installation, and maintenance occur in partnership with Bangladesh's leader in solar home systems, Grameen Shakti, with which SOLshare split a US $1 million prize from the United Nations in November.

SOLshare installed seven grids, connecting a total of 150 homes between 2015 and 2017—what Groh terms the company's "experimental" phase. Now it has begun to scale up. In January, for example, SOLshare began work in a tightly packed community where it could connect up to 1,500 homes.

As the minigrids scale up, so should their value. More power on the grid, for example, means users can run comparatively power-hungry devices such as refrigerators.

The question is whether SOLshare can entice enough villagers to join. Part of that will mean squeezing the cost of the SOLbox so that it adds less than 10 percent to the total price of the solar system. "We're below $100 and transitioning right now to a next-generation SOLbox below $50. But we want to go down even further," says cofounder and chief technology officer Kirchhoff.

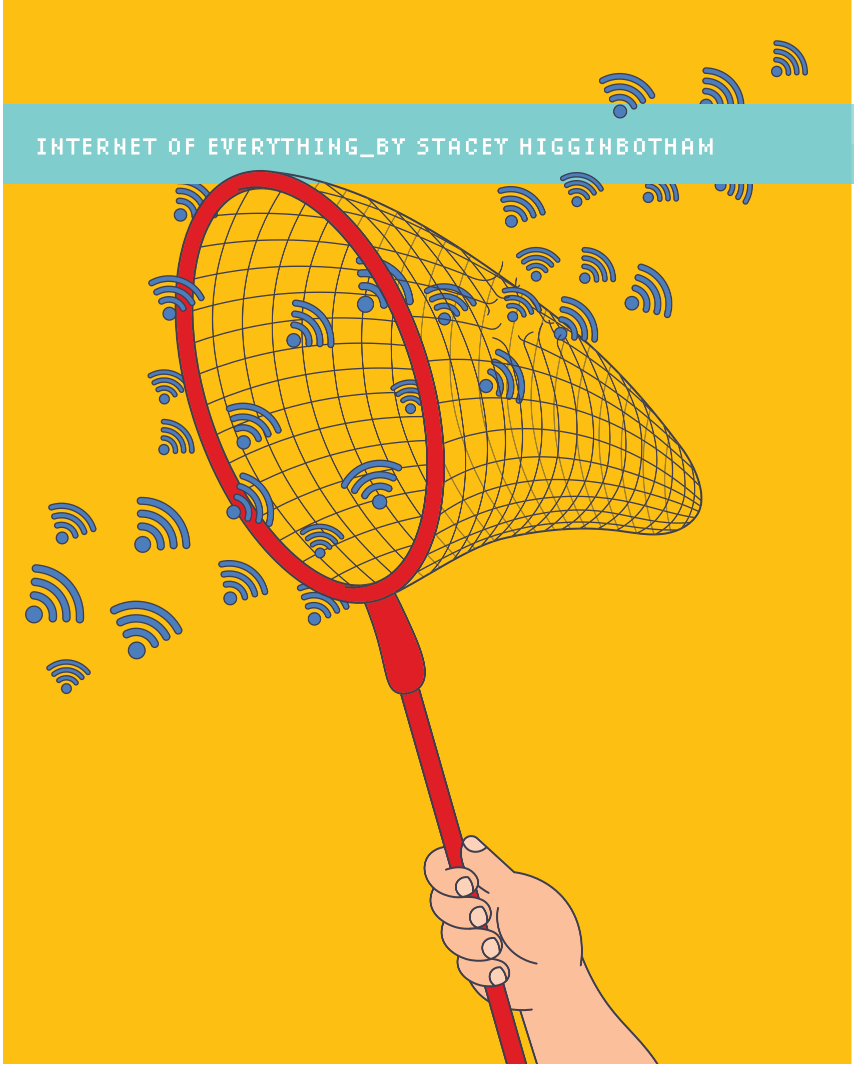
Selling SOLshare's vision also requires trust. Villagers are sensitive to the risk of being exploited by outsiders—especially foreigners. "At first, people are reluctant to give access to an asset that they have paid for, for two or four years, with a large portion of their income," says Kirchhoff.

Peter Asmus, a microgrid analyst with Navigant Research, says planning for solar home systems has not kept pace with their accelerating deployment. He says SOLshare's swarm electrification approach has merit and could find demand in densely built rural communities well beyond the Indian subcontinent.

Sticking with DC makes a lot of sense, says Asmus, since there is a growing world of DC appliances that village residents and businesses yearn to plug in. As Asmus puts it, "When people get a little electricity—enough for a light or a cellphone—pretty soon they want more." **—PETER FAIRLEY**

Founded: 2015 **HQ:** Dhaka, Bangladesh **Employees:** 30 **Founders:** Sebastian Groh, Hannes Kirchhoff, Daniel Ciganovic **Capital raised to date:** US $500,000

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/solshare0418



WI-FI vs. INTERNET OF THINGS

WI-FI IS THE INVISIBLE WORKHORSE of modern life. But Wi-Fi is struggling. And the next phase of the Internet–the Internet of Things–could break it.

Startups and Internet service providers are developing an application layer that divorces some functions from the base networking standard, IEEE 802.11. Many new features sprouting up within this layer–such as mesh networks (a set of routers that work together to extend wireless coverage) and provisioning tactics (which define how wireless devices connect to networks)–have been developed in response to the Internet of Things.

It reminds me of the Zigbee mesh-network specification for small, low-power digital radios, which has layers for specific classes of devices built on top of the radio. This has sowed confusion among customers about which Zigbee devices actually work with one another. I fear that Wi-Fi is heading in the same direction.

Consider a mesh Wi-Fi system. Companies including Eero, Google, and Securifi have created products that promise reliable coverage throughout every square centimeter of a home. But this works only if you buy all of your mesh routers from the same vendor.

Companies soon realized they could pop a network-based security product into mesh routers and add the ability to prioritize devices. But where does an application layer end and the core Wi-Fi standard begin?

Comcast Corp. offers a good case study. In 2017, it revamped its Wi-Fi products, layering on services such as parental controls. Comcast implemented software from a startup called Cirrent to make it easier to provision, or add, a device to your network. Cirrent's software sits on Comcast routers and also lives on a variety of consumer devices from Bose, Electrolux, and others.

When a product with Cirrent's software comes into a Comcast home, it automatically connects to the Wi-Fi network. But Cirrent's solution is implemented piecemeal by vendors. And if you don't have Cirrent's software on your router, your Electrolux washer may not connect.

Applications like Cirrent's do solve common Wi-Fi problems, but they also lock users into certain chip vendors, router makers, and service providers.

"If you want to think of it as an application layer on top of the standard, as an economic matter, it makes sense," says Fahri Diner, CEO of the startup Plume.

Plume's own software improves coverage by tweaking the capacity on routers around the home. Comcast uses it, and Plume has signed deals with companies, including Samsung, to turn their devices into mesh routers that run its software.

Diner is working with major Wi-Fi chip vendors to ensure compatibility, and he is open-sourcing some of the necessary code. But if not every vendor uses it, Plume's dynamic network optimization won't operate on an incompatible router.

The only solution to fragmentation will be at the Wi-Fi Alliance, which certifies Wi-Fi devices. Brian Bedrosian, vice president of marketing for IoT at Cypress Semiconductor Corp., says simpler provisioning and neighbor-aware networks (which let devices speak to one another without a Wi-Fi access point) must become part of the Wi-Fi certification specification.

"By comparison, it could be like the Zigbee spec, which has been a disaster," he says. Hopefully, the Wi-Fi Alliance won't let that happen. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/wifi-vs-iot0418

ILLUSTRATION BY BloodBros

APRIL 1838: CROSSING THE ATLANTIC

COMMERCIAL SAILING SHIPS had long taken three, sometimes four weeks to make the eastbound crossing of the Atlantic; the westbound route, against the wind, usually took six weeks. The first steamship made the eastward crossing only in 1833, when the Quebec-built SS *Royal William* went to England, after stopping to take on coal in Nova Scotia. It was only in April 1838–180 years ago this month–that steamships pioneered the westward route. It happened in an unexpectedly dramatic way. • Isambard Kingdom Brunel, one of the great 19th-century British engineers, built the SS *Great Western* for the Great Western Steamship Company's planned Bristol-New York run. The ship was ready on 31 March 1838, but fire damage scared most of its passengers away, delaying departure until 8 April. • Meanwhile, the British and American Steam Navigation Company tried to steal a march by chartering the SS *Sirius,* a small wooden paddle-wheel vessel built for the Irish (London-Cork) service. The *Sirius* left Cobh, Ireland, on 4 April 1838, its boilers operating under 34 kilopascals (4.9 pounds per square inch), for a peak engine power of 370 kilowatts. With 460 metric tons of coal on board, the ship could travel nearly 5,400 kilometers (2,916 nautical miles)–almost but not quite all the way to New York Harbor. • In contrast, the *Great Western* was the world's largest passenger ship, displacing 1,360 metric tons, with 128 beds in first class. The ship's boilers also worked at 34 kPa, but its engines could deliver about 560 kW, and on its first transatlantic journey it averaged 16.04 kilometers per hour. Even with its four-day head start, the *Sirius* (averaging 14.87 km/h) barely beat the larger and faster ship, arriving in New York on 22 April 1838 after 18 days, 14 hours, and 22 minutes. • Later stories dramatized the final dash by claiming that the *Sirius* ran out of coal and had to burn furniture and even its spars to reach the port. Not true, but it did have to burn several drums of resin to make port. When the *Great Western* arrived the next day, after 15 days and 12 hours, it still had 200 metric tons of coal to spare.

Steam more than halved the transatlantic travel time, and new records kept coming. By 1848, Cunard's SS *Europa* made it in eight days and 23 hours. By 1888, it took barely over six days, and in 1908, the steam-turbine-powered RMS *Lusitania* won the Blue Riband with a crossing time of four days, 20 hours, and 22 minutes. The final record holder, SS *United States,* made it in three days, 10 hours, and 40 minutes in 1952.

The next era, in which commercial piston-engine aircraft crossed in 14 or more hours, was a brief one. By 1958, America's first commercial turbojet, the Boeing 707, was making regularly scheduled flights from London to New York in less than 8 hours. Cruising speeds have not changed much: The Boeing 787 Dreamliner cruises at 913 km/h, and London-New York flights still last about 7.5 hours.

The expensive, noisy, and ill-fated supersonic Concorde could do it in 3.5 hours, but that bird will never fly again. Several companies are now developing supersonic transport planes, and Airbus has patented a hypersonic concept with a cruising speed of 4.5 times the speed of sound. Such a plane would arrive at JFK International 1 hour after leaving Heathrow. Crossing westward would take longer.

I wouldn't complain. Compared with the *Sirius*'s time in 1838, we have cut the crossing time by more than 98 percent. The time aloft is just right for reading a substantial novel. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/transatlantic0418

PHOTO-ILLUSTRATION BY Stuart Bradford

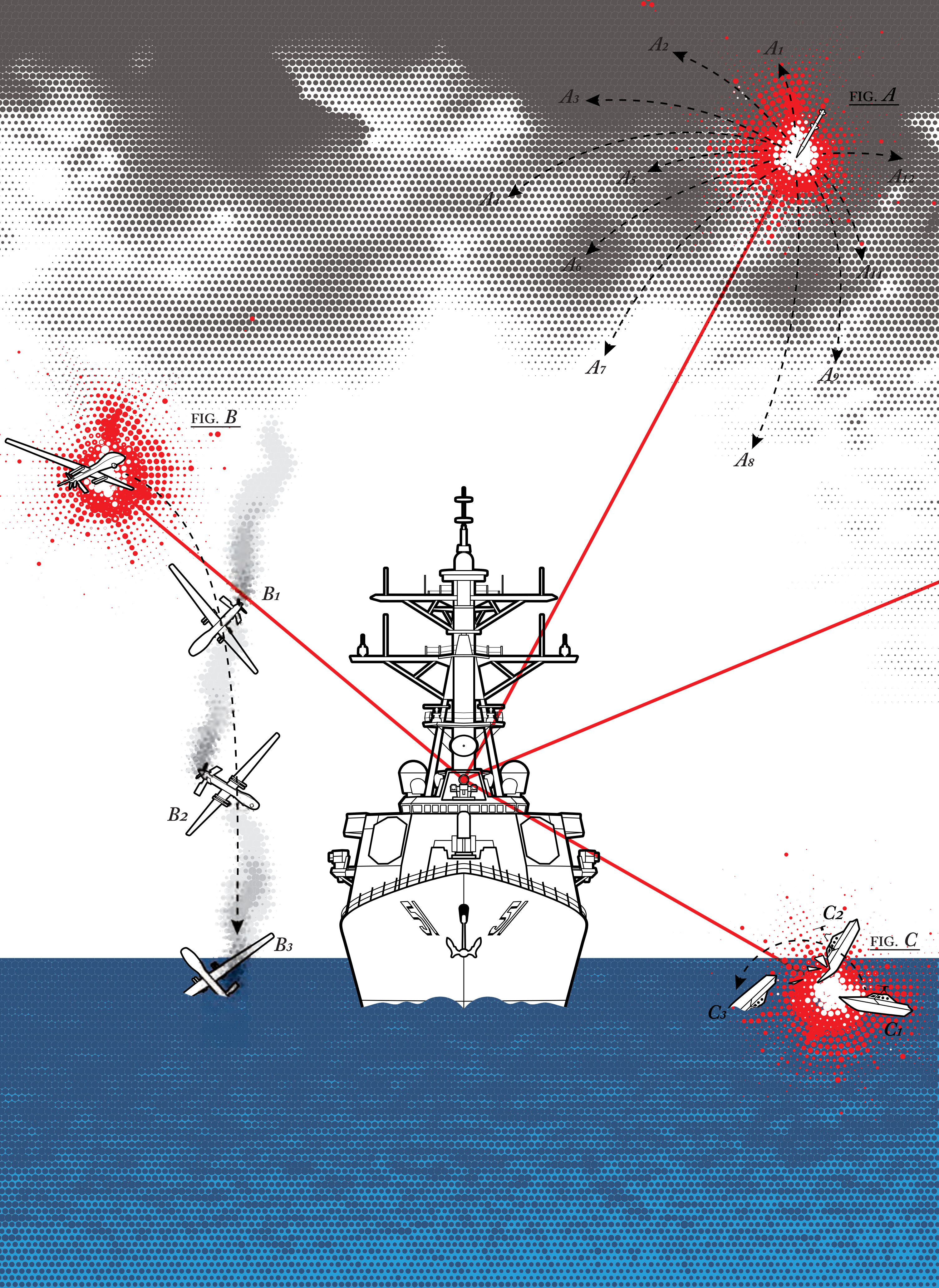


FIG. A
A1
A2
A3
A7
A8
FIG. B
B1
B2
B3
FIG. C
C1
C2
C3
51

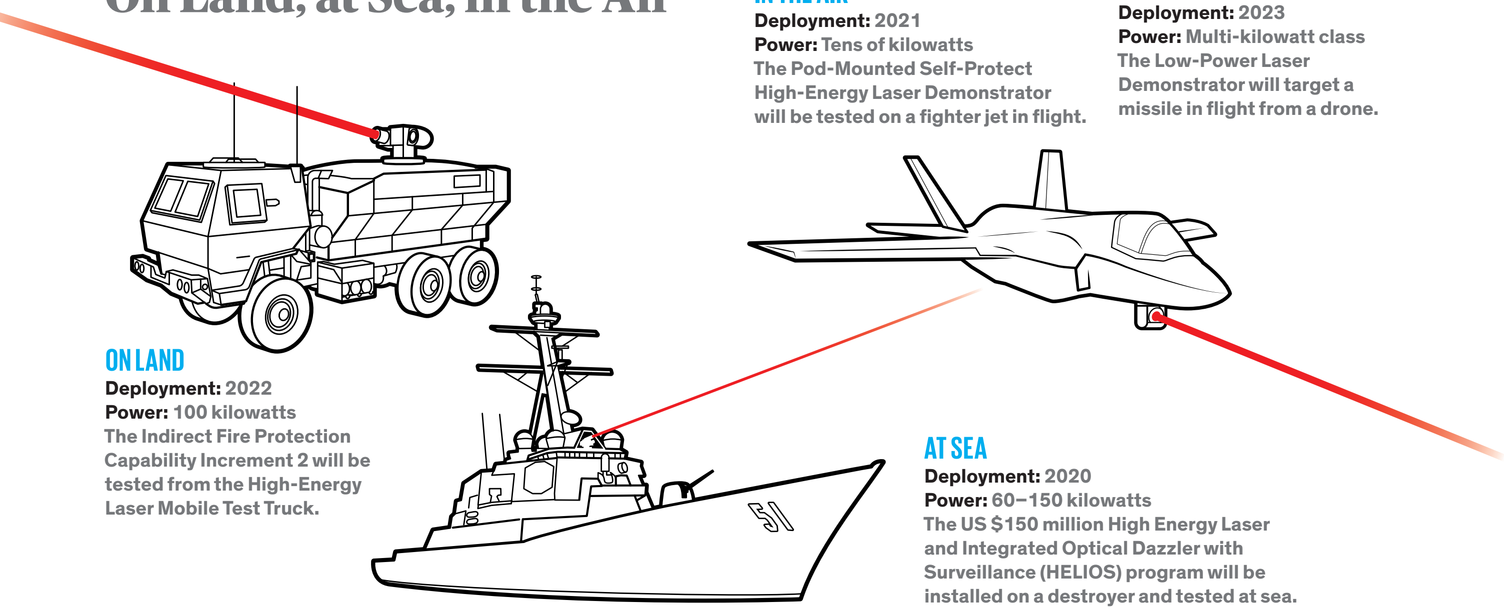
THE RAY GUNS ARE COMING

BY JEFF HECHT

Illustration By MCKIBILLO

A CLEVER CONFIGURATION OF OPTICAL FIBERS IS SET TO FINALLY MAKE LASER WEAPONS PRACTICAL

On Land, at Sea, in the Air



THE U.S. NAVY'S MOST ADVANCED LASER WEAPON LOOKS LIKE A PRICEY AMATEUR

telescope. As it emerges from a chassis high on the USS *Ponce* to look out onto the daytime sky above the Persian Gulf, its operator sits in a darkened room elsewhere on the ship holding what looks like a game controller. The screen before him is showing a small boat floating near the *Ponce*, carrying a dark object. The infrared beam hitting the object is invisible, but you can see one spot grow brighter until the object suddenly explodes, sending metal shards spiraling into the water.

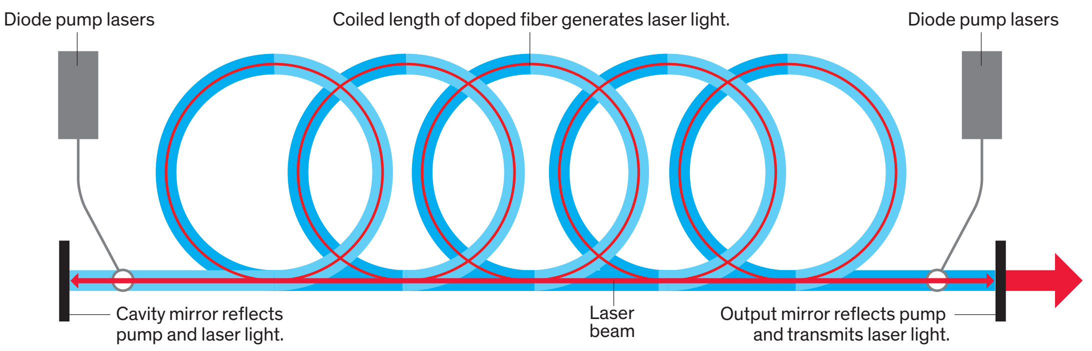
This weapon, cobbled together from a half-dozen industrial cutting and welding lasers to produce a total power of only 30 kilowatts, was hardly the megawatt monster military scientists dreamed of decades ago to shoot down ICBMs. But it's a major milestone, advocates say, toward a future in which directed-energy weapons are deployed in real military engagements. Such a future, they add, will come from changes in mission and in technology. The mission shift has been going on for years, from global defense against nuclear-armed "rogue states" to local defense against insurgents. The technology shift has been more abrupt, toward the hot new solid-state technology of optical-fiber lasers. These are the basis of a fast-growing US $2 billion industry that has reengineered the raw materials of global telecommunications to cut and weld metals, and it is now being scaled to even higher power with devastating effect.

Pentagon officials think the technology for high-energy lasers, like the one tested on the now-decommissioned *Ponce*, can serve a variety of roles on land and at sea: zapping the cheap rockets, artillery, drones, and small boats loaded with weapons that insurgents have deployed in places like Iraq and Afghanistan. Today, destroying an insurgent rocket costing around a thousand dollars can require a tech-laden Patriot interceptor costing $2 million to $3 million. By comparison, a laser shot from a fiber-laser weapon would cost only $1 in diesel fuel, officials claim.

Other military powers besides the United States are also aiming for fiber lasers at the 100-kW level needed to reliably destroy targets kilometers away. China's Poly Technologies, Israel's Rafael, and the German defense firm Rheinmetall have developed fiber lasers at least as powerful as the prototype the U.S. Navy demonstrated on the *Ponce*. The United Kingdom is spending £30 million to build a 50-kW laser called Dragonfire, and Japan is investigating fiber lasers to block attacks by short-range rockets as well as North Korean ballistic missiles. But the United States has led the way since launching a program 15 years ago to develop electrically pumped high-energy lasers, and it has benefited from the rapid growth of high-power industrial fiber lasers, led by IPG Photonics. Based in Oxford, Mass., the company was founded in Russia in 1990 but moved its headquarters to the United States in 1998. It now has facilities around the world and dominates the global market for fiber lasers.

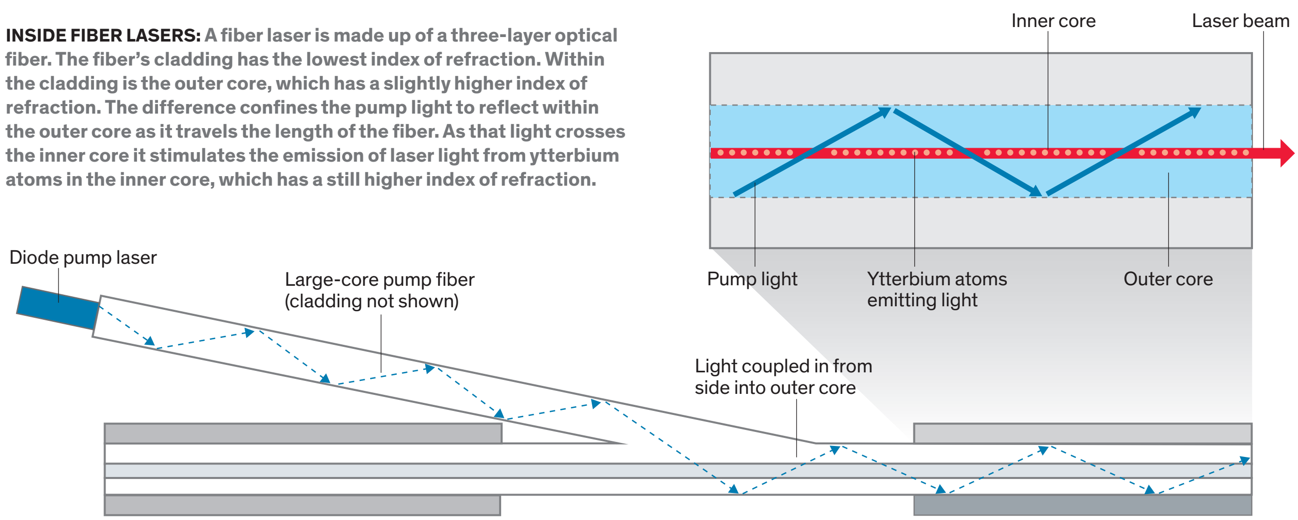
"The Defense Department has wanted a laser weapon system ever since the laser was invented," says Robert Afzal, senior fellow for laser and sensor systems at the defense contractor Lockheed Martin, in Bothell, Wash. "The key element has been to build this high-power electric laser small enough and powerful enough that we can put it on Army trucks, Air Force planes, and Navy ships, and not take everything [else] off" to make room for it. Though there are still other technologies in development, it appears that fiber lasers will be the technology that will accomplish that mission first.

ILLUSTRATION BY MCKIBILLO



FIBER-LASER GUN: Energy from diode lasers is pumped into a long string of specialized optical fiber that is doped with light-emitting ytterbium atoms. The laser light travels the fiber's long length, reflecting between mirrors built within the fiber and exiting at one end.

INSIDE FIBER LASERS: A fiber laser is made up of a three-layer optical fiber. The fiber's cladding has the lowest index of refraction. Within the cladding is the outer core, which has a slightly higher index of refraction. The difference confines the pump light to reflect within the outer core as it travels the length of the fiber. As that light crosses the inner core it stimulates the emission of laser light from ytterbium atoms in the inner core, which has a still higher index of refraction.



THE PENTAGON HAS BEEN DAZZLED by visions of laser weapons since physicist Gordon Gould walked into the then months-old Advanced Research Projects Agency in 1959 with a proposal to build a laser. Gould, one of three people credited with conceiving the laser, had gotten the idea of generating coherent light as a 37-year-old grad student at Columbia University in late 1957. Within weeks of his inspiration, he had sketched out his vision of a pair of mirrors at opposite ends of a long, thin cylinder. Chain smoking over a pile of references and a notebook at his kitchen table, he realized the laser could concentrate light into a powerful beam. Once he worked out the laser idea, Gould abandoned his Ph.D. studies and set out to patent his invention, eventually enlisting the help of TRG, the company where he started working in early 1958.

Nuclear-missile defense was among the top items on the agenda the U.S. Department of Defense handed its new research arm. So the fledgling agency was deeply intrigued by the prospect of a speed-of-light weapon. ARPA bestowed $1 million (about $8 million today) on Gould's proposal. (Unfortunately for him, though, once the Pentagon decided to classify the work, his youthful dalliance with the Communist Party blocked him from getting the security clearance he needed to work on his own project.)

Making a powerful beam required more than a pair of mirrors. It needed something to put between the mirrors that emitted light and a way to pump energy into that material. The first functioning laser was built around a solid, synthetic ruby, which contained light-emitting chromium atoms that could be energized by bright pulses of photons from a flash lamp. Other types soon followed: An electric discharge passing through a tube filled with helium and neon, it was found, could generate coherent light. So could pulses of current in gallium arsenide diodes with their edges polished as mirrors.

But the Pentagon wanted high power, and that was impossible to get from any of these sources. In ARPA's initially classified Project Seaside, researchers built solid-state lasers with rods several centimeters thick, but most of the input light energy went into heating the light-emitting solid, while too little came out in the beam. So that approach was abandoned. Similar problems eliminated early gas and semiconductor lasers from consideration.

The U.S. military was about to give up on laser weapons in the mid-1960s when researchers at the Avco-Everett Research Laboratory, near Boston, came up with a startling new approach. They burned a hydrocarbon

DIAGRAMS BY Mark Montgomery

NAVAL ENERGY WEAPON: Experimental fiber lasers seem likely to deliver the energy and efficiency wanted to strike drones, small boats, and other needed targets. A 30-kilowatt laser weapon was tested aboard the USS *Ponce*. It was made up of several fiber lasers fired through a telescope at a single target. The target, a spot on a small boat, was tracked using a system below deck.

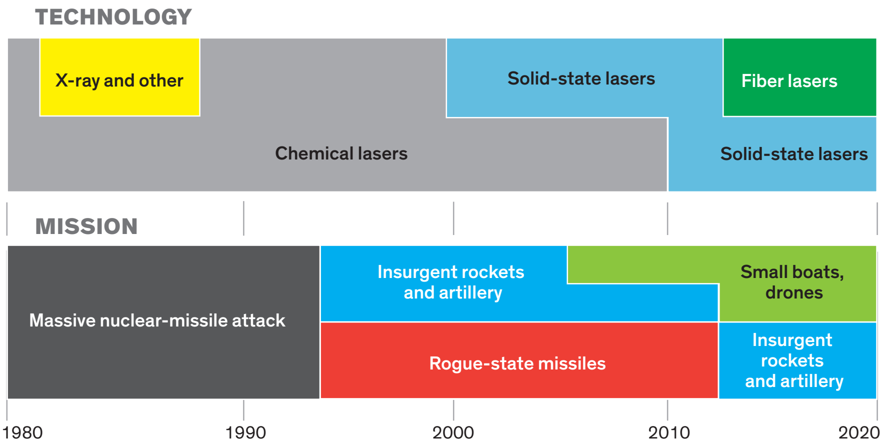
U.S. NAVY (3)

fuel and forced the hot exhaust gas through a set of rocketlike nozzles so it flowed between a pair of mirrors, generating tens of kilowatts of infrared laser light. [See “Gasdynamic Lasers,” *IEEE Spectrum*, November 1970.]

That flowing-gas technology would fuel U.S. laser weapon research throughout the Cold War. New fuels capable of delivering megawatt levels of power led to dreams of orbiting laser battle stations. U.S. president Ronald Reagan’s Strategic Defense Initiative spent billions researching space-based lasers to shoot down Soviet ICBMs. After the Cold War ended, the U.S. Air Force spent billions more to squeeze a huge missile-defense laser into a Boeing 747, to combat launches by rogue states like North Korea. In 2010, this megawatt-level behemoth actually shot down a ballistic missile in a test—a first—but it was far from practical. Then Secretary of Defense Robert Gates killed the program, declaring, “There’s nobody in uniform that I know who believes that this is a workable concept.”

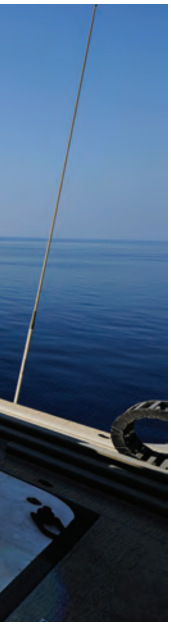
Smaller, less-powerful chemical lasers developed for the Pentagon’s new anti-insurgent mission ultimately met a similar fate. In 1996, the United States and Israel joined in a program to test a 100-kW-class chemically fueled gas laser built by TRW (now part of Northrop Grumman). The Tactical High Energy Laser shot down rockets and artillery shells in 2000 and 2001. Around the same time, the 2000 suicide attack on the USS *Cole* underlined the danger of small boats and the need to find a countermeasure for them.

But this TRW laser had two big problems: First, it was impractically large, consisting of four 18-wheeler-size trailers and a separate beam director about as large as a supersize searchlight. Second, and more important to Pentagon logistics experts, were its special chemical fuels. Special fuels are always logistics liabilities because any supply glitch can leave weapons useless. Worse, the chemicals in question were basically weapons all by themselves. They react to form hydrogen fluoride, a gas that can destroy corneas, scorch lungs, and severely damage skin—posing serious risks to the soldiers operating it.



THROUGH THE YEARS: Military laser technology has changed as its potential applications have shifted toward smaller targets.

DIAGRAM BY Mark Montgomery



MEANWHILE, ANOTHER LASER TECHNOLOGY was advancing rapidly. In the 1960s, Zhores Alferov in Russia and IEEE Medal of Honor recipient Herbert Kroemer in the United States invented structures that dramatically improved the performance of semiconductor devices, including diode lasers, by confining light and current flow—an accomplishment that earned them the 2000 Nobel Prize in Physics. Over a period of about seven years, ending around 1977, Bell Labs had stretched diode-laser lifetimes from mere seconds to 100 years for use in fiber-optic communications. After that, others increased power dramatically and improved efficiency to the point where diode lasers could convert about half of the input electricity into laser light.

Diode lasers don't generate the tightly focused beams needed for weapons, but they opened up another possibility: replacing lamps as the source of input energy in solid-state lasers. Fired into slabs of glass or crystal doped with light-emitting elements, these lasers have a huge advantage over lamps because they generate light far more efficiently and emit a single wavelength. Fiddle with the composition of the semiconductor that makes up the laser and its wavelength can be matched to one soaked up almost completely by the crystal, allowing it to convert that input light into laser energy very efficiently. Diode-laser pumping allowed the first solid-state laser weapon test bed to convert about 20 percent of the input electric energy into the output laser beam—a huge improvement on 1 percent for lamp-pumped lasers.

Here, high efficiency means much more than saving the Pentagon a few bucks on the power bill. The input energy not converted into light winds up as waste heat, which limits performance and must be removed from the laser. In practical terms, diode lasers put kilowatts and even tens of kilowatts within reach, though not the megawatts needed for long-range missile defense.

The High Energy Laser Joint Technology Office (HEL-JTO) was launched to develop solid-state laser weapons. These systems, using slabs of glass or crystal, reached their peak in March 2009 with a Northrop Grumman demonstrator. It delivered a steady 105-kW beam for a full 5 minutes. [See "Ray Guns Get Real," *IEEE Spectrum*, July 2009.] The laser didn't require special fuels or produce toxic gases, but it weighed 7 metric tons and occupied 10.8 cubic meters—about the volume of a large cement truck.

THE U.S. MILITARY, OF COURSE, wanted something smaller than a cement truck. And another of the HEL-JTO programs, the Robust Electric Laser Initiative, managed to do it. With a mandate to develop solid-state lasers that were better suited for the battlefield, HEL-JTO set itself a goal of building a 100-kW laser that occupied about 1.2 cubic meters and could generate more than 150 watts per kilogram, operating at 30 percent efficiency or better. Two of the four projects HEL-JTO launched considered new variations on a hot technology for laser machine tools: fiber lasers.

A fiber laser is essentially an optical fiber with some important modifications. It has a central core with a slightly higher refractive index than the surrounding glass cladding. A telecom fiber uses that structure to guide optical signals from laser transmitters through its central core, which is made of extremely pure and nearly lossless silica. In a fiber laser, however, this central core contains light-emitting atoms, usually ytterbium.

Fiber lasers also have an extra layer, between the light-emitting central core and the outer cladding. This intermediate layer, called the outer core or inner cladding, has a refractive index in between that of the core and the outer cladding. The inner cladding is also made | CONTINUED ON PAGE 48

THE DRIVER'S 360-DEGREE VIEW [inset] is made possible by ultranarrow carbon-fiber roof pillars.

Top 10 Tech Cars: 2018

A great disconnect looms between the EV future and the gas-guzzling present

By Lawrence Ulrich

McLAREN AUTOMOTIVE (2)

IN THIS YEAR'S TOP 10 TECH CARS, as in the global auto industry at large, the Great Disconnect becomes more obvious. On the one hand, virtually every carmaker offers models that deploy technology in unabashed pursuit of energy efficiency and reduced environmental impact. In our group of honorees this year, the Tesla Model 3 and the charming Kia Niro hybrid fit in this category. Yet for all the talk of a Tesla-driven tipping point in electric transportation, EVs still make up a 0.5 percent drop in the global ocean of new cars. So in the real world—well, at least in the United States, where Washington is actually looking to weaken fuel economy standards and where a record two-thirds of buyers are choosing an SUV, pickup, or other light truck—today's automotive innovation is arguably more about utility, horsepower, and performance.

McLAREN 720S

For the multimillionaire who has everything

ENGINE 530 kilowatts

0–100 KM/H 2.9 seconds

PRICE US $288,000

A bit cheeky, those Brits. McLaren had me test-drive its new supercar, the 720S, in Italy, home to its rivals Ferrari and Lamborghini. The 720S is the technical triumph you'd expect from the Formula One wizards who invented the carbon-fiber automobile. Yet the 720S adds a stereotypically Italian feature: knee-wobbling sex appeal, which eluded some previous McLarens, regarded by some as coldly technical.

That sex appeal includes a body that knows more about air than snowboarder Shaun White and flies through it just as effectively. Like all McLarens since the famed F1 of the early '90s, the 720S is built on a rigid carbon-fiber structure. It helps deliver a dry weight of just 1,283 kilograms (2,829 pounds), lighter than a Toyota Prius. And yet stuffed inside is a midmounted, twin-turbo V-8 with 530 kilowatts (710 horsepower) and 770 newton meters (568 foot-pounds) of torque.

Strapped inside this British missile, I launched my sneak attack on Autodromo Vallelunga Piero Taruffi, a Formula One test circuit a short drive from Rome. Under the car's jet-fighter-style canopy, I enjoyed a virtual 360-degree glass bubble; I've never driven a midengine supercar with better outward visibility. There are roof pillars, of course, but they're formed from carbon fiber, and they're slimmer than a supermodel's forearm. That greenhouse is surrounded by bravura vents that disappear when viewed from the sides. Those vents cleave deeply into the double-skinned, swing-up "dihedral" doors, and send cold and therefore dense air to radiators for the engine. To feed turbochargers at the rear, the McLaren inhales still more air through its novel, hollow "eye sockets."

On Vallelunga's aptly named Curva Grande, among the fastest sections of any European track, I can feel the winged Airbrake—now 30 percent more efficient than the version on the departed 650S—as it helps slow and stabilize the McLaren under hard braking.

A dual-clutch, seven-speed transmission delivers 45 percent quicker shifts. Other eye-popping particulars include a 2.9-second rip to 100 kilometers per hour (62 miles per hour), 200 km/h in 7.8 seconds, and 300 km/h in 21.4 seconds, or 4 seconds quicker than the departing 650S model. Top speed is 341 km/h, or 212 mph.

Another feature of the 720S is hydrau-

CONTINUED ON PAGE 41

RIMAC

Concept One

POWER PLUS LIGHTNESS let this three-wheeler surge to 60 miles per hour in just 4 seconds.

It shows what EVs can do when cost is no object

ENGINE 913 kilowatts TOP SPEED 354 km/h PEAK BATTERY POWER 1 megawatt

Tesla has nothing to fear from Rimac. Nor does Porsche, nor any other purveyor of electrified performance. Richard Hammond may be another story: The former "Top Gear" star nearly killed himself by flipping the Rimac Concept One while filming an episode of Amazon's TV show "The Grand Tour."

Yet while the Concept One saw just eight copies built (now seven, thanks to Hammond), the US $1.2 million Croatian hypercar showed the awe-inspiring potential of electric performance.

Born from the garage-hobby tinkering of the Croatian engineer Mate Rimac (whose company now numbers 150 employees), the Concept One generates an insane 913 kilowatts (1,224 horsepower) and 1,600 newton meters (1,180 foot-pounds) of torque from four oil-cooled electric motors. With an individual motor, power inverter, and gearbox at each wheel—including two-speed, dual-clutch units at the rear—a torque-vectoring system can speed or slow individual wheels hundreds of times per second, dramatically boosting control and agility. The upshot is a 2.5-second catapult to 60 miles per hour (97 kilometers per hour) and a 354-km/h top speed (210 mph).

Rimac claims that the Concept One's 8,450 liquid-cooled lithium nickel manganese cobalt oxide cells generate 1 megawatt of power under acceleration, absorb 400 kW under regenerative braking, and store 82 kilowatt-hours. With a dry weight of 1,900 kilograms (4,189 pounds), the Concept One can also travel 350 km (217 miles) on a charge. Unless you flip it over first, of course. ■

TOP: VANDERHALL MOTOR WORKS; BOTTOM: RIMAC AUTOMOBILI

Vanderhall Edison

It's a fast three-wheeler that feels even faster

LAST YEAR, I TOOK a thrill ride in the petrol-powered Vanderhall Venice. There isn't any other kind of ride you can take in a Vanderhall. It made me eager to feel more rushing breeze in the startup company's latest reverse trike, the Edison, with its hushed electric power train.

The Edison wraps its composite body around a rigid, lightweight aluminum frame, with two drive wheels up front and a single rear wheel attached with a motorcycle-style swing arm. A pair of electric motors sends 134 kilowatts (180 horsepower) to those front tires, juiced by a 30-kilowatt-hour lithium-ion battery pack. That's roughly half the battery capacity of a Chevy Bolt or a Tesla, but the Edison has a claimed curb weight of just 645 kilograms (1,400 pounds).

Vanderhall claims a 4-second squirt from 0 to 60 miles (97 kilometers) per hour, a sticky 0.95 *g*'s of lateral grip, and an entirely respectable 320-km (200-mile) driving range. Top speed is 170 km/h (105 mph). And with the Vanderhall's open roof and ground-hugging shape—you can touch the pavement when you're sitting inside—you'll feel like you're going 120 mph when you're only doing 80. You know, like a motorcycle, but without having to wonder what it would be like to feel your helmeted head sliding along the pavement.

Vanderhall hopes to begin selling the Edison, hand-built in Provo, Utah, in the second quarter of 2018 for US $34,950 to start, roughly the price of a Mazda Miata or a bare-bones Tesla Model 3. Take one look and guess which of those cars will be the most fun. ■

TOP 10 TECH CARS

ONE WHOLE MEGAWATT of battery power is what lets Rimac's designers dream big.

Dodge Challenger SRT Demon

This drag monster gives NASA-quality launches

LOOKING AT THE Dodge Challenger SRT Demon [right], it's easy to dismiss it as a knuckle-dragger, a relic of Detroit's street-racing '60s. But in my palpitating hands at the drag strip at the Lucas Oil Raceway (formerly Indianapolis Raceway Park), the Demon shows what deft application of modern technology can do: namely, enable a US $83,295 muscle car to accelerate faster than a $900,000 Porsche 918 Spyder or a $2.7 million Bugatti Chiron. Yes, the Demon was born for drag racing, where it's the fastest-accelerating production car in history, as certified by the National Hot Rod Association, with a 9.65-second quarter mile (0.4 kilometer). It will reach 30 mph in 1 second flat and smoke 60 mph (97 km/h) in 2.3 seconds, faster than any other car on this year's list.

Every component is optimized for speed, from its barely street-legal Nitto tires to its 6.2-liter Hemi V-8. The 2,700-cc supercharger inhales atmosphere at 1,150 cubic feet (32.5 cubic meters) per minute. Fun fact: The engine's thermal energy could, in theory, take a gallon of water from room temperature to boiling in 1 to 3 seconds, depending on your assumptions. Tea, anyone?

More production-car firsts: The trans-brake, long used in professional drag rac-

ing, binds the output shaft of the eight-speed automatic transmission, allowing you to launch the Dodge without holding the mighty engine in check with the foot brake. Torque reserve is another key to NASA-quality launches. The belt-driven supercharger's bypass valve closes to "prefill" the engine with 8 pounds per square inch of boost.

Another dashboard switch preps the Demon to run on 100-octane racing fuel, which unlocks the full 626 kilowatts (840 horsepower—you get "only" 808 hp on premium unleaded).

Then there's the Power Chiller, which diverts refrigerant from the air conditioner to a finned heat exchanger. The chilled coolant then flows to the supercharger's heat exchangers, reducing the temperature of the charge air and thus increasing its density, for a faster burn. Diverting all the A/C turned my Demon's cabin into a sweaty sauna. But I was having way too much fun to care. ■

Air

Accelerates as fast as a falling anvil

AN INSANE 1,000 horsepower is packed inside a car that's one part spaceship, one part California spa.

The United States is already littered with the ruins of failed or failing electric car companies: Aptera, Coda, Faraday Future, Fisker. But Lucid Motors might just have a shot at being a viable, smaller-scale competitor to Tesla.

First, there's experience: Peter Rawlinson, the company's chief technology officer, was chief engineer on Tesla's Model S. Chief designer Derek Jenkins is a former Mazda man, and his keen eye for modern design shows: The car is one part spaceship, one part California spa.

The Silicon Valley company claims the Air will arrive with hurricane force in 2019, including first-in-class acceleration: as little as 2.5 seconds from 0 to 60 miles (97 kilometers) per hour, for the top-end model with all-wheel-drive, dual electric motors, and an insane 1,000 horsepower. Lucid has already released videos of the Air hustling to 378 km/h (235 mph), and the company claims it's not done yet. A maximum 644-km (400-mile) driving range would be on par with many gasoline-powered cars, and it would whip any current EV, including Tesla's.

Lucid claims that a unique lithium-ion battery chemistry, in cells developed with LG Chem and Samsung SDI, will exceed current benchmarks in energy density, power, and battery life, including "breakthrough tolerance" of DC fast charging.

Rawlinson points out the battery's shape in the Air as well: It's shaped to create more foot room in the back seat, where optional 55-degree reclining chairs and fold-down "picnic tables" create the effect of a first-class airliner seat. The Air is prepped for the coming age of autonomy as well, with Mobileye cameras, radars, and lidar that Lucid says could deliver fully autonomous operation. Those lidar sensors would be a first for any production automobile.

Lucid hopes to build 10,000 Airs in 2019, eventually expanding to 100,000 per year, with about half of them destined for Chinese buyers. It'll kick things off with a rear-drive model with 400 horsepower and 240 miles of range, priced from US $60,000 in the United States, or $52,500 after a $7,500 federal tax break. Yet even $100K—for the promised top-shelf model—wouldn't be unreasonable for an eye-catching EV that has space like a limo and can go faster and farther than any electric sedan yet. ■

MOTOR 298 kilowatts RANGE (BASE MODEL) 386 km PRICE US $60,000

TOP: LUCID MOTORS; BOTTOM: FIAT CHRYSLER AUTOMOBILES

TESLA

Model 3

RANGE 350 km TOP SPEED (LONG-RANGE MODEL) 225 km/h PRICE (BASE MODEL) US $36,200

A dream EV—if it can exit “production hell”

The Tesla Model 3 is finally here, and even critics are slobbering all over it. Now all Tesla needs to do is build a half million of them.

The car might not claim the mantle of the world’s first affordable, long-range EV: Chevrolet beat Tesla to market with its roughly US $37,000 Bolt, a car we roundly praised in last year’s Top 10 Tech Cars. But where the Bolt is essentially a peppy, utilitarian hatchback that happens to run on electricity, the Model 3 sedan has larger ambitions in design, performance, innovative interfaces, self-driving tech, charging infrastructure, and even production volumes. More than any previous Tesla, the Model 3 seems to herald a coming age of electrified transport for the masses. Traditional automaking giants—such as Ford, General Motors, and Volkswagen (and its Porsche and Audi brands)—are gearing up to mount challenges to Tesla, and they may even crush the company through sheer global scale and know-how. But for now, every automaker in the world is playing catch-up with Tesla.

The Model 3’s price can soar to nearly $60,000 with a slate of way-cool options, yet its $36,200 starting price, even before federal or state tax breaks, still slightly undercuts the cost of the average new car sold in America. That baseline Model 3 can cover 350 kilometers (220 miles) on a single charge of its 55-kilowatt-hour lithium-ion battery. Or, for just $9,000 more, you can get the 75-kWh battery, and vanquish range anxiety by enjoying 500 km (310 miles) between charges.

TESLA

THE BASELINE MODEL 3 can cover 350 kilometers (220 miles) on a single charge; for US $9,000 more, you can go 500 km (310 miles).

My spin in the Model 3 was all too brief, but still a delight. On slinky, woodsy roads in Connecticut, the Tesla felt even quicker than its official acceleration figure of 0 to 60 miles per hour (97 kilometers per hour) in 5.1 seconds, thanks to the surge of instant-on torque from its single AC induction motor. Top speed of the long-range model is 225 km/h (140 mph).

Tesla has been mum on power output, but a Tesla filing with the United States' Environmental Protection Agency cites 192 kW (258 horsepower) for the version with the bigger battery. Even the baseline car springs to 60 mph in a fleet 5.6 seconds. Later this year, Tesla hopes to offer a dual-motor, all-wheel-drive version that includes the Ludicrous mode made famous on other Teslas.

The styling is handsome, but it's the interior and packaging that underline what's so different about a Tesla. The clean, minimalist vibe makes even a Scandinavian-simple Volvo seem cluttered. Climate-controlled air flows through ingeniously hidden vents in the upper dashboard. The elimination of internal combustion frees space under the hood for a Porsche 911–style "frunk" that's large enough for a roller bag. Fold the 60/40 split rear seats and you open enough space for a passenger to lie down, in a pinch.

The Tesla's boldest innovation may be the way it eliminates the traditional driver's instruments. They're replaced by a 38-centimeter (15-inch) touch screen positioned in the center of the dash, between the driver and passenger, that controls virtually all vehicle functions—speedometer, other gauges, and media. It requires a bit too much eyes-off-the-road time, in my experience. Clearly, the system would work fine in the self-driving car of the future, but right now it's facing some pushback from customers. Tesla CEO Elon Musk has already promised to address the problem with a more comprehensive set of voice commands to be delivered as an over-the-air software update. The Model 3 also comes with Tesla's latest radar-and-camera-based Autopilot system (but no lidar as of yet) to allow semiautonomous driving, and Musk has promised, a bit vaguely, a "full self-driving capability" for $3,000 at a later date.

On the road, the Model 3's steering is a bit too feather light, but it's deadly accurate and responsive. The Model 3 dances through corners like a top-shelf sport sedan. It helps that the long-range Model 3 weighs barely 1,730 kilograms (3,800 pounds), about 360 kg fewer than the Model S. Body roll is virtually nil, made possible by the under-floor battery, which creates a limbo-low center of gravity.

Whereas Model S and Model X owners get about 400 kWh of free Supercharger credits per year, Model 3 owners will have to pay fees for access. But their ability to access Tesla's unmatched, fast-charging Supercharger network gives the cars another major advantage over other EVs and plug-in hybrids. The DC units charge at up to 145 kW, enough to juice a Tesla to 80 percent capacity in under 40 minutes.

In California, with electricity priced at 20 U.S. cents per kilowatt-hour, Tesla estimates that customers will pay about $15 for a road trip from San Francisco to Los Angeles. For a reasonably thrifty conventional car that gets 7.8 liters per 100 kilometers (30 miles per gallon) on the highway, that 615-km (382-mile) trip would cost about $40 in unleaded gasoline. Driving from Los Angeles to New York would cost a piddling $120, or figure on €60 to hop from Paris to Rome.

Yet though the cars and chargers are fast, the factory in Fremont, Calif., has been painfully slow. Musk made headlines around the world in July when he admitted the company faced a good six months of "production hell." He was right: Fewer than 1,000 Model 3s were delivered between July and December, and under 2,000 by year's end, not nearly enough to satisfy the roughly 500,000 fans who have plopped down deposits.

Tesla still insists it will boost production to an annual rate of 500,000 units during 2018. If Musk can figure out how to get mass quantities of Model 3s to his patient and adoring fans, his legend will be assured. ■

NISSAN

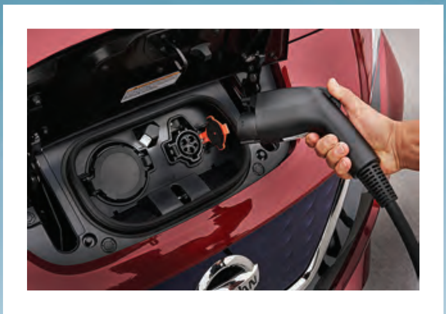
Leaf

The best-selling EV gets more range and power

MOTOR 110 kilowatts RANGE 240 km PRICE US $30,875

Give Nissan credit: The first-generation Leaf has been the world's best-selling electric car, with more than 300,000 buyers—even if the EV market remains tiny, at just 0.5 percent of the global total. But now other affordable EVs are bringing vastly superior range and performance, namely the Chevy Bolt and Tesla Model 3. So Nissan has anted up with a greatly improved 2018 Leaf, even if its 240-kilometer (150-mile) range falls well short of the Bolt's 383 km or the Tesla's 362.

The new hatchback Leaf looks far more appealing than the frog-faced original. Subtle ribs on the hood divert air around the side mirrors, reducing wind noise, which can become especially noticeable in an otherwise hushed EV. A new electric motor spools up 110 kilowatts (147 horsepower), up from just 80 kW before, with a healthy 320 newton meters (236 foot-pounds) of torque. A 40-kilowatt-hour battery pack outdoes the 24-kWh storage of the original Leaf, yet because of the tumbling price of batteries, Nissan was still able to cut the car's base price to US $30,875 in the United States, versus the Tesla's $36,200 and the Bolt's $37,495. By late 2018, Nissan promises to release a pricier Leaf SL whose upsized 60-kWh battery will precisely match the Bolt's storage, and boost range to about 362 km (225 miles).



THE LEAF CAN CHARGE from a solar-powered home system; it can give back to the grid during peak hours as well.

Buyers in Japan are even more fortunate. Nissan is offering some owners free installation of a solar array for zero-cost, zero-emission home charging. The Leaf also allows a vehicle-to-grid (V2G) connection, so owners can reduce electricity bills by powering their homes during peak hours from the Leaf's battery.

The Leaf also refines the "one-pedal" driving that many EV fans love: Just lift your foot off the gas and the regenerative brakes bring the car to a complete stop, with no need to even brush the brake pedal, as many EVs require. Nissan's new ProPilot Assist offers modest semiautonomy as well. Using a forward-facing camera and radar, the system's software does an especially good job at automatically centering the Nissan in its lane, without ping-ponging between lane markers, as some systems do.

Unfortunately, Nissan has stuck with its CHAdeMO plug for DC fast charging, a weirdly named standard that's been left for dead outside of Japan by both the SAE International's elegant combo plug (adopted by most every U.S. and European EV maker) and Tesla's own proprietary Superchargers. That stubborn misstep aside, the Leaf's unbeatable price and heightened range and power give it a fighting chance to maintain its top-selling status—especially if Tesla keeps struggling to get Model 3s out of the factory and into the hands of impatient buyers. ■

TOP: KIA MOTORS; BOTTOM: NISSAN (2)

Kia Niro

This boxy hybrid sculpts the air

THE KIA NIRO is the quiet ecocar. All you get is terrific mileage, pleasing style, and capability, in three affordable flavors: a hybrid, a plug-in hybrid, and soon, a full EV version.

The Niro sandwiches a 32-kilowatt (43-horsepower) electric motor between a 1.6-liter, four-cylinder gasoline engine and a nifty dual-clutch, six-speed transmission. Combine those gas and electric sources and you've got a peak power of 104 kW (139 hp) and the thrust of 264 newton meters (195 foot-pounds) of peak torque.

The Niro joins the Ioniq as the world's first production cars with no 12-volt lead-acid battery. The Kia packages a 12-V, 30-ampere-hour lithium-ion starter battery below its back seat, sharing a housing with the 240-V hybrid battery.

The EPA credits the Niro with up to 4.7 liters per 100 kilometers (49 miles per gallon) in combined city and highway driving, but I saw 61 mpg on one highway run in upstate New York. Over a week, the Niro returned 53 mpg, including mileage-sapping crawls through Manhattan.

For 2018, the Niro adds a plug-in model whose larger, 8.9-kilowatt-hour battery pack (versus 1.6 kWh) allows 26 miles of all-electric range at 105 mpge (2.2 L/100 km), the electric equivalent of a gasoline mileage rating. That plug-in Niro starts at US $28,840, versus $24,280 for the standard hybrid.

In January, Kia showed a Niro concept with a 64-kWh battery, a 150-kW (201-hp) motor, and a 383-km (238-mile) range, precisely matching the power output and range of the Bolt. This silent EV even broadcasts spoken alerts of its presence. Perhaps they'll come from some Ratso Rizzo, in reverse: "I'm drivin' here!" ■

DUAL-AXIS FRONT STRUTS keep this front-wheel-drive performance car on the road even during fast turns.

CADILLAC CT6

Right now, it's the self-driving champion of the world

MAPPED ROADS 210,000 km MAP ACCURACY 5 centimeters PRICE OF SUPER CRUISE OPTION US $5,000

Sharp-eyed readers may wonder: "Hey, the Cadillac CT6 was in last year's Top 10 Tech Cars. What gives?" What gives is Super Cruise.

Super Cruise sets a high new bar for semiautonomous systems. It's smarter and safer than anything from Audi, Mercedes, or Volvo. It's safer than even Tesla's fine-but-flawed Autopilot. The CT6 is expressly designed for hands-off-the-wheel highway driving. On a highway north of Manhattan, I drove for more than 2 hours without once touching the wheel, gas, or brakes.

The first groundbreaker: The Cadillac is constantly updated, every 25 meters (82 feet) of travel, with GM's proprietary lidar-based 3D maps of 210,000 kilometers (130,000 miles) of divided highways in the United States and Canada. That detailed information, including every last elevation change, guardrail, or bridge abutment, is combined with real-time, onboard sensor-fusion data from cameras, radar, and high-precision GPS.

The next coup is a driver monitoring system that addresses the major challenge of current semiautonomy: how to make a system robust and reliable without lulling drivers into text-messaging distraction or a false sense of security. Six infrared emitters in the Caddy's steering wheel rim illuminate the driver's face, allowing the gumdrop-size camera atop the steering column to monitor facial position, eyelid movements, and the focal point of the driver's pupils. The system sees you, and it knows what you're seeing.

TOUCH A BUTTON, then relax. But do pay attention: Super Cruise sees you, and it knows what you're seeing.

I could look away from the road for just under 5 seconds—plenty of time to, say, change a radio station—before the Caddy's steering-wheel rim flashed red to demand that I get my eyes back on the road. Keep ignoring the system and it disengages, while escalating visual and auditory warnings. Ultimately, the system will stop the car in its lane, turn on hazard lights, and summon help via the OnStar phone connection. Return your eyes to the task on first warning and the Caddy continues chauffeuring you.

You don't have to keep grabbing the steering wheel every minute or so to prove that you're there. For now, drivers are on their own for lane changes, but even here the system clearly demarcates responsibilities: The steering wheel flashes blue whenever you assume physical control, then goes back to green once you've settled into the next lane. Simple. Transitions between robotic and human control are crystal clear.

Still, it's not flawless yet. Every now and then, in certain locations and conditions, Super Cruise essentially calls in sick, and you'll have no idea what made it stop working: The system errs on the side of caution, especially when it spots, say, disappearing lanes, poor markers, tangled interchanges, or construction zones. In that vein, Super Cruise for now works almost exclusively on highways with on- and off-ramps—essentially every major freeway in the United States and Canada, but not secondary roads. Still, by establishing clear and clearly communicated boundaries on when it can be safely used, Super Cruise represents a great leap toward genuine autonomy.

I'm also sold on the Cadillac's ability to reduce fatigue on long trips or in snarled freeway traffic, which can wear out the most attentive pilot. I love to drive, but that kind of driving simply isn't fun. Why not turn things over to a digital copilot? It's relaxing to ease the seat back a bit and stretch your legs. Or heck, wave your hands to music from the Caddy's 34-speaker Bose Panaray audio system, as I did to the surprise of some fellow motorists.

One bummer is that Super Cruise is a US $5,000 option for now, though standard on the roughly $85,000 CT6 Platinum model. But expect other automakers to mimic Super Cruise's features, now that the bar has been raised. The current neither-nor state of "semiautonomy" has vexed the brightest minds in the business, as they wonder how to take the human driver out of the loop. As with aviation, it seems the answer is to keep the human in the loop—explicitly—at least until cars truly earn the "self-driving" honorific.

My hunch? It won't be long until Cadillac drivers can roll from sea to shining sea with Super Cruise. ■

TOP: HONDA; BOTTOM: GENERAL MOTORS (2)

Honda Civic Type R

Front wheel drive that feels like all-wheel drive

I'M BACK IN THE PITS of Connecticut's historic Lime Rock Park. And if you'd told me even a decade ago that a front-wheel-drive hatchback could rock a track like this, yet still reliably perform its everyday duties—you know, like a Honda—I'd have doubled over in laughter.

With 228 kilowatts (306 horsepower), a 4.9-second leap to 60 miles (97 kilometers) per hour, 1.0 *g*'s worth of lateral traction, and braking distances on par with a Porsche 911, this Civic is the rare car that feels like more than the sum of its parts. Fans already know that the US $34,990 Honda is essentially the fastest front-driver in history, but where you'd expect a ruinous ride from such a powerful front-drive machine, the Honda carves up corners with unbreakable grip and confidence.

Honda's dual-axis front strut suspension is a big reason why this Civic performs more like a rear- or all-wheel-drive car. Front wheels can get overwhelmed when they're required to both power and steer a car, because there's only so much grip to do both. By using one axis for the suspension and the other for steering, Honda separates the two functions: The system's damper knuckle puts the axis of steering closer to the center of the wheels themselves. In turn, the ability to tilt that steering axis gave engineers much more freedom to adjust "caster" and "camber" angles, which describe the relationship of the wheels to the ground. The upshot is that tires stay more perpendicular to the road.

Performance fans of a certain age may chafe at the Type R's Japanimation *mecha* robot styling. But hey, you want gravitas? Get a Porsche. ■

Cadillac CT6

McLAREN

CONTINUED FROM PAGE 31

lically linked shock absorbers—the only ones in the auto industry—which control bumps and wheel motions so flexibly that they do the job of antiroll bars in a conventional car, limiting the body roll during fast cornering. But the company seems proudest of its new strategy for controlling the body, called Optimal Control Theory. Its algorithms now react to vehicle parameters—such as a sudden change in direction—within 2 milliseconds, using data from 12 more sensors than the old 650S had. Switched to its comfort mode, the McLaren seems to glide effortlessly along the pavement, a rare feat for such a brutally capable machine.

A chronic McLaren weakness has been the cars' interiors, a challenge for an independent company that lacks a giant corporate parent. But the 720S is finally up to supercar par. It has a novel power-folding display, for example, which lets the driver power the entire instrument panel down into the dashboard to reduce distraction and expand those outward sightlines. All that's left is a slim-edge display for speed and other critical data.

That cabin incorporates another company first: variable drift control, a feature that makes a science of sliding. It's demonstrated to me by Gareth Howell, the company test driver and a many-time British touring car champion. Using a fingertip slider on a digital screen, he sets the precise angle of drift the car will allow before electronic nannies step in to prevent a full-on spin; then he slides the McLaren around the racetrack like a Hollywood stuntman. Owners can dial through nine different levels of fishtailing fun as their skills improve.

All this can be yours for as little as US $288,000. It's still fantasy territory, but it's a bargain for a carbon-fiber supercar with these levels of power, performance, and technology. ■

FUTURISTIC COMPUTER: Google's new quantum computers look like props from a sci-fi film. Whether these complex devices will prove truly useful remains to be seen.

Tech giants and startups alike are making a big push to bring quantum computing into the mainstream. Their plans will surely

WORK
FAIL

Quantum Computing: Both Here and Not Here

By Lee Gomes

CHRISTOPHER PAYNE/ESTO

Schrödinger's cat you've met—the one that is both alive and dead at the same time. Now say hello to Schrödinger's scientists, researchers who are in an eerie state of being simultaneously delighted and appalled.

Schrödinger's famous thought experiment has come to life in a new form because quantum researchers are at the cusp of a long-sought accomplishment: creating a quantum computer that can do something no traditional computer can match. They've spent years battling naysayers who insisted that a quantum computer was an unachievable sci-fi fantasy, and now these researchers are finally beginning to indulge in some well-deserved self-congratulation.

But they are simultaneously cringing at a torrent of press accounts that wildly overstate the progress they've made. Exhibit A: *Time* magazine's quantum-computing feature of 17 February 2014, with the editors declaring on the cover that "the Infinity Machine" is so revolutionary that it "promises to solve some of humanity's most complex problems." And since then, many press accounts have been equally hyperbolic.

Graeme Smith, a quantum-computing researcher at the University of Colorado Boulder, explains the conundrum now facing the field. "It used to be that if you were working in this area, you were the optimist telling everyone how great it's going to be. But then things shifted, and now researchers like me can't believe the things we're hearing about how quantum computers will very soon be able to solve every problem blazingly fast. There's almost a race to the bottom in making claims about what a quantum computer can do."

The reason for the current excitement is that sometime this year, quantum computing is expected to reach an important milestone. Led by a research group at Google with another at IBM giving chase, scientists are expected to demonstrate "quantum supremacy." That means the system will be able to solve a problem that no existing traditional computer has the memory or processing power to tackle.

But despite the click bait proclaiming "the arrival of quantum computing" that this event will inevitably generate, the accomplishment will be less significant than popular accounts might lead you to believe. For one thing, the algorithm Google is running to demonstrate quantum supremacy doesn't do anything of practical importance: The problem is designed so that it is just beyond the computational reach of any current conventional computer.

Building quantum computers that can solve the sorts of real-world computing problems people actually care about will require many more years of research. Indeed, engineers working on quantum computing at both Google and IBM say that a quantum "dream machine" capable of solving computing's most vexing problems might still be *decades* away.

And even then, virtually no one in the field is expecting quantum computers to replace traditional ones—despite popular accounts about how, with Moore's Law of conventional computing losing steam, quantum stands ready to take over. All current designs for quantum computers involve pairing them with classical ones, which carry out myriad pre- and postprocessing steps. What's more, many everyday programming tasks that can now be executed quickly on traditional computers might actually run more *slowly* on a quantum one, given the hardware and software overhead associated with getting a quantum computer to work in the first place.

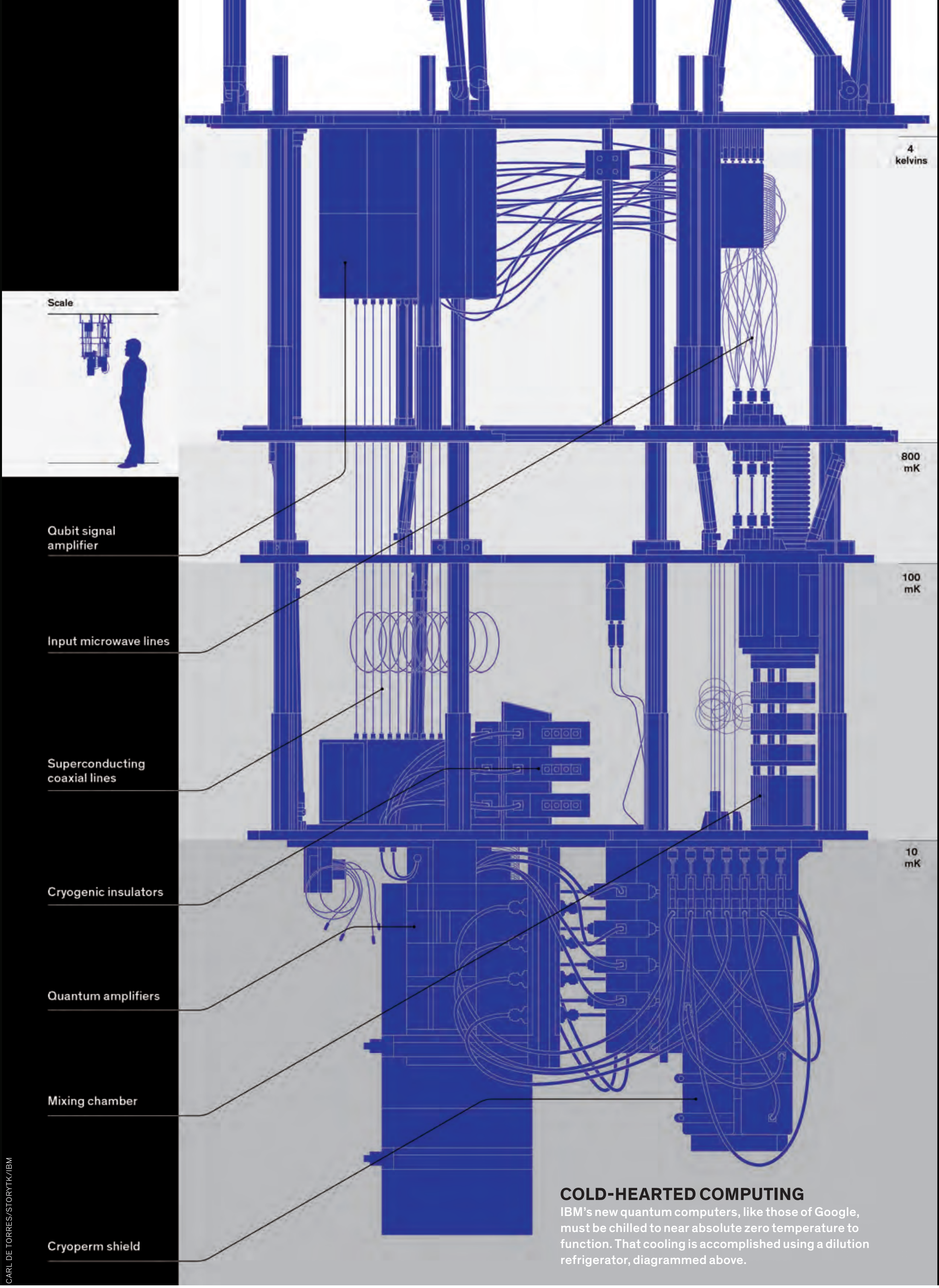
"I don't think anyone expects quantum computers to replace classical ones," says Stephen Jordan, a quantum researcher who worked for many years at the National Institute of Standards and Technology (NIST) and recently joined Microsoft Research in Redmond, Wash. Rather, quantum machines are likely to be useful only for a select group of computing jobs that have massive payoffs but that can't be readily handled by today's computers.

The idea for a quantum computer is usually traced to a 1981 speech by the Nobel Prize–winning physicist Richard Feynman, who speculated about the possibility of using the peculiar properties of subatomic particles to model the behavior of other subatomic particles. But a better starting point is a remarkable 1994 paper by Peter Shor, then of AT&T Bell Laboratories and now of MIT, which showed how a quantum computer—assuming one could be built—could quickly find the prime factors of large numbers, thus defeating commonly used public-key encryption systems. Such a computer would have basically broken the Internet.

Many people took notice, especially the U.S. security agencies involved with encryption, which quickly began investing in quantum hardware research. Billions have been spent over the past two decades, mainly by governments. Now that the technology is closer to being commercialized, venture capitalists are getting in on the act as well, a phenomenon very likely correlated with the extent of the current quantum hype.

So how exactly do quantum computers work?

Providing a brief and user-friendly explanation is a forbidding task, which is why Canadian prime minister Justin Trudeau became a geek hero in April of 2016 when he did the job about as well as any layperson ever has. In a press conference appearance that quickly went viral, Trudeau explained that with "normal computers…it's 1 or a 0. They're binary systems. What quantum states allow for is much more complex information to be encoded into a single bit."



CARL DE TORRES/STORYTK/IBM

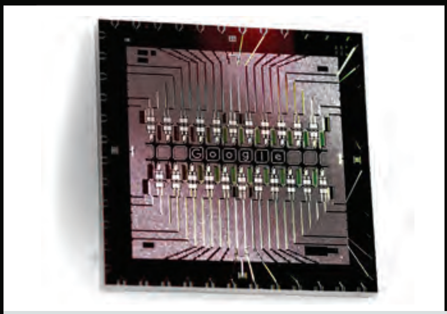
COLD-HEARTED COMPUTING

IBM's new quantum computers, like those of Google, must be chilled to near absolute zero temperature to function. That cooling is accomplished using a dilution refrigerator, diagrammed above.

A Peek Into Five Quantum Computers

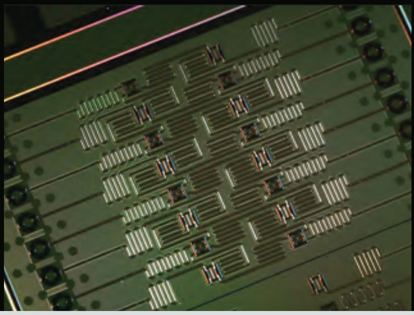
GOOGLE

Google is using superconducting quantum processors such as this design with its 22 qubit elements arranged in two rows.



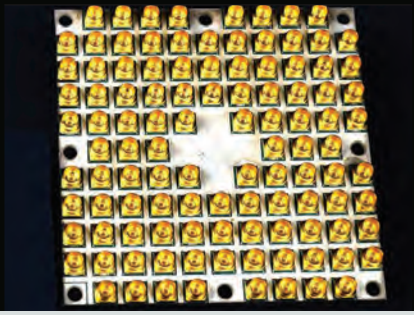
IBM

This 16-qubit superconducting processor powers IBM's publicly available platform for exploring quantum computing.



INTEL

This past January, Intel announced the fabrication of a 49-qubit superconducting quantum-computing chip, dubbed Tangle Lake.



If Trudeau had had more time, he might have gone on to say that the main building block of a quantum computer is a "qubit," which is a quantum object and thus can be in an infinite number of states, ones that are related to the probability of finding it in one of the two states it can assume when it is measured. Anything with quantum properties, like an electron or photon, can serve as a qubit, as long as the computer can isolate and control it.

Once fashioned inside a computer, each qubit is attached to some mechanism capable of transmitting electromagnetic energy to it. To run a particular program, the computer zaps the qubit with a carefully scripted sequence of, say, microwave transmissions, each at a certain frequency and for a certain duration. Those pulses amount to the "instructions" of the quantum program. Each instruction causes the unmeasured state of the qubit to evolve in a specific way.

These pulsing operations are done not just on one qubit but on all the qubits in the system, often with each qubit or group of qubits receiving a different pulsed "instruction." The qubits in a quantum computer interact through a process known as entanglement, which, in a manner of speaking, links their fates. The important point here is that quantum researchers have figured out how to use these successive changes to the state of the qubits in the computer to perform useful computations.

Once the program is finished—thousands or even millions of pulses later—the qubits are measured to reveal the final result of the computation. Doing so causes each qubit to become either a 0 or a 1, the famous wave function collapse of quantum mechanics.

This would be a straightforward piece of engineering were it not for the fact that qubits must be kept isolated from even the most minute amount of outside interference, at least for as long as it takes for the computation to be completed. The difficulty of doing so is the main reason why, until a few years ago, the biggest quantum machines had only one or two dozen qubits and were capable of only the simplest arithmetic.

Because of all the noise that surrounds them, qubits tend to be error prone. To deal with this problem, quantum computers need to have extra qubits standing by as backups. If one qubit goes off-kilter, the system consults with the backups to restore the errant qubit to its proper state.

Such error correction occurs in regular computers too. But the number of required backups is much greater in quantum systems. Engineers estimate that for a reliable quantum computer, every qubit used might need 1,000 or more backups. Because many advanced algorithms require thousands of qubits to begin with, the total number of qubits necessary for a useful quantum machine, including those involved with error correction, could easily run into the *millions*.

Compare that with Google's recently announced quantum-computing chip, which contains only 72 qubits. Just how valuable those qubits will prove to be for computation will depend on how error prone they are.

Work on Google's quantum computer is spearheaded by a team hired en masse in 2014 from the University of California, Santa Barbara. And this past November, IBM announced that it had constructed a 50-qubit quantum computer. The two companies, along with Rigetti Computing, a startup in Berkeley, Calif., and Intel, which recently announced a 49-qubit array, rely on chips specially designed to have quantum properties by virtue of the superconducting circuit loops they contain. These chips must be kept at very low temperatures, necessitating elaborate cooling mechanisms that look like Hollywood sci-fi props and make for closet-size systems.

There is an entirely different quantum hardware architecture in which an actual quantum particle, an ion, is suspended in a system that runs at room temperature. IonQ, a startup in College Park, Md., cofounded by Duke University physicist Jungsang Kim and Christopher Monroe of the University of Maryland, is working to build a machine based on this approach, using ytterbium ions.

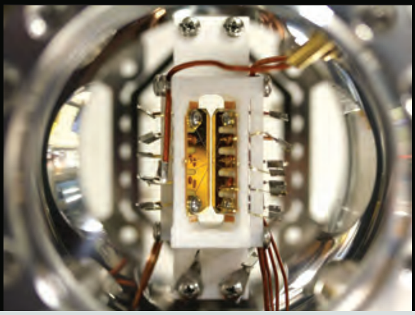
Microsoft is pursuing a third strategy, known as topological quantum computing. It holds theoretical promise, but no working hardware has yet been built.

None of those systems bears much resemblance to the quantum-related computer platform that has received the most publicity in recent years,

FROM LEFT: GOOGLE; IBM; INTEL

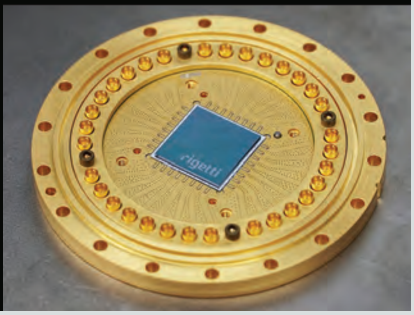
IonQ

In 2016, IonQ demonstrated a working 5-qubit computer using lasers to manipulate ytterbium ions trapped in this device.



RIGETTI

Rigetti, a Berkeley, Calif., startup, has recently begun fabricating 19-qubit superconducting processor chips.



from Canada's D-Wave Systems. While D-Wave's machines have been installed at such high-profile companies as Google and Volkswagen, a significant portion of the quantum research community views these devices with skepticism. Those scientists doubt that the D-Wave system will ever be able to do anything a traditional computer can't, and indeed, they question whether it achieves any quantum speedup at all.

The Google-IBM-Rigetti superconducting strategy appears to be leading the hardware horse race, but it's unclear yet what form of hardware will ultimately prove the most advantageous, or if all three approaches might end up coexisting. For their part, quantum programmers say they don't care which design wins, as long as they get their qubits to play with.

One of the many unknowns about quantum computing is how rapidly the machines will be able to offer additional qubits. With traditional computer technology, Moore's Law long guaranteed a doubling of transistor counts every two years or so. But because of the complex electronics associated with quantum machines, no such predictions are yet possible. Many engineers anticipate that for the intermediate future, we'll be limited to machines with a relatively small number of qubits, perhaps in the few hundreds. Because bare-bones demonstrations of quantum supremacy probably can't provide any useful results, and because mature systems are still many years away, engineers are focusing on algorithms that will work with the modestly sized quantum systems expected to be available in the near future.

The emerging consensus: While surprises are always possible, expect progress to be gradual.

"I don't think anyone who claims that quantum computers will soon be able to solve real-world problems, or that you will be able to make any money with them, is being entirely honest," says Wim van Dam, a physicist at UC Santa Barbara. "You're going to need much bigger systems for those to happen. But that doesn't mean that the field isn't incredibly exciting right now."

In the two decades since MIT's Shor developed his factoring algorithm, quantum computing has been closely linked with cryptography. But concern about broken Internet encryption has abated in recent years, partly because the quantum community realized that a Shor-worthy machine is still a long way off and partly because of the rise of "postquantum cryptography" designed to be impervious to any form of quantum attack. Even now, NIST is evaluating various candidates for a postquantum cryptographic infrastructure.

Instead of being preoccupied with encryption, researchers these days tend to focus on using the machines to model atoms and molecules, in the spirit of Feynman's original insight about quantum computing. Algorithms that simulate physics and chemistry are the most numerous in NIST's Quantum Algorithm Zoo, and the payoffs could be substantial, researchers say. Imagine, for example, metals that are superconductive at close to room temperature.

Here, too, irrational exuberance should be avoided. Andrew Childs, a physicist and computer scientist at the University of Maryland, predicted that the first generation of quantum computers will be able to tackle only relatively simple physics and chemistry problems. "You can answer questions that people in the condensed-matter physics community would like to have the answer to with a reasonably small number of qubits," he says. "But understanding high-temperature superconductivity, for example, is going to require many more."

While researchers warn against excessive optimism about fresh-out-of-the-box quantum computers, they also don't rule out the prospect of breakthroughs that will allow the machines to do much more with less. The more practice programmers get, the better their algorithms are likely to be, which is why IBM currently has its quantum machines online for researchers to tinker with.

"I could write down on this whiteboard the names of every single quantum algorithm researcher on the planet. And that's a problem," declares Chad Rigetti, of the eponymous Berkeley quantum-computing company. "We need more advances in algorithms, and having machines available for tens of thousands of students to learn on will help to catalyze the field."

For their part, those students seem to relish being present at the dawn of a new era, with all its potential for surprising discoveries. Daniel Freeman, a physics graduate student at the University of California, Berkeley, says the fact that quantum machines are still in their very early days is a feature of the research field, not a bug.

"We're essentially at the point that classical computing was at 100 years ago," he says. "We're not even at vacuum tubes yet. But I think that's actually very cool." ■

FROM LEFT: SHANTANU DEBNATH; RIGETTI

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THE RAY GUNS ARE COMING

CONTINUED FROM PAGE 48

of high-purity glass because its job is to guide light from external diode pump lasers directed into the outer cladding through separate optical fibers. From there, the light bounces along inside the outer core as it travels the length of the fiber, repeatedly passing through the inner core, where the ytterbium atoms grab the photons and emit laser light. The outer core is deliberately shaped unevenly—a D shape, an ellipse, even a rectangle—to ensure that as much light as possible is directed through the central core.

Like the signal in a telecommunication fiber, the light emitted by ytterbium atoms in a fiber laser remains confined within the light-guiding central core. But instead of traveling tens of kilometers in one direction to the next optical amplifier or receiver, the light in a fiber laser bounces back and forth between a pair of reflectors fabricated into each end of the fiber. With each pass, more ytterbium atoms amplify the light, building up the laser power.

The tight connection between the inner and outer cores ensures that most of the pump light is absorbed by ytterbium atoms. And in 2016, IPG Photonics reported converting just over half of the electric power to light in the lab, well above what you could get from the bulk crystal or glass of older, solid-state laser schemes. Generating light in the long, thin fiber core also produces a beam that can be focused tightly over long distances, which is exactly what's needed for delivering lethal energy to targets a few kilometers away. Because fiber lasers are thin—with diameters in the range of 125 to 400 micrometers—they have a high surface-to-volume ratio, allowing them to dissipate heat much faster than shorter and thicker lasers.

Fiber lasers started small, largely as spin-offs of the development of fiber amplifiers for long-haul telecommunications in the 1990s. The push to high power came from IPG. Starting with a 1-W fiber laser in 1995, the company has basically added an order of magnitude to that figure every three years through 2012. The company grew along with the power of its lasers. Its 2017 sales of $1.4 billion accounted for about a third of the revenue of the entire market for industrial lasers that year.

Industrial fiber lasers can be made very powerful. IPG recently sold a 100-kW fiber laser to the NADEX Laser R&D Center in Japan that can weld metal parts up to 30 centimeters thick. But that high of a power output comes at the sacrifice of the ability to focus the beam over a distance. Cutting and welding tools need to operate only centimeters from their targets, after all. The highest power from single fiber lasers with beams good enough to focus onto objects hundreds of meters or more away is much less—10 kW. Still, that's adequate for stationary targets like unexploded ordnance left on a battlefield, because you can keep the laser trained on the explosive long enough to detonate it.

Of course, 10 kW won't stop a speeding boat before it can deliver a bomb. The Navy laser demonstration on the USS *Ponce* was actually half a dozen IPG industrial fiber lasers, each rated at 5.5 kW, shot through the same telescope to form a 30-kW beam. But simply feeding the light from even more industrial fiber lasers into a bigger telescope would not produce a 100-kW beam that would retain the tight focus needed to destroy or disable fast-moving, far-off targets. The Pentagon needed a single 100-kW-class system for that. The laser would track the target's motion, dwelling on a vulnerable spot, such as its engine or explosive payload, until the beam destroyed it.

Alas, that's not going to happen with the existing approach. "If I could build a 100-kW laser with a single fiber, it would be great, but I can't," says Lockheed's Afzal. "The scaling of a single-fiber laser to high power falls apart." Delivering that much firepower requires new technology, he adds. The leading candidate is a way to combine the beams from many separate fiber lasers in a more controlled way than by simply firing them all through the same telescope. Two approaches looked promising.

One idea was to precisely match the phase of the light waves emerging from several identical fiber lasers so they add together to form a single, much more powerful beam. The light waves of each fiber laser are coherent, meaning all emitted waves march along in lockstep, with every crest locked in synchrony with every other crest, and every trough with every other trough, and so on. In principle, coherently combining the beams of several different fiber lasers should make a powerful beam that could be tightly focused onto targets kilometers away. Phased-array antennas can combine, in synchrony, the coherent outputs of many radio transmitters, but the trick is much more difficult with light. That's because light wavelengths are orders of magnitude shorter—around 1 micrometer compared with centimeters for radar—making it extremely hard to align the waves precisely enough for them to add together constructively rather than interfere with one another.

The other approach is to ignore phase and combine beams from many fiber lasers that each have optics that limit them to emitting in a unique spectral slot. The resulting beams each occupy a different wavelength. So when they are combined into a single beam, that beam spans a range of wavelengths, which don't interfere with one another. Called "spectral beam combining," the technique is adapted from wavelength-division multiplexing technology, which has been enormously successful in packing more data into fiber-optic communications channels. [See "Is Keck's Law Coming to an End?," *IEEE Spectrum*, February 2016.]

To implement the technology, Lockheed developed special optics that bend light from separate fiber lasers at angles that differ slightly depending on their wavelength, the same way prisms separate the colors of the spectrum. That bending merges their outputs to form a single beam. In 2014, the company "built and tested on our own money a 30-kW laser to figure out the physics and basic engineering," says Afzal. That system combined 96 beams of 300 W each at different wavelengths into a single beam with a total power of 30 kW. The lasers produce higher-quality beams when run at such relatively low powers, and it is easier to combine their output to produce a high-power beam than to build a single high-power laser with the same beam quality, says Afzal.

Lockheed scaled that technology to 60 kW in a laser it delivered to the U.S. Army Space and Missile Defense Systems Command, in Huntsville, Ala., last year for installation in a battlefield-ready military truck. That laser "set a world record for [weapons-grade] solid-state laser efficiency, in excess of 40 percent," claims Adam Aberle, lead of the command's high-energy laser technology development and demonstration. Such high efficiency greatly eases the problem of thermal management. With that efficiency, a laser system whose beam is at 100 kW generates less than 150 kW of waste heat. Compare that with more than 400 kW of waste heat, which is what Northrop Grumman's 2009 nonfiber laser put out while delivering a beam of the same power. On 1 March, Lockheed announced that by 2020, it would supply the U.S Navy with two copies of a similar laser, called HELIOS, that will deliver at least as much power. The Navy will install one on a destroyer and integrate it with the ship's battle management system, and it will test the second on land at the White Sands Missile Range, in New Mexico.

"We view development of the high-power, beam-combined fiber laser as the final piece of the puzzle," says Afzal. Maybe so, but the quest for laser weapons is far from over. Now that a high-energy laser technology looks viable, armed services around the world will need to figure out how to deploy it in combat, and against what. Those challenges, in turn, will require designing, building, testing, and refining the hardware needed to turn a powerful laser into a mobile weapon system, including trucks, ships, and aircraft to carry the laser; sensors and computer systems to spot and track targets; power management systems to deliver the electricity to the laser; cooling systems to keep it from overheating; and optics to focus the powerful beam onto moving targets long enough to destroy or disable them.

Nor is hardware the full extent of the challenge. Military R&D groups will be turning their powerful new lasers over to operational groups like the U.S. Naval Sea Systems Command to integrate the new technology into combat plans and develop procedures to support it in operation. The operational groups also are charged with critical tests of laser lethality against potential targets and with the strategy and tactics for using lasers in the field.

In short, the ability to blast some rockets out of the sky over a test range won't be enough to earn laser weapons a place in the arsenal. It has taken the military almost 60 years to get to the point where lasers look like they might actually be useful in combat. But the Pentagon is full of military brass who grew up with "kinetic weapons"–guns and rockets–and must be thoroughly convinced that the age of Buck Rogers has really arrived. Without such widespread support, there won't be money for the hard and expensive work of deploying a radically new weapon. As one wag put it famously (and in a completely different context), "No bucks, no Buck Rogers." ■

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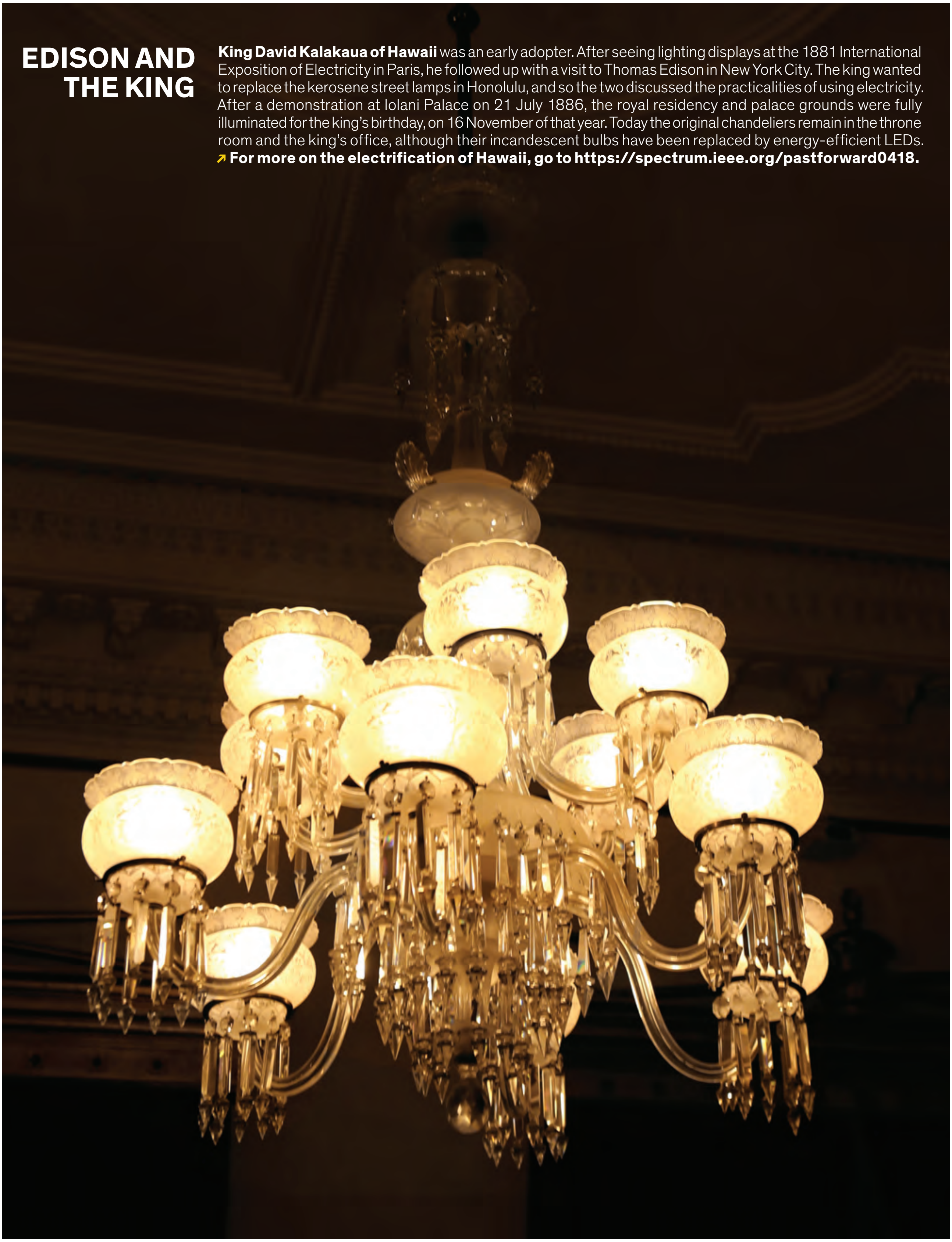
Senior Quantitative Risk Analyst (Regions - Birmingham, AL) The Quantitative Risk Analytics Group within Risk Management is seeking a quantitative analyst to develop, enhance and maintain loss estimation models. This hands-on role involves translating economic theory into meaningful models that estimate portfolio losses based on adverse macroeconomic conditions. Minimum Requirements: Must have a Master's degree or foreign degree equivalent in economics or a related field and 2 years of experience in the job offered or 2 years in an academic quantitative research position. Experience may have been obtained concurrently and must include: (i) 2 years of experience in Economic theory; (ii) 2 years of experience building econometric time series models; (iii) 2 years of experience testing model performance, in model design and for ongoing monitoring; (iv) 1 year of research experience in banking and financial institutions; (v) 2 years of experience working with any of the following: R, SAS, SQL, or VBA; (vi) 1 year of experience analyzing bank data from the Federal Reserve; and (vii) 2 years of experience with either technical writing or model documentation. Must have legal authority to work in U.S. Any suitable combination of education, training or experience is acceptable. Resume to Regions Bank, Attn: Jeffrey Hodges, Corporate Human Resources, 1900 5th Ave N, 7th Floor, Birmingham, AL 35203

EDISON AND THE KING

King David Kalakaua of Hawaii was an early adopter. After seeing lighting displays at the 1881 International Exposition of Electricity in Paris, he followed up with a visit to Thomas Edison in New York City. The king wanted to replace the kerosene street lamps in Honolulu, and so the two discussed the practicalities of using electricity. After a demonstration at Iolani Palace on 21 July 1886, the royal residency and palace grounds were fully illuminated for the king's birthday, on 16 November of that year. Today the original chandeliers remain in the throne room and the king's office, although their incandescent bulbs have been replaced by energy-efficient LEDs.

↗ For more on the electrification of Hawaii, go to https://spectrum.ieee.org/pastforward0418.



THE FRIENDS OF IOLANI PALACE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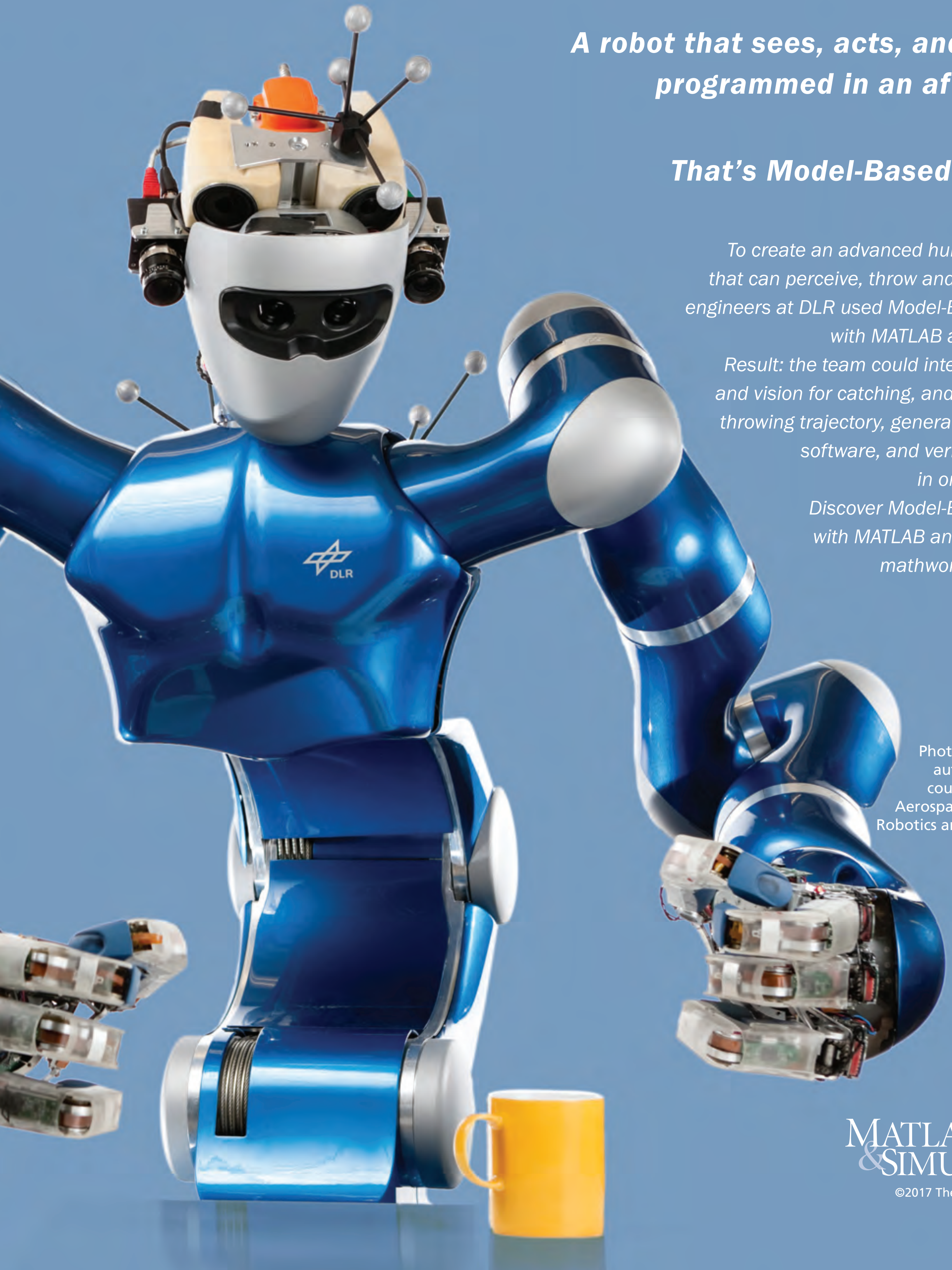
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