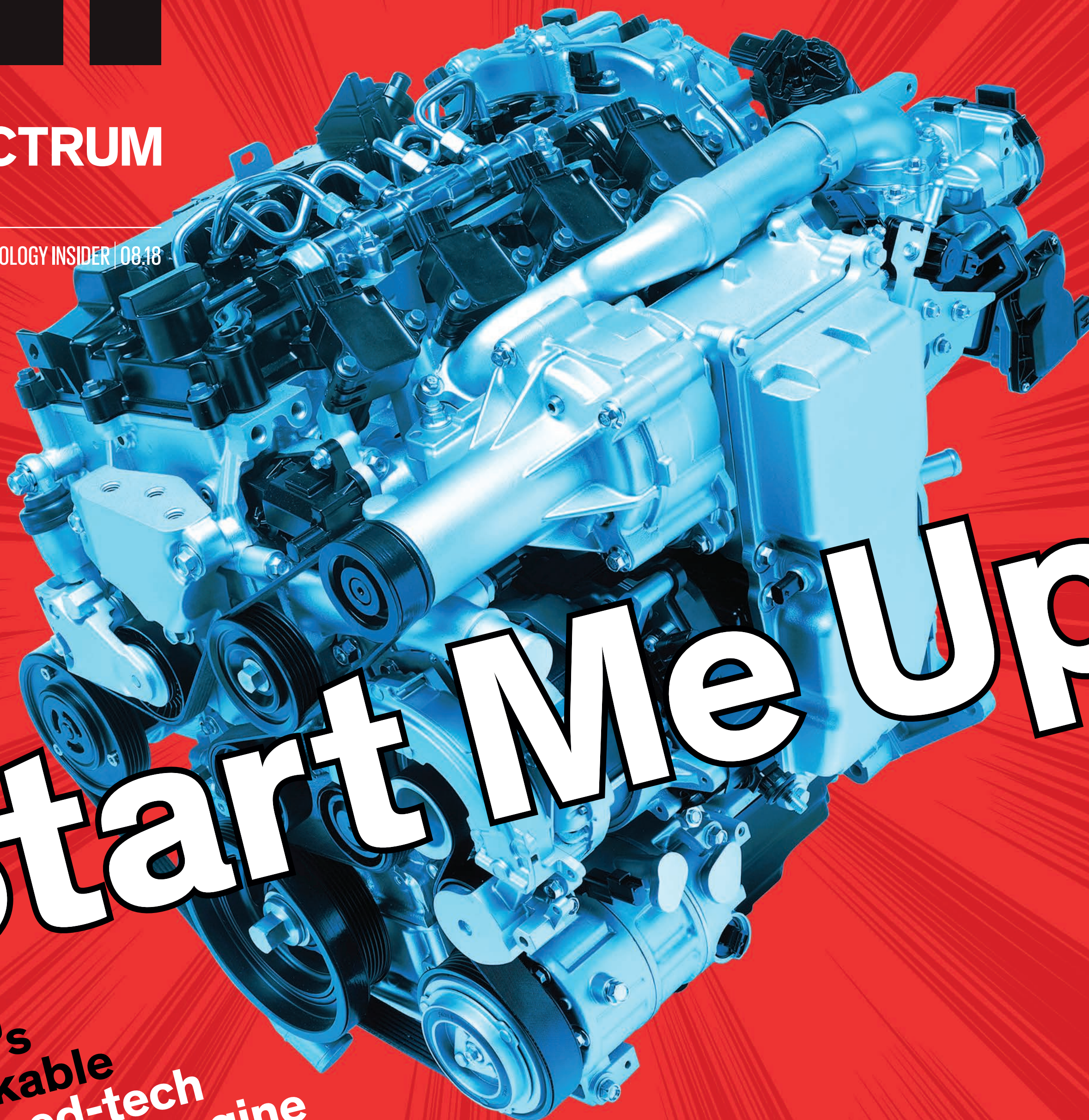
IEEE SPECTRUM

FOR THE TECHNOLOGY INSIDER | 08.18



Start Me Up

Mazda's remarkable advanced-tech combustion engine shows that the electric-car future is further away than you think P. 20

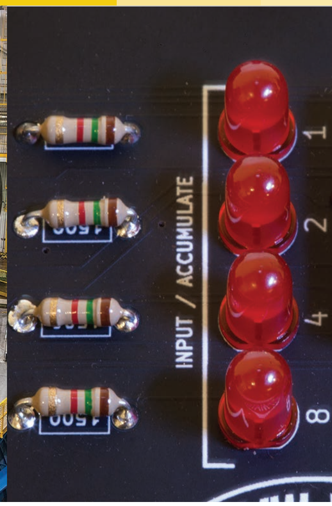
IEEE

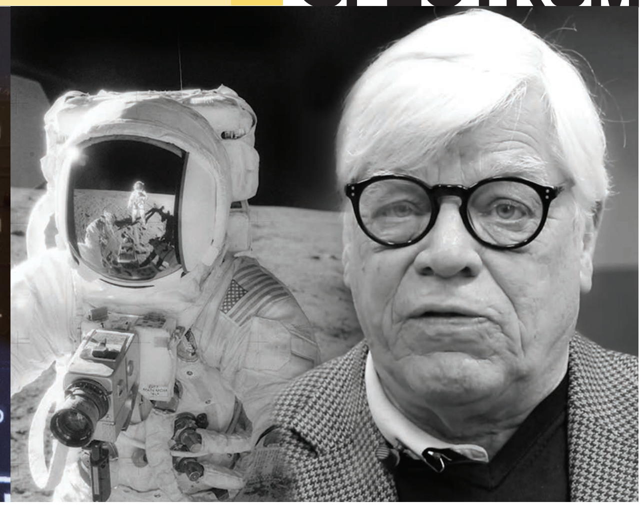
IEEE SPECTRUM

CURT MASON/PROJECT HABU

On the cover **Photo-illustration by Mark Montgomery**

IEEE SPECTRUM





FROM LEFT: SPACEX; RANDI KLETT; NASA/CHRISTINA DABNEY

ADDITIONAL RESOURCES

Tech Insider / Webinars

Available at spectrum.ieee.org/webinars

- Modeling the Etching of Nanostructures

White Papers

Available at http://spectrum.ieee.org/whitepapers

- Selecting Common-Mode Filter Chokes for High-Speed Data Lines
- Advancing the ACME Lead Screw System
- New Requirements for Medical EMC

The Institute

Available at theinstitute.ieee.org

BLOCKCHAIN SPECIAL REPORT
Many industries are incorporating blockchain technology for a host of applications beyond cryptocurrency transactions. It is already being adopted to manage supply chains, protect medical records, and other purposes. To help advance the field, IEEE launched its Blockchain Initiative to work on a number of activities, including professional development courses and standards.

BECOMING A BLOCKCHAIN DEVELOPER
More than 20 percent of large companies are working on blockchain applications and are in need of designers, developers, and project managers. Leaders in the field offer insights into how to break in.

TWO IEEE MILESTONES The site of the Shockley Semiconductor Laboratory will be honored as the birthplace of both Silicon Valley and of Moore's Law during a ceremony in Mountain View, Calif. Gordon Moore began his career at Shockley, which also manufactured the first silicon devices in the area.

IEEE SPECTRUM
(ISSN 0018-9235) is published monthly by The Institute of Electrical and Electronics Engineers, Inc. All rights reserved. © 2018 by The Institute of Electrical and Electronics Engineers, Inc., 3 Park Avenue, New York, NY 10016-5997, U.S.A. Volume No. 55, issue No. 8. The editorial content of IEEE Spectrum magazine does not represent official positions of the IEEE or its organizational units. Canadian Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40013087. Return undeliverable Canadian addresses to: Circulation Department, IEEE Spectrum, Box 1051, Fort Erie, ON L2A 6C7. Cable address: ITRIPLEE. Fax: +1 212 419 7570. INTERNET: spectrum@ieee.org. ANNUAL SUBSCRIPTIONS: IEEE Members: $21.40 included in dues. Libraries/institutions: $399. POSTMASTER: Please send address changes to IEEE Spectrum, c/o Coding Department, IEEE Service Center, 445 Hoes Lane, Box 1331, Piscataway, NJ 08855. Periodicals postage paid at New York, NY, and additional mailing offices. Canadian GST #125634188. Printed at 120 Donnelley Dr., Glasgow, KY 42141-1060, U.S.A. IEEE Spectrum circulation is audited by BPA Worldwide. IEEE Spectrum is a member of the Association of Business Information & Media Companies, the Association of Magazine Media, and Association Media & Publishing. IEEE prohibits discrimination, harassment, and bullying. For more information, visit http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html.

SCOTT MACAFEE/JOBY AVIATION

THE ANSWER IS BLOWING ON THE WING

IN 2012, ALEX STOLL GRADUATED from Stanford with a degree in aeronautical engineering and took a job at Joby Aviation. During his first year there, Joby consisted of a few people in Santa Cruz, Calif., intent on designing and constructing a novel kind of electric aircraft, one that could take off vertically but then transition to flying horizontally, supported by wings.

"I thought it would be incredibly exciting to be working on that kind of aircraft," says Stoll. Joby is carefully guarding details of its design, though, now that a gaggle of companies are pursuing similar aims. So Stoll can only suggest in hushed tones the fun he's been having trying to make people's Jetson-like dreams come true.

But he is free to report about another project of Joby's—a collaboration with NASA to use electric motors to create what's called a "blown wing," which promises to make conventional aircraft more efficient [see p. 26]. After the successful ground experiments that he and others at Joby helped to carry out, NASA is now gearing up to test such a wing on its new experimental electric aircraft, the X-57 Maxwell. It will have a full-blown blown wing, if you will.

The X-57 is a conversion of a twin-engine passenger aircraft to electric propulsion, using a dozen small motors arrayed along the wing for takeoff and landing. Other phases of flight will use a pair of larger cruise motors—whose brightly anodized stator Stoll is shown holding here.

Stoll's favorite part of his work is when he and his colleagues test things, including Joby's mysterious vertical-takeoff-and-landing aircraft, a prototype of which has been flying recently from the company's private airfield. How extensively has it been tested? That's not clear, but Stoll gives us a clue when he says that the thrill of seeing it take to the air "hasn't gotten old yet." ■

CONTRIBUTORS_

Stuart Bradford

Bradford has been illustrating Vaclav Smil's Numbers Don't Lie since January 2017. "I love that column," Bradford says. "It makes me think." For this month's column, about the Model T [p. 19], the illustrator and fine artist focused on the car's assembly from discrete parts. His illustrations undergo a similar process: "I research the elements, I may use my own photos, I'll scan in other images, and then the whole thing gets assembled in [Adobe] Photoshop."

Dan Carney

Carney took apart a lawn mower engine at age 10, rebuilt his own car at 14, and spent 25 years as a Sports Car Club of America racing driver before turning his hand to writing. As Carney describes in "Not So Fast, Electric Car" in this issue [p. 20], emerging technology is making cars environmentally friendly, and it's not all because of the wonders of electric propulsion–internal combustion engines are getting cleaner, too.

Barry M. Lunt

Lunt is a professor of information technology at Brigham Young University, in Provo, Utah. In "A View to the Cloud" [p. 40], he walks readers through the mechanics of how digital data is stored, both locally and in the cloud. "The fact that the technology works as well as it does is a salute to the countless engineers who over the decades have developed storage devices, data centers, and the data links that make it all possible," Lunt says.

Allison Marsh

Marsh is a history professor at the University of South Carolina. For this month's Past Forward, about toys designed to teach quantum mechanics [p. 48], she played with the toys herself in hopes of understanding the underlying physics. They weren't exactly intuitive, she says. "You have to already know Pauli spin matrices and linear operators to appreciate how the toys function," Marsh says. "But once you do, you recognize the brilliance behind their design."

Curt Mason

Mason works as a communicator at Kennedy Space Center in Florida. When he learned that his photos of NASA's LEAPTech experimental wing would appear in this issue [p. 26], he was elated. "I have a lot of engineers in my family, going back five generations," Mason says. That includes his great-great-grandfather, radio pioneer Robert H. Marriott, who cofounded and served as first president of the Institute of Radio Engineers, a predecessor society of the IEEE.

IEEE SPECTRUM

EDITOR IN CHIEF
Susan Hassler, s.hassler@ieee.org
EXECUTIVE EDITOR
Glenn Zorpette, g.zorpette@ieee.org
EDITORIAL DIRECTOR, DIGITAL
Harry Goldstein, h.goldstein@ieee.org
MANAGING EDITOR
Elizabeth A. Bretz, e.bretz@ieee.org
SENIOR ART DIRECTOR
Mark Montgomery, m.montgomery@ieee.org
SENIOR EDITORS
Stephen Cass (Resources), cass.s@ieee.org
Erico Guizzo (Digital), e.guizzo@ieee.org
Jean Kumagai, j.kumagai@ieee.org
Samuel K. Moore, s.k.moore@ieee.org
Tekla S. Perry, t.perry@ieee.org
Philip E. Ross, p.ross@ieee.org
David Schneider, d.a.schneider@ieee.org
DEPUTY ART DIRECTOR Brandon Palacio, b.palacio@ieee.org
PHOTOGRAPHY DIRECTOR Randi Klett, randi.klett@ieee.org
ASSOCIATE ART DIRECTOR Erik Vrielink, e.vrielink@ieee.org
SENIOR ASSOCIATE EDITOR
Eliza Strickland, e.strickland@ieee.org
NEWS MANAGER
Amy Nordrum, a.nordrum@ieee.org
ASSOCIATE EDITORS
Willie D. Jones (Digital), w.jones@ieee.org
Michael Koziol, m.koziol@ieee.org
SENIOR COPY EDITOR Joseph N. Levine, j.levine@ieee.org
COPY EDITOR Michele Kogon, m.kogon@ieee.org
EDITORIAL RESEARCHER Alan Gardner, a.gardner@ieee.org
ADMINISTRATIVE ASSISTANT
Ramona L. Foster, r.foster@ieee.org
VIDEO INTERN Christina Dabney
CONTRIBUTING EDITORS Evan Ackerman, Mark Anderson, Robert N. Charette, Peter Fairley, Tam Harbert, Mark Harris, David Kushner, Robert W. Lucky, Prachi Patel, Morgen E. Peck, Richard Stevenson, Lawrence Ulrich, Paul Wallich

DIRECTOR, PERIODICALS PRODUCTION SERVICES Peter Tuohy
EDITORIAL & WEB PRODUCTION MANAGER Roy Carubia
SENIOR ELECTRONIC LAYOUT SPECIALIST Bonnie Nani
PRODUCT MANAGER, DIGITAL Shannan Brown
WEB PRODUCTION COORDINATOR Jacqueline L. Parker
MULTIMEDIA PRODUCTION SPECIALIST Michael Spector
ADVERTISING PRODUCTION +1 732 562 6334
ADVERTISING PRODUCTION MANAGER
Felicia Spagnoli, f.spagnoli@ieee.org
SENIOR ADVERTISING PRODUCTION COORDINATOR
Nicole Evans Gyimah, n.gyimah@ieee.org

EDITORIAL ADVISORY BOARD
Susan Hassler, *Chair*; David C. Brock, Sudhir Dixit, Limor Fried, Robert Hebner, Joseph J. Helble, Grant Jacoby, Leah Jamieson, Jelena Kovacevic, Deepa Kundur, Norberto Lerendegui, Steve Mann, Allison Marsh, Jacob Østergaard, Umit Ozguner, Thrasos N. Pappas, H. Vincent Poor, John Rogers, Jonathan Rothberg, Umar Saif, Takao Someya, Maurizio Vecchione, Yu Zheng, Kun Zhou, Edward Zyszkowski

MANAGING DIRECTOR, PUBLICATIONS Michael B. Forster

EDITORIAL CORRESPONDENCE
IEEE Spectrum, 3 Park Ave., 17th Floor, New York, NY 10016-5997
TEL: +1 212 419 7555 FAX: +1 212 419 7570
BUREAU Palo Alto, Calif.; Tekla S. Perry **+1 650 752 6661**

DIRECTOR, BUSINESS DEVELOPMENT, MEDIA & ADVERTISING Mark David, m.david@ieee.org

ADVERTISING INQUIRIES
IEEE GLOBALSPEC
30 Tech Valley Dr., Suite 102, East Greenbush, NY 12061
+1 844 300 3098 Toll-free: +1 800 261 2052
www.globalspec.com
VP, DIGITAL MEDIA & ENGINEERING INSIGHT Don Lesem
+1 518 238 6514, don.lesem@ieeeglobalspec.com
VP, SALES & CUSTOMER CARE Peter Hauhuth
+1 303 594 8007, peter.hauhuth@ieeeglobalspec.com
SENIOR DIRECTOR, PRODUCT MANAGEMENT & MARKETING Christian Noe
+1 518 238 6611, christian.noe@ieeeglobalspec.com
SENIOR PRODUCT MANAGER Linda Uslaner
+1 518 238 6527, linda.uslaner@ieeeglobalspec.com

REPRINT SALES +1 212 221 9595, ext. 319
REPRINT PERMISSION / LIBRARIES Articles may be photocopied for private use of patrons. A per-copy fee must be paid to the Copyright Clearance Center, 29 Congress St., Salem, MA 01970. For other copying or republication, contact Managing Editor, *IEEE Spectrum*.

What's the Best City for Software Engineers?

Hint: It's not San Jose or San Francisco

If you're a software engineer, where should you live to maximize your income?

Moving and storage company SpareFoot analyzed what it says was an exclusive batch of data obtained from ZipRecruiter covering the 30 days ending 1 May 2018. SpareFoot offers online tools for booking self-storage facilities, so it keeps its eye on people who are relocating, hence its interest in software engineering careers.

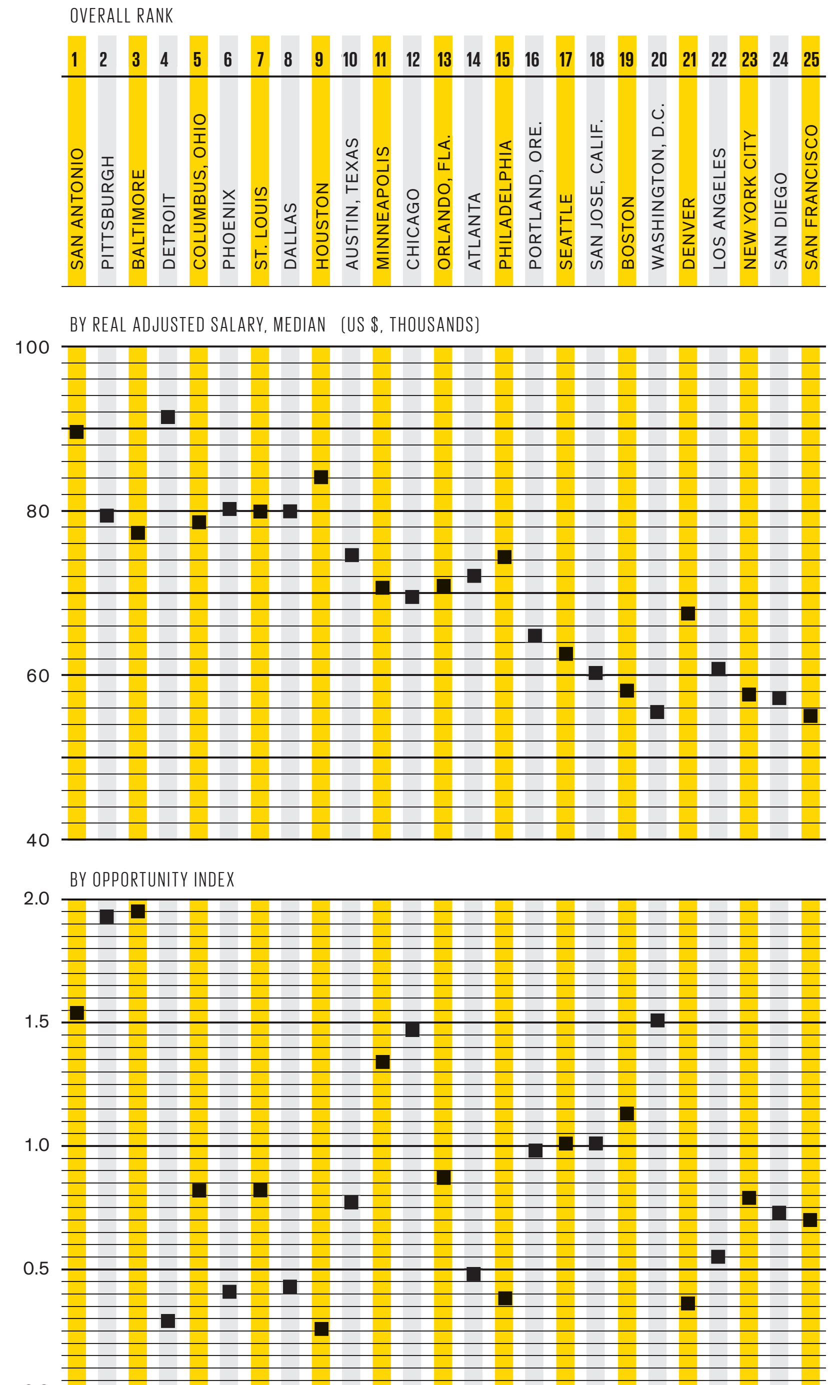
The company narrowed the list to the 25 U.S. metropolitan areas with the most opportunities for software engineers, as determined by dividing the number of job openings listed on ZipRecruiter by the number of active job seekers in each area. SpareFoot then took the median software engineering salary for each area, as determined by PayScale, and adjusted that according to cost-of-living data from AreaVibes. Finally, it combined the real adjusted salary data with the opportunity data, giving double weight to the opportunity data. Got that?

After churning these numbers, SpareFoot came out with San Antonio on top, with Dallas, Houston, and Austin joining it in the top 10. It's a bit suspicious that so many Texas cities did so well, given that SpareFoot is located in Austin, so its formula construction may reflect a bit of hometown bias.

What about cities outside of the United States? SpareFoot is working on collecting additional data and expects to have an updated list toward the end of 2018.

In addition to SpareFoot's calculated rankings, I took apart the data the company provided to date, listing cities by adjusted average salaries and by software engineer demand. Detroit came out on top in terms of salary and Baltimore in terms of opportunity. The top 25 appear in the chart. –TEKLA S. PERRY

A version of this article appears in our View From the Valley blog.



Source: SpareFoot

Correction: The article "What Will the Electricity Miracle Be?" [June] misstated the unit for the amount of uranium waste that both TerraPower's traveling wave reactor and a typical light water reactor would produce. The amounts are 5 metric tons and 21 metric tons per gigawatt year, respectively, not metric megatons.

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/softwarecities0818

CLOCKWISE FROM TOP RIGHT: BOEING (3); SPACEX (3)

NEWS

BOEING AND SPACEX TEST THE NEXT U.S. RIDE TO SPACE

The International Space Station is expecting two visitors this month: Starliner and Crew Dragon

Two possible successors to NASA's space shuttle are scheduled to visit the International Space Station this month, in their last big step before they transport humans. A successful flight test for Boeing's CST-100 Starliner and SpaceX's Crew Dragon spacecraft would show that these vehicles are finally ready to carry both NASA astronauts and space tourists into orbit.

Much is riding on these flight tests as NASA seeks to renew U.S. capability for crewed spaceflight. Back in 2014, Boeing and SpaceX received NASA contracts worth a combined US $6.8 billion, to transport astronauts to the space station. But both companies have repeatedly pushed back their original launch dates.

NASA and Boeing officials have suggested that the first crewed flights of the commercial spacecraft may not happen until 2019 at the earliest—and that's only if both spacecraft perform smoothly during their upcoming tests.

"Commercial crew is the only game in town for launching American astronauts to the International Space Station from American soil on American launch systems," says Marcia Smith, founder of the Virginia-based Space and Technology Policy Group, a news and analysis organization. "If the United States wants to stop using Russian vehicles, NASA will have to make commercial crew work, whatever the cost and whatever the schedule turns out to be."

Boeing has named its first flight demonstration Orbital Flight Test; SpaceX has named its effort Demo-1 Flight Test. Both tests share the same goals: Show that

the spacecraft can launch into orbit, perform automated docking with the space station, and land safely back on Earth.

These dry runs, without any astronauts aboard, also aim to support the companies' claims that their spacecraft can function autonomously. "We will be proving that every system that does not interact with a human operates as intended on the Orbital Flight Test," says Rebecca Regan, a Boeing representative.

In future, crewed missions, the Boeing Starliner and SpaceX Crew Dragon will let astronauts on board and mission controllers on the ground take over during key phases of flight. Starliner, in particular, allows for manual control after the spacecraft separates from its rocket in orbit and prior to when it deploys its parachute upon the return to Earth.

Boeing's Starliner will hitch a ride into space aboard a United Launch Alliance Atlas V rocket, which has achieved nearly 80 successful launches since 2002. SpaceX's Crew Dragon will fly aboard the Block 5, the latest version of the company's Falcon 9 rocket, which has launched about 60 times in different forms since 2010.

Each spacecraft accommodates up to seven passengers, who will wear temperature-controlled suits–blue for Boeing and black-and-white for SpaceX–designed to withstand a sudden loss of pressure or a fire in the crew module. Flight controls

BUCKLE UP: Artists' renderings show SpaceX's Crew Dragon [top left] and Boeing's Starliner [top right]. Both spacecraft will travel to the space station and back this month. The Crew Dragon [middle left] is a modified version of the Dragon, which has already made multiple supply runs. Each Starliner capsule [middle right] can be reused up to 10 times. Eventually, the vehicles will transport crew sporting custom spacesuits designed by SpaceX [bottom left] and Boeing [bottom right].

on both vehicles consist of touch screens and tablets instead of the switches, dials, and paper flight logs from the early days of spaceflight.

Though built for identical missions, the spacecraft and their operations differ in certain design details. For example, Crew Dragon has three windows as opposed to Starliner's two windows.

Each vessel also has an abort system to carry astronauts to safety during emergencies that occur while the spacecraft waits on the launchpad or as it rockets into space. To make sure those systems operate as intended, SpaceX is planning an in-flight test of its abort technology, whereas Boeing will conduct an abort test from the pad (SpaceX completed a version of this test in 2015).

The return to Earth will also look different for Starliner and Crew Dragon. Both vehicles will rely on the tried-and-true parachute approach to slow their descent after reentry through the Earth's atmosphere. But Starliner aims to land on solid ground with the help of an airbag system to cushion the shock, while Crew Dragon will cool its heels with a water landing in the ocean.

Successful test flights would allow Boeing and SpaceX to move ahead with their first crewed flight tests as soon as 2019. Starliner and Crew Dragon must also clear NASA's final certification review to get the green light to regularly ferry astronauts to the space station. And the companies will need to secure official certification to begin selling seats to space tourists–assuming that customers are willing to pay. "For the commercial crew program overall, the biggest uncertainty is whether it really is a business," Smith says.

–JEREMY HSU

POST YOUR COMMENTS at https://spectrum.ieee.org/spaceflights0818

MAKING MEDICAL AI TRUSTWORTHY

Researchers are trying to crack open the black box of AI so it can be deployed in health care

The health care industry may seem the ideal place to deploy artificial intelligence systems. Each medical test, doctor's visit, and procedure is documented, and patient records are increasingly stored in electronic formats. AI systems could digest that data and draw conclusions about how to provide better and more cost-effective care.

Plenty of researchers are building such systems: Medical and computer science journals are full of articles describing experimental AIs that can parse records, scan images, and produce diagnoses and predictions about patients' health. However, few–if any–of these systems have made their way into hospitals and clinics.

So what's the holdup? It's not technical, says Shinjini Kundu, a medical researcher and physician at the University of Pittsburgh School of Medicine. "The barrier is the trust aspect," she says. "You may have a technology that works, but how do you get humans to use it and rely on it?"

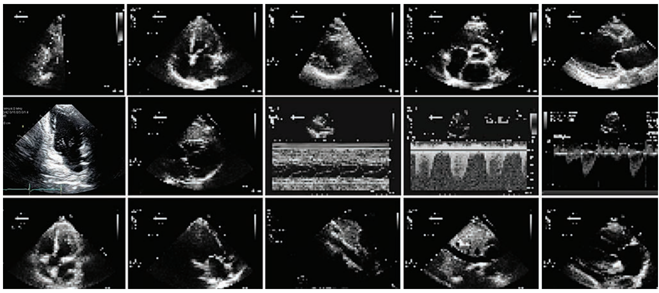
Most medical AI systems operate as "black boxes" that take in data and spit out answers. Doctors are understandably wary about basing treatments on reasoning they don't understand, so researchers are trying a variety of techniques to create systems that show their work.

PAINT US A PICTURE

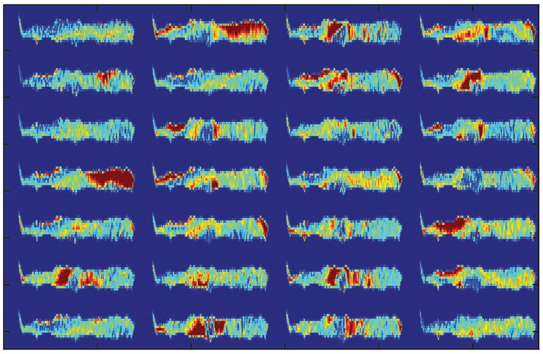
Kundu, who described her research at the United Nations' recent AI for Good conference, is working on AI that analyzes medical images and then explains what it sees. Her system starts with a machine-learning component that examines images such as MRI scans and discovers patterns of interest to doctors.

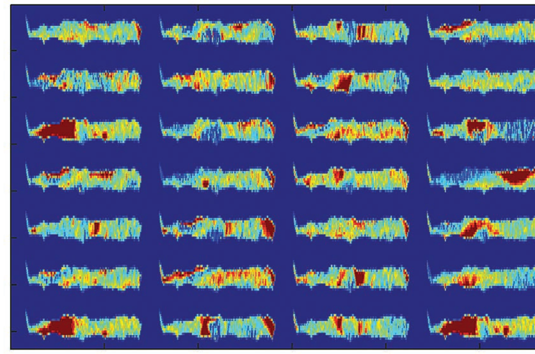
In Kundu's most recent experiments, the AI analyzed knee MRIs and predicted which knees would develop osteoarthritis within three years. Then, using a technique called "generative modeling," the AI created a new image–its version of an MRI scan showing a knee that was guaranteed to develop that condition. "We enabled a black box classifier to generate an image that demonstrates the patterns it's seeing as it makes its diagnosis," Kundu explains.

The AI's generated image revealed that it was basing its predictions on subtle changes to the cartilage shown in the MRI scans–which



HEART BEATS: An AI program classifies low-resolution images from echocardiograms based on which parts of the heart are in view. A next-gen version will use this anatomical understanding to make diagnoses.

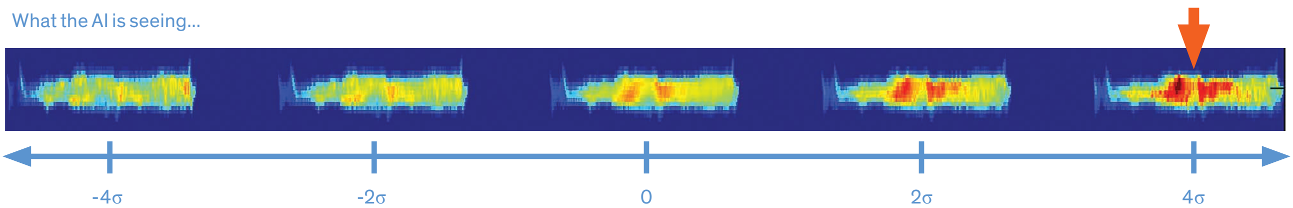




No osteoarthritis in 3 years

Osteoarthritis in 3 years

What the AI is seeing...



No osteoarthritis in 3 years

Osteoarthritis in 3 years

THE POWER TO PREDICT: Human eyes can't tell the difference between MRI scans of those patients who won't develop osteoarthritis in their knees within three years and those who will [top]. But an AI program found subtle differences in the patterns of cartilage, which it showed to researchers [bottom].

LEFT: ALI MADANI/DIGITAL MEDICINE; RIGHT, TOP: OSTEOARTHRITIS INITIATIVE (2); BOTTOM: UNIVERSITY OF PITTSBURGH SCHOOL OF MEDICINE

human doctors hadn't noticed. "That was another powerful aspect of this work," says Kundu. "It helped humans understand what the early developmental process of arthritis might be."

NOW WHAT DO YOU SEE?

Rima Arnaout, an assistant professor and practicing cardiologist at the University of California, San Francisco, trained a neural network to classify echocardiograms, the ultrasound scans crucial for diagnosing heart ailments. The first version of her AI, described in the journal *Digital Medicine* in March, was more accurate than human cardiologists at sorting tiny, low-resolution images by their angle of perspective on the heart. The next version will use this information to identify the anatomical structures in view and diagnose cardiac diseases and defects.

But such a diagnostic system isn't likely to be used: "I'm never going to make a diagnosis that doesn't sit well with me, and say, 'The computer made me do it,' " Arnaout says. So she used two techniques to understand how her classifier was making decisions. In occlusion experiments, she covered up parts of test images to see how it changed the AI's answers; with saliency mapping, she traced the neural network's final answers back to the original image to discover which pixels carried the most weight.

Both techniques showed which parts of the image the AI relied on to make decisions. Encouragingly, the structures that contributed most to the AI's decisions were also those that human experts judged important.

MOVING BEYOND CORRELATION

At Microsoft Research in Redmond, Wash., principal researcher Rich Caruana has been on a mission for decades to make machine-learning models that aren't just intelligent but also intelligible. His AI uses electronic health records from hospitals to make predictions about patient outcomes. But he has found that even models that appear highly accurate can hide serious flaws.

He cites his ongoing research using a data set of pneumonia patients. In one study, he trained a machine-learning model to distinguish between high-risk patients, who should be admitted to the hospital, and low-risk patients, who could safely stay home to recuperate. The model found that people with heart disease were less likely to die of pneumonia and confidently asserted that these patients were low risk.

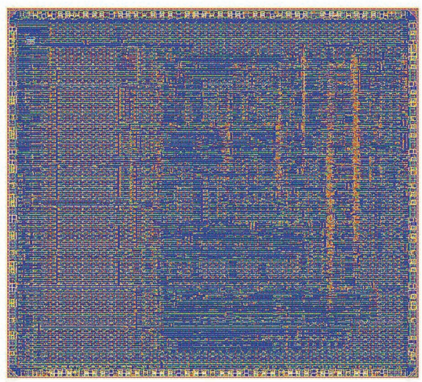
Caruana explains that heart disease patients who are diagnosed with pneumonia have better outcomes—not because they're low risk but because they typically go to the emergency room at the first sign of breathing problems and therefore get immediate diagnosis and treatment. "The correlation the model found is true," Caruana says, "but if we used it to guide health care interventions, we'd actually be injuring—and possibly killing—some patients." Based on his troubling discoveries, he's now working on machine-learning models that clearly show the relationship between variables, letting him judge whether the model is not only statistically accurate but also clinically useful. —ELIZA STRICKLAND

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/medicalai0818

IBM'S NEW DO-IT-ALL AI CHIP

The company says its chip can do both high-precision learning and low-precision inference across the three main flavors of deep learning

The field of deep learning is still in flux, but experts now recognize that neural nets can maximize computation with minimal energy if a chip uses low-precision math to estimate answers. That's especially useful in mobile and other power-constrained devices. But some tasks, such as training a neural net, still need precision. IBM recently revealed a prototype chip at the IEEE VLSI Symposia that does both equally well.



SHOW-OFF: IBM's prototype deep-learning chip relies on a new architecture and "scratch pad" memory systems.

IBM

The disconnect between the needs of training an artificial neural network and having that net execute its function, called inference, has been a challenge for those designing chips that accelerate artificial-intelligence functions. IBM's new AI accelerator chip is capable of what the company calls scaled precision. That is, it can do both training and inference at 32, 16, or even 1 or 2 bits.

"The most advanced precision that you can do for training is 16 bits, and the most advanced you can do for inference is 2 bits," explains Kailash Gopalakrishnan, who led the effort at IBM's research center in Yorktown Heights, N.Y. "This chip potentially covers the best of training known today and the best of inference known today."

The chip's ability to do all of this stems from two innovations aimed at keeping all the processor components fed with data and working.

"One of the challenges that you have with traditional [chip] architecture when it comes to deep learning is that the utilization is typically very low," says Gopalakrishnan. Even though a chip might be capable of a very high peak performance, only 20 to 30 percent of its resources can be brought to bear on a problem. IBM aimed for 90 percent, for all tasks, all the time.

Low utilization is usually due to bottlenecks in the flow of data around the chip. Gopalakrishnan's team came up with a data-flow system that speeds the movement of data from one processing engine to the next. It is customized according to whether it's handling learning or inference and for the different scales of precision.

The second innovation was the use of a specially designed "scratch pad" form of on-chip memory. Traditional cache memory found on a CPU or graphics processing unit obeys rules that make sense for general computing but cause delays in deep learning. For example, there are situations where a cache might push a chunk of data out to the computer's main memory. But if that data is needed as part of the neural network's inferencing or learning process, the system must wait for it to be retrieved.

A scratch pad keeps data flowing through the chip's processing engines, making sure the data is at the right spot at just the right time.

The resulting chip can perform all three of today's main flavors of deep-learning AI: convolutional neural networks (CNN), multilayer perceptrons (MLP), and long short-term memory (LSTM). Together these techniques dominate speech, vision, and natural-language processing. At 16-bit precision—typical for training—IBM's new chip cranks through 1.5 trillion floating-point operations per second; at 2-bit precision—best for inference—that leaps to 12 trillion operations per second.

Gopalakrishnan points out that because the chip is made using an advanced silicon CMOS manufacturing method (GlobalFoundries' 14-nanometer process), all those operations per second are packed into a pretty small area. That's important "because in a lot of applications you are cost constrained by size," he says.

IBM, of course, is one player in a crowd that seems to be getting bigger every day, as more and more startups appear and big firms continue to come out with new ideas. And despite some distinguishing characteristics, they all have a lot in common. "These solutions are created by the shape of the problem," says Dave Fick, chief technology officer of deep-learning-chip startup Mythic. So it makes sense that "everyone is converging on similar solutions." Mythic and other startups *IEEE Spectrum* spoke with target 2019 as the year when things will really pick up with customers.

There's no word on when IBM's new technology might be commercialized in Watson or another form, but Mukesh Khare, IBM's vice president of semiconductor research, says to expect it to evolve and improve. "This is the tip of the iceberg," he says. —SAMUEL K. MOORE

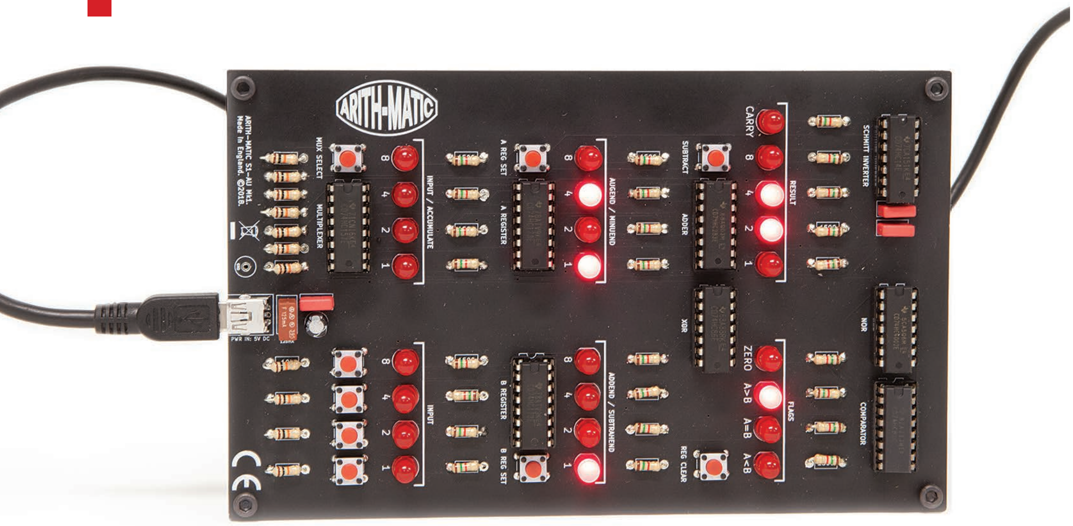
A version of this article appears in our Tech Talk blog.

POST YOUR COMMENTS at https://spectrum.ieee.org/smartchip0818

PHOTOGRAPH BY Giorgos Georgiou/Nur Photo/Getty Images

SLAVE TO TECHNOLOGY

PERFORMANCE ART often combines visual art and live action in an attempt to deliver a message by engaging several of the audience's senses. The creators of the *Inferno* robotic performance project, which appeared in May at the Athens Digital Arts Festival, sought to place the audience in a world where the Singularity and eventual human subordination to machines are the punishment for technological sins committed for the sake of progress. The artists pulled it off by deconstructing the basic elements of performance. At the start of each show, the "audience" members were outfitted with robotic exoskeletons, making them fully immersed in the world presented on the screens. These cyborg viewers were sometimes free to move but were frequently forced by the machines to assume submissive positions or otherwise react in a certain way.



FOUR-BIT ACTION: This handheld ALU has two internal registers to hold numbers for addition and subtraction. The result can also be fed back into a register to accumulate arithmetic results [below], and flags test for conditions such as a zero.

4-BIT WONDER

EXPLORE THE GUTS OF COMPUTING WITH ARITH-MATIC'S S1-AU KIT

I don't normally review Kickstarter projects that haven't reached the verified shipping stage. Even when they manage to hit their targets, too many times I've seen crowd-funded projects flame out for various reasons. Such causes might be a high-minded concept that pushes the available technology beyond feasibility, problems with the harsh realities of manufacturing, or occasional outright malfeasance, where money is taken for projects that exist only as vaporware.

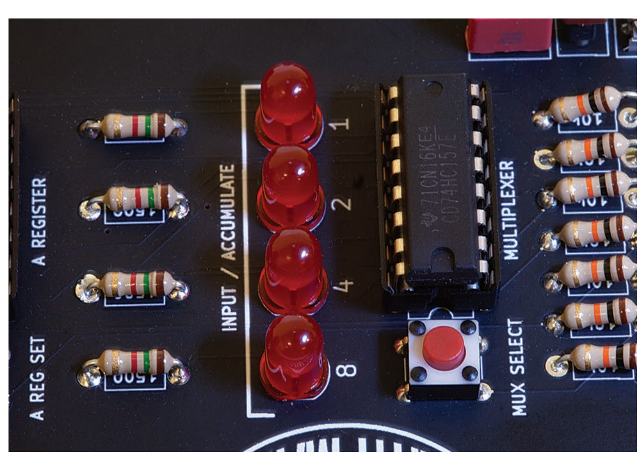
But I made an exception for Arith-Matic's S1-AU 4-bit arithmetic logic unit (ALU) kit. Since the 7400 series of integrated circuits upon which the kit is based has been around since the 1960s, I felt that the enabling tech fell safely into the category of "mature technology, low risk." And Arith-Matic was willing to send me a sample from a beta production run that was very real and fully functional.

I was attracted to the S1-AU because I like kits that expose important elements of electrical engineering normally hidden away in little black boxes. Such kits are the equivalents of the gleaming metal models of engines that mechanical engineers get to decorate their spaces with, and which are instructional and iconic in equal measure. In S1-AU's case what's being exposed is an essential part of every processor: the ALU, which does the real work of computation by performing mathematical operations on data.

We've gotten so used to CPUs as single-chip devices—where an entire processor core may be treated as just another plug-and-play component—that it's easy to forget that a CPU is made up of distinct subsystems. These include the ALU, registers to store working data, and the control unit, which decodes incoming machine code instructions. The S1-AU puts the user in the role of the control unit, sending data to the ALU and selecting what mathematical operation it should perform.

The S1-AU is of course very simple, capable of performing just two operations—addition and subtraction—on two 4-bit operands. But to be fair, that's not much less than the capability offered by the ALU in the 4004, the 4-bit CPU that launched the microprocessor revolution (the 4004's ALU was also capable of rotating the bits in a binary number left and right). In addition, the S1-AU allows you to accumulate results, so that you can repeatedly increment or decrement one operand by the other. The S1-AU also tests and sets several status flags, which can indicate if the result of an operation is zero, whether the two operands are equal, or which operand is greater than the other.

Building the S1-AU was a straightforward job of soldering components into a PCB that took about two and half hours. The kit has a few nice aesthetic touches: The PCB comes in a stylish black, and a second, blank PCB board is provided to mount below the functional PCB. This second PCB means you can hold the S1-AU in one hand as you play with it, without getting stabbed by the sharp protrud-



RANDI KLETT (2)

ing stubs of component leads. Arith-Matic even took care to supply all but one of the capacitors in rectangular casings, rather than the usual cylindrical or disk shapes, which gives the kit a neat, squared-off look. The whole thing is powered by a USB mini connection.

Playing with the S1-AU is great way to understand some quirks of machine code or assembly-level programming of processors. A key quirk relates to how branching is done on many processors. In higher-level language code, branching usually happens by performing some arithmetic operation, explicitly comparing the result to some test value, and then continuing to the next instruction or jumping to some other part of the program, depending on the result. In machine code, you can often set things up to take advantage of the fact that a typical ALU automatically tests the results of every arithmetic operation for certain properties, in particular whether or not the result is equal to zero. The true or false values of these tests are indicated by flag bits in a processor's status register, and these bits dictate the consequences of machine-code branch instructions.

So, for example, you might have a loop in which the value of a counter variable starts out as some positive integer and is decremented by one each time the computer goes through the loop. As long as the counter is greater than zero, the computer should branch back to the top of the loop. At the bottom of the loop, then, just after the computer subtracts one from the counter to decrement it, you can code a "branch if not zero" instruction. This will either send the program back to the top of the loop or direct it to carry on with the next instruction after the loop, with no separate comparison instruction required.

Understanding flag bits, and how they are silently updated as a side effect of ALU operations, is critical to learning how to program "on the metal." Another quirk of programming on the metal that the S1-AU can help clarify is the representation of negative numbers in binary. Generally, this is done using a bit of mathematical magic called "two's complement." Two's complement is great in that negative numbers are handled in the same way as positive numbers by the ALU's circuitry. Two's complement is also one of those things that I can review, understand, do a test exercise by hand—and then completely lose the thread of how it works by the end of the day, my understanding disappearing like water poured onto sand. The S1-AU is a great way to experiment with, and reinforce your understanding of, two's complement.

All in all, S1-AU is a lovely kit. It's functional enough to be educational and pretty enough to display. Unfortunately, just as this article was going to press, it missed its Kickstarter target. However, Arith-Matic emailed me to announce that it will make the kit available through a series of microrun releases instead, albeit at a higher price than what would have been possible through Kickstarter. **—STEPHEN CASS**

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/ALU0818

DEUS EX MACHINA

GABRIELE TROVATO ASKS IF A ROBOT CAN BE A SACRED OBJECT

Robots are on a trajectory toward becoming AI-enabled entities that we interact with socially and emotionally. It's not clear where this is going to end up—people frequently toss around the idea of robot companionship and even robot love. What hasn't been explored nearly as much is the idea of robots in a religious context. What if robots could do more than just assist someone in performing a religious task and actually become sacred objects themselves?

At the ACM/IEEE International Conference on Human-Robot Interaction this past March, Gabriele Trovato from Waseda University, in Tokyo (with colleagues from Pontificia Universidad Católica del Perú), presented a paper on whether divine robots might be possible, and why it could be useful to develop them in the first place. Contributing editor Evan Ackerman interviewed Trovato by email about this unusual study.

Evan Ackerman: What made you decide to do this research, and why is it important?

Gabriele Trovato: I previously specialized in cultural aspects of human-robot interaction, and I traveled across many countries to perform cross-cultural studies, finding out how robots should be customized in order to adapt to different countries. However, studies performed by researchers across the world usually neglect the impact of religion, which is a critical factor within cultures and something that people are very accustomed to.

E.A.: Can you describe what characteristics would make a robot divine?

G.T.: In order to define how a robot can look divine, we have to investigate how humanity represents the divine across religions. The answer is that across world religions there are divine humans, divine animals, divine objects. Therefore, a theomorphic robot is a robot that takes the appearance of an existing divine entity. This does not mean that any divine form should become a robot, but the idea certainly opens a new range of possibilities [to take an

A DIVINE DESIGN? This robot can pray with users and share scripture.

GABRIELE TROVATO/WASEDA UNIVERSITY

existing sacred object and enhance it with capabilities that robotics and AI can bring].

E.A.: What are some advantages of theomorphic robots?
G.T.: The biggest advantage is that believers can feel at ease with, and even hold in high regard, a robot that has the appearance and identity of a familiar religious entity or an icon. The sacred appearance can be seen as a mask—which covers the robotic component—for a device that will perform some service that can range from keeping [worshippers] company during prayer to even performing catechesis, teaching positive values of a certain religion.

E.A.: Do you think that religious people will accept the idea of theomorphic robots?
G.T.: Two main factors should be considered: appearance and content. [To appearance] I applied the concept of skeuomorphism, creating a new object that retains some design features inherent to another, already existing object [for example, making a book-reading app interface look like a wooden bookshelf]. In our case, it translates to hiding the robotic component. Regarding content, the development of a theomorphic robot should always be done with the collaboration of theologists and the support of religious authorities.

E.A.: Have you discussed your ideas with the religious establishment?
G.T.: I have discussed [these ideas] with several members of the clergy at the Vatican. Their reaction has been cautious: They are open to the idea of a Catholic robot and very interested in its development, but they also warn about the robot possessing an AI capable of giving advice to the believers, because that, including also the interpretation of the Bible, is a role that belongs to the Church.

E.A.: What are you working on next?
G.T.: So far, I have made a robotic Daruma (a talisman of good luck in Shinto and Buddhism) for elderly people, and SanTO, a robot specifically designed for practicing Catholics. I have plans of refining the current SanTO prototype with the purpose of making a product that can effectively become popular and be present in many Catholic homes. I am also planning to explore other religions such as Islam and Hinduism in the future, conscious that it will be an even tougher challenge.

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

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/sacred0818

ANOTHER THREE DOCUMENTARIES FOR ENGINEERS

BOMBSHELL, *GAMECHANGERS*, AND *SCIENCE FAIR* ALL MAKE FOR FASCINATING VIEWING

With summer in full swing, here are some more documentaries we think will make great vacation viewing: *Bombshell* and *GameChangers* are recently available for download. *Science Fair* is currently making the rounds of the international film festivals, so even if it's not coming to your neck of the woods, check to see if it's playing at your vacation destination!

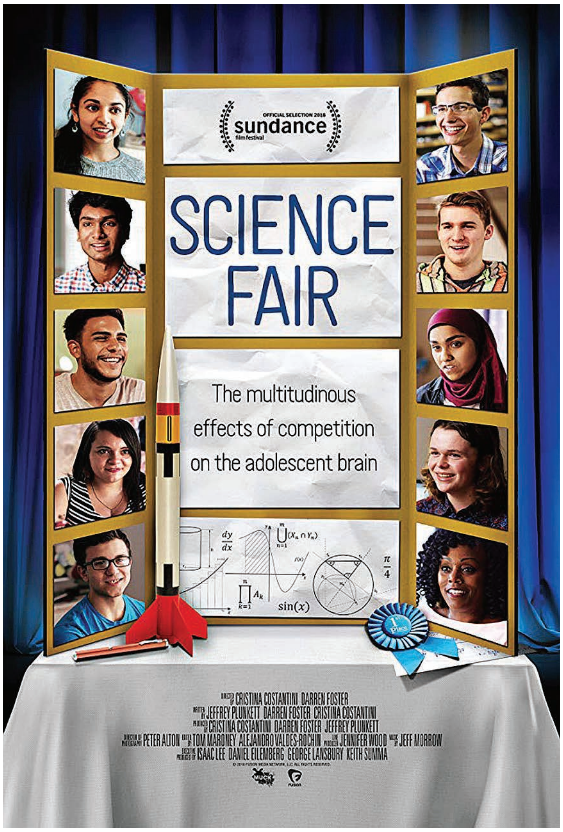
Bombshell: The Hedy Lamarr Story
Hedy Lamarr invented frequency hopping, one of the fundamental techniques that underpin modern telecommunications. Lamarr was also a huge Hollywood star in the 1940s, having fled her native Austria in the 1930s to escape a controlling husband who was a Fascist arms dealer. *Bombshell* introduces us to a complex woman who was frustrated by the simplistic ways in which she was perceived: as an avatar of glamour and beauty, as a trophy, and later in life, as an object of parody.

The idea of a young actress inventing such critical technology as frequency hopping, seemingly out of the blue, led some to downplay her role, suggesting that she had lifted the idea from someone at her first husband's munitions factory, or that George Antheil, the second name on the frequency-hopping patent, was the dominant contributor. But *Bombshell* shows how Lamarr had a long track record as an autodidactic inventor, and that her inspiration for frequency hopping likely came about from her fascination with a Philco remote control for her radio. Lamarr has become something of a tech icon in recent years, and this documentary demonstrates that it is for her brains, rather than her looks, that she is now revered.

BOMBSHELL: ZEITGEIST FILMS; SCIENCE FAIR: MUCK MEDIA


Hedy Lamarr

GameChangers



GAMECHANGERS: GAMECHANGERS FILM

GameChangers: Dreams of BlizzCon

Back in the early 1990s, people started regularly linking computers together in their homes to play fast-paced games such as *Doom*. The action soon spread to the Internet, and by the late 1990s professional video gaming leagues had emerged.

Nowhere has pro gaming, or eSports, been more fervently embraced than in South Korea. And perhaps no game is more strongly identified with eSports than *StarCraft II*, a real-time strategy game created by Blizzard Entertainment. The objective of *StarCraft* is to extract local resources to build powerful armies and then to use those armies to destroy the forces of opposing players. Over the course of a year, *GameChangers* follows the fortunes of two well-known Korean *StarCraft* pro gamers: MC (a.k.a. Jang Min Chul) and MMA (Mun Song Wan).

MC and MMA can see the end of their careers looming: They are in their mid-twenties, no longer possessing quite the blisteringly fast reactions or all-consuming mania for the game that teenage players have. The goal for MC and MMA is to win the annual BlizzCon tournament. A victory there would mean a large cash prize and the chance to retire as the world's best player.

Frustratingly, *GameChangers* provides little context for those not familiar with *StarCraft*. There's the briefest of discussions of how the game is actually played, and no interviews with any of Blizzard's designers or developers. There's also little eSport history, although the film does do a good job of explaining how South Korea's global dominance arose from its particular "PC bang" gaming café culture.

What *GameChangers* does do very well is convey the scale and intensity of modern pro gaming. If you want to understand why eSports are being considered for inclusion in the Olympics, this is the movie to watch.

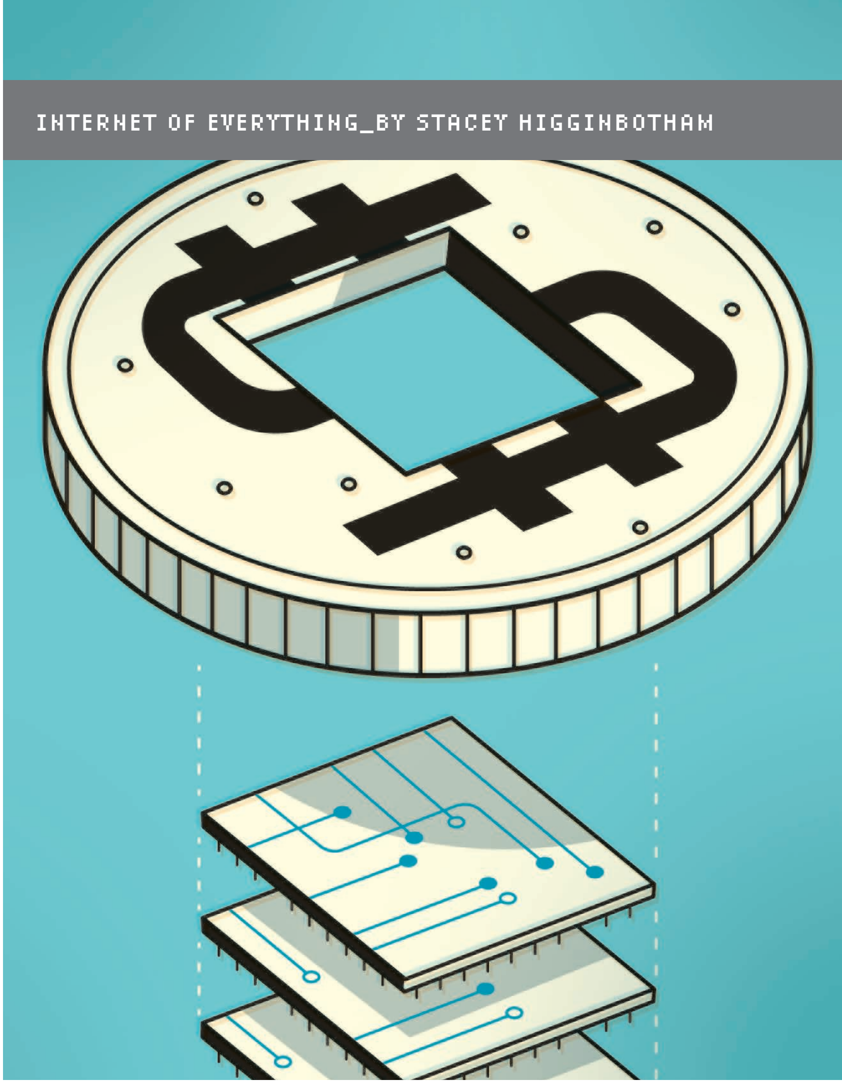
Science Fair

Science Fair

I got the chance to see this documentary at the SXSW Festival, slipping out from IEEE's official series of conference events. Judging by the laughter and occasional sniffle around me, I can say I was not alone in my emotional response. *Science Fair* follows a passel of high school students—mostly from the United States but also from Germany and Brazil—on their road to compete at the Intel International Science and Engineering Fair. These students come from many different backgrounds and income levels, but they are all smart, ambitious, and self-possessed. You can't help but like them all deeply, even when some typical teenage obnoxiousness surfaces. If you're ever worried about the future, here's a group of young people who will give you hope.

—STEPHEN CASS

↗ POST YOUR COMMENTS at https://spectrum.ieee.org/film0818



THE RISE OF RISC

IN THE PAST DECADE, many technologists have adopted the mantra that software is eating the world. However, all of that software has to run on something. And that something is silicon. ● Unfortunately, the chip world has hit a roadblock with the fade-out of Moore's Law. ● The challenge of building circuits that require years of research and development, combined with rapid advancements in software, is making it more difficult for silicon designers to predict the future. Given the multimillion-dollar stakes associated with new chip architectures, every investment is a big risk. ● Meanwhile, Apple, Facebook, Google, and Samsung have decided to build their own silicon instead of relying on Intel, Qualcomm, or others. Thus, investing hundreds of millions of dollars into a new chip architecture becomes even riskier, with less potential to win a major new customer. ● These shifts have produced a boom of interest in a chip architecture called RISC-V (pronounced "risk-five"), which was created eight years ago at the University of California, Berkeley. RISC-V is the fifth generation of the "reduced instruction set computer" type of architecture. Just like the instruction sets for the ARM, PowerPC, or *x*86 architectures, RISC-V defines how the computer operates at the most basic software level. ● But what's so compelling about RISC-V isn't the technology—it's the economics. The instruction set is open source. Anyone can download it and design a chip based on the architecture without paying a fee. If you wanted to do that with ARM, you'd have to pay its developer, Arm Holding, a few million dollars for a license. If you wanted to use *x*86, you're out of luck because Intel licenses its instruction set only to Advanced Micro Devices.

For manufacturers, the open-source approach could lower the risks associated with building custom chips. Already, Nvidia and Western Digital Corp. have decided to use RISC-V in their own internally developed silicon. Western Digital's chief technology officer has said that in 2019 or 2020, the company will unveil a new RISC-V processor for the more than 1 billion cores the storage firm ships each year. Likewise, Nvidia is using RISC-V for a governing microcontroller that it places on the board to manage its massively multicore graphics processors.

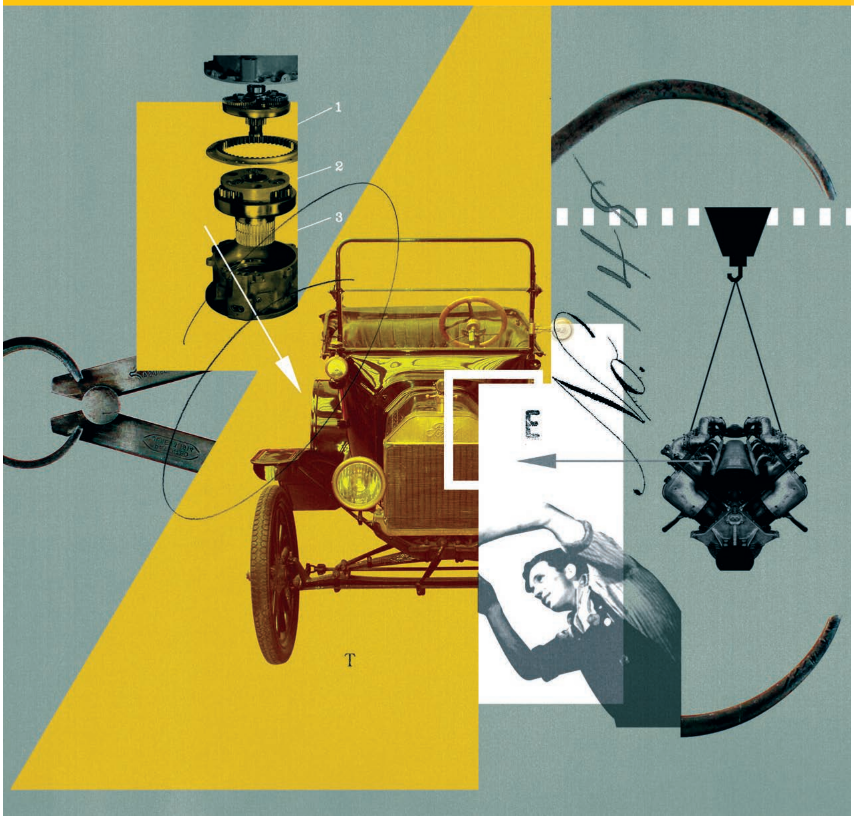
For years, giant tech firms have designed their own silicon to handle special jobs associated with their equipment. With RISC-V, a tech firm can now start with an instruction set and then invest in CPU architects and other engineers to build out and test chips without paying a huge up-front licensing fee.

For example, a startup in France called GreenWaves Technologies has built a dedicated chip for the Internet of Things. The company chose the RISC-V architecture because it wanted to avoid raising the crazy amounts of money typically needed for chip startups. GreenWaves CEO Loic Lietar said the company has raised €3.1 million (US $3.6 million) and has already managed to produce a sample of its silicon.

This technology lowers the cost of creating custom chips, which means more and more companies may elect to build their own. As for the existing players, I don't think RISC-V represents a bigger threat to Intel than does the slow fade of Moore's Law and former customers deciding to build their own dedicated silicon. And I don't think Arm will necessarily lose licensing fees to RISC-V right away—but the technology could bring on a wave of competitive silicon that hurts incumbents in the long run. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/riscv0818

ILLUSTRATION BY Harry Campbell



AUGUST 1908: FIRST FORD MODEL T COMPLETED

IN 1908, HENRY FORD HAD BEEN WORKING in the auto business for more than a decade, and the Ford Motor Co., five years old and already profitable, had so far followed its peers by catering to the well-to-do. Its Model K, introduced in 1906, was priced at around US $2,800, and the smaller Model N, introduced the same year, sold for $500—about what the average person earned in a year. ● Then, on 12 August 1908, the age of the automobile began, because on that day the first Ford Model T was assembled at Detroit's Piquette Avenue Plant. It went on sale on 1 October. ● Ford made his goals clear: "I will build a car for the great multitude. It will be large enough for the family, but small enough for the individual to run and care for. It will be constructed of the best materials… after the simplest designs that modern engineering can devise. But it will be so low in price that no man making a good salary will be unable to own one." He met those goals, thanks to his vision and to the talent he was able to recruit, notably the designers Childe Harold Wills, Joseph A. Galamb, Eugene Farkas, Henry Love, C. J. Smith, Gus Degner, and Peter E. Martin. ● The four-cylinder water-cooled engine put out 15 kilowatts (20 horsepower), the top speed was 72 kilometers per hour (45 miles per hour), and the price was low. Runabout, the most popular model, sold for $825 in 1909, but continuous design and manufacturing improvements let Ford lower the price to $260 by 1925. That represented about two and a half months' wages for the average worker at the time. Today, the average new-car price in the United States is $34,000, or about 10 months' median salary.

The first key step on the car's road to market dominance was the introduction of a moving assembly line in the Highland Park factory in 1913. This brought substantial economies of scale: Already by 1914 the plant was turning out 1,000 automobiles a day. The second step was Ford's decision to pay unprecedented wages for unskilled assembly labor. In 1914 the rate was more than doubled to $5 an hour, and the working day was reduced to 8 hours.

The outcome was impressive. Ford Motor Co. produced 15 percent of all U.S. cars in 1908, 48 percent in 1914, and 57 percent in 1923. By May 1927, when the production run ended, the company had sold 15 million Model Ts.

Ford stood at the very beginning of manufacturing globalization, using standardized procedures and dispersing car assembly around the world. Foreign assembly began in Canada and then fanned out to the United Kingdom, Germany, France, Spain, Belgium, and Norway, as well as to Mexico, Brazil, and Japan.

But even though Ford staked much on this one car, it didn't quite become the best-selling vehicle in history. That primacy belongs to the "people's car" of Germany—Volkswagen. Soon after he came to power, Adolf Hitler decreed its specifications, insisted on its distinct beetlelike appearance, and ordered Ferdinand Porsche to design it.

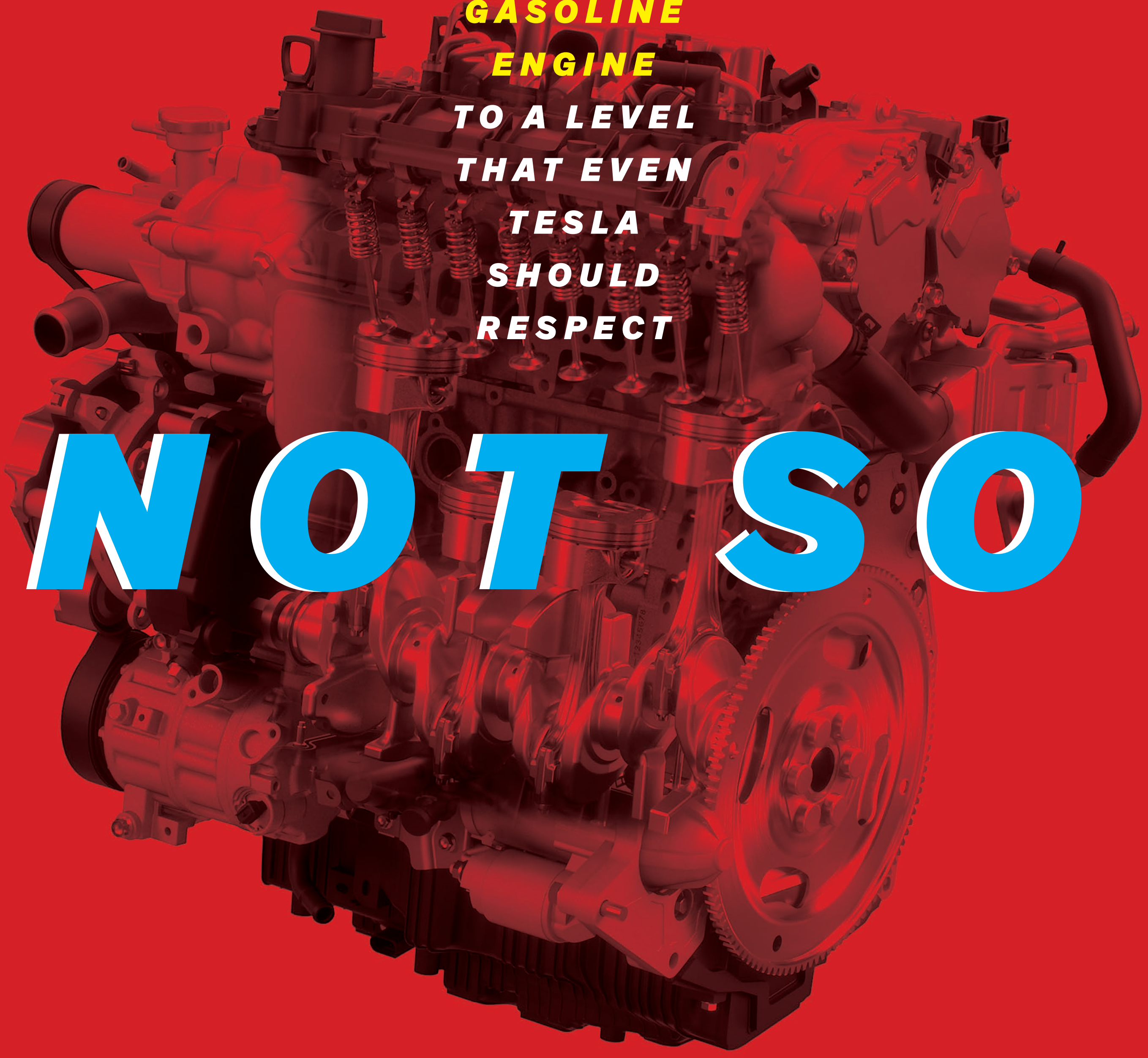
By the time it was ready for production, in 1938, Hitler had other plans, and the car's assembly didn't begin until 1945, in the British-occupied zone. German production ended in 1977, but the original VW Beetle continued to be assembled in Brazil until 1996 and in Mexico until 2003. The last car, made in Puebla, was number 21,529,464.

But in many ways the Beetle was just an updated emulation of the Model T. There can never be any dispute over who got there first. ■

↗ **POST YOUR COMMENTS** at https://spectrum.ieee.org/firstmodelt0818

PHOTO-ILLUSTRATION BY Stuart Bradford

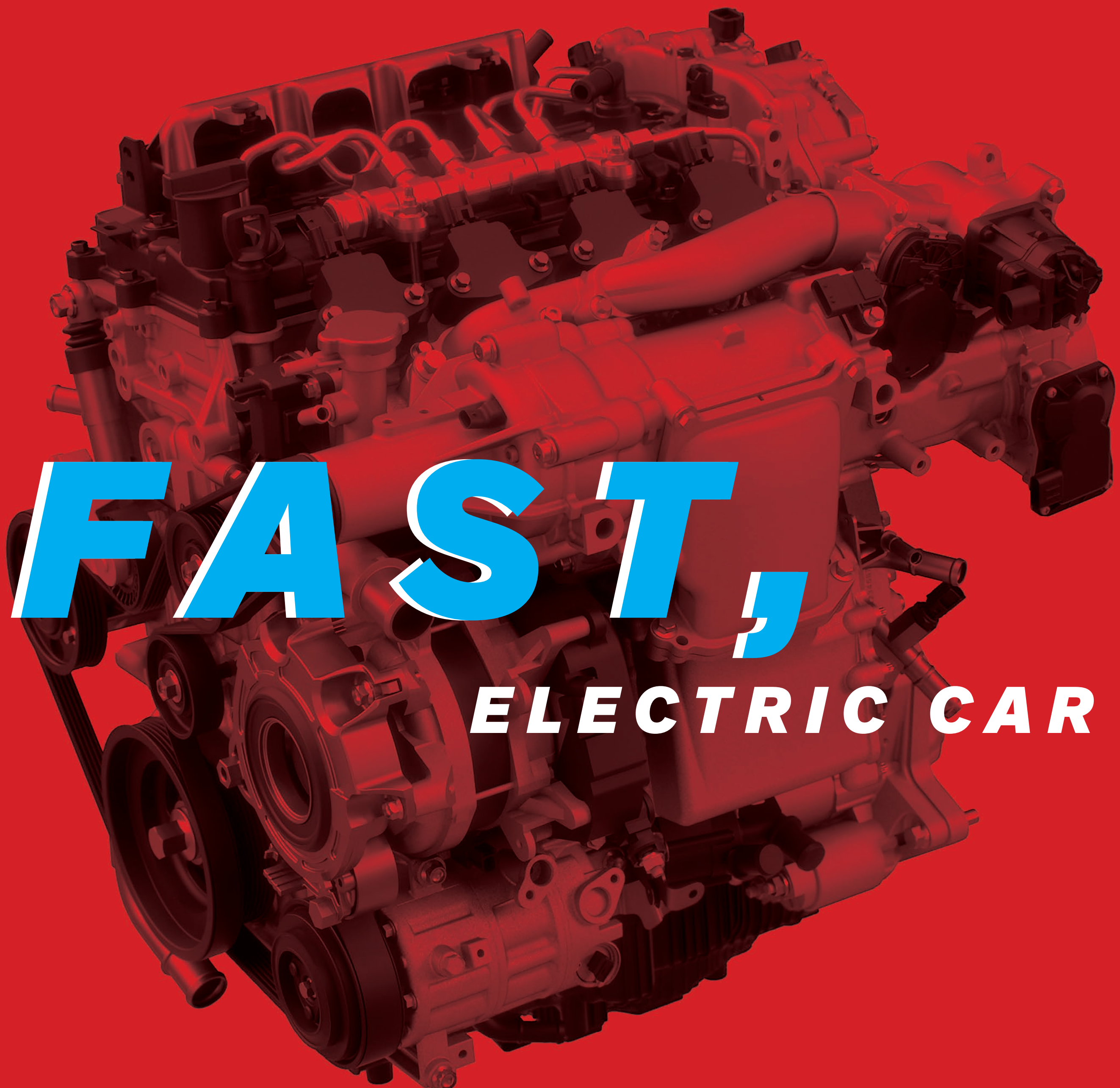
MAZDA HAS IMPROVED THE GASOLINE ENGINE TO A LEVEL THAT EVEN TESLA SHOULD RESPECT



NOT SO

BY DAN CARNEY

FAST, ELECTRIC CAR



TAKE A SPIN: Mazda's new Skyactiv-X gasoline engine [shown here from two angles] borrows a trick from the diesel engine: It uses a spark plug to control a compression-based ignition system.

THERE ARE LOTS OF REASONS why we're not all driving electric vehicles now. You've probably thought of two or three already, but let me add one that I'm sure you haven't. It's a big obstacle to EVs, and it's rarely remarked upon.

It's the internal combustion engine, which is no sitting duck. It's a moving target, and a fast-moving one at that.

There's no better example of this agile, relentless progress than Mazda's Spark Controlled Compression Ignition (SPCCI) system, which is scheduled to reach the car-buying public in the form of a new combustion engine in late 2019. Mazda borrowed a trick from the diesel engine, which compresses a fuel-air mixture to the point of ignition rather than igniting it with a spark plug, as gasoline engines do. It's the biggest advance in combustion engines since electronic fuel injection, which started proliferating in the 1970s.

The new engine operates under some conditions with compression ignition, like a diesel engine, and at other times with spark ignition, like a standard gasoline engine. It will sell under the name Skyactiv-X, building on Mazda's current engine design, known as Skyactiv-G (*G* is for gasoline). "We've dubbed it Skyactiv-X because it is kind of the intersection of gasoline and diesel technologies," said Mazda power-train engineer Jay Chen, in a press briefing.

Mazda claims that the 2.0-liter four-cylinder Skyactiv-X provides from 10 to 30 percent more torque and from 20 to 30 percent better fuel efficiency than the Skyactiv-G. So, using the 2.0-L Skyactiv-G as the reference, figure on torque somewhere between 224 and 264 newton meters (165 to 195 foot-pounds) for the Skyactiv-X. If you put it in the Mazda3, a compact car, and assume it has only a minimal hybrid-electric design, then its fuel economy should come to between 6.36 and 5.88 liters per 100 kilometers (37 and 40 miles per gallon). Mazda has not yet announced which model will debut Skyactiv-X.

True, an all-electric car posts better numbers. The U.S. Environmental Protection Agency gives the Chevrolet Bolt EV the e-car equivalent of 119 mpg (1.98 L/100 km). On the other hand, the Bolt will go just 383 km (238 miles) on a charge, while the Mazda3, using today's Skyactiv-G engine, can manage 785 km (488 miles) on a tank of gas.

"The biggest thing I believe Skyactiv-X does is demonstrate that the internal combustion engine is not dead and that EVs are not a shoo-in," says George Peterson, president of industry consultancy AutoPacific. "There's a lot of life left in internal combustion power trains until cost and range issues with EVs are solved."

TO UNDERSTAND HOW SPCCI WORKS, start with the fundamentals of ignition in the three kinds of combustion engine–the diesel engine, the standard gasoline engine, and the immediate forerunner to the SPCCI, called the homogeneous charge compression ignition (HCCI) engine.

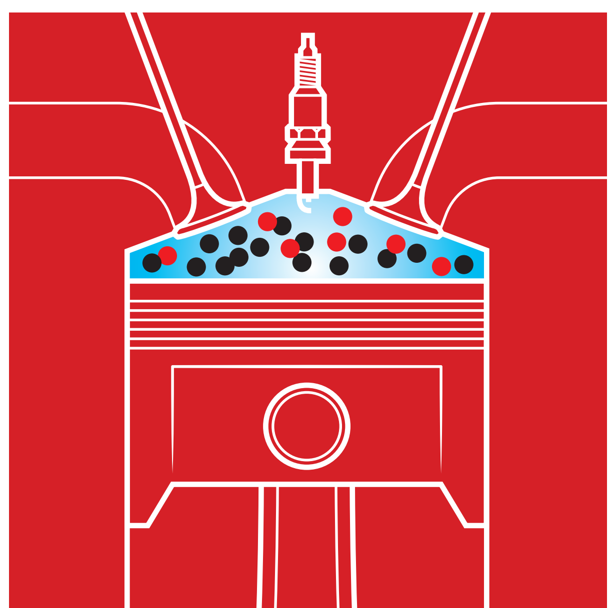
In ideal combustion, each hydrocarbon molecule is paired with an oxygen molecule, producing water and carbon dioxide. The molecules are present in the chemically correct ratio that engineers describe as lambda 1. In a lean fuel condition, when there's more oxygen, lambda is greater than 1. That's good when the goal is to reduce fuel consumption. And, because such lean combustion mixtures burn cooler than those at lambda 1, they produce less nitrogen oxide pollution.

However, it's not always easy to get that lean mixture to burn. "The less and less fuel you have in a mixture, the harder and harder it gets to ignite," Chen explains. "Just like lighting your barbecue without enough lighter fluid."

The solution, employed in both HCCI and SPCCI engines, is to keep compressing the air-fuel mixture until it is so hot and under so much pressure that it detonates spon-

PREVIOUS PAGES: MAZDA

BLOW UP—NOW!



LEAN UNDER PRESSURE

The SPCCI engine is designed to compress the fuel-air mixture to almost, but not quite, the threshold of ignition. This goal is accomplished, in part, by keeping the fuel-to-air ratio lean.

ILLUSTRATIONS BY James Provost

taneously. Diesel engines also use such compression ignition, but they first compress pure air into the combustion chamber, then inject the diesel fuel. Only then does the fuel burst into flame.

This sequence is important because the fire starts at the spot where the fuel is injected and spreads to the rest of the combustion chamber. High temperatures in this expanding flame front cause diesel's characteristic emission of soot particles and nitrogen oxides.

In HCCI combustion, air and fuel mix together in the cylinder during the compression stroke and spread homogeneously throughout the combustion chamber, as they would in a direct-injected gasoline engine. Only after that spreading and mixing are they compressed to the point of autoignition, as in a diesel engine.

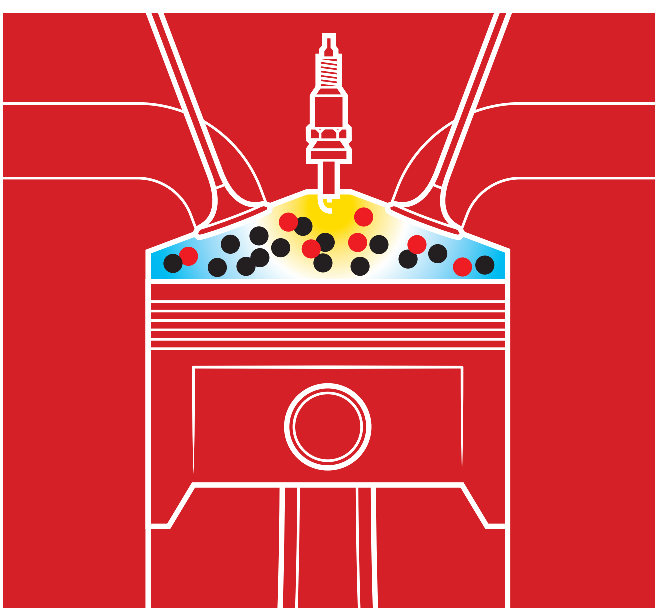
So, in a traditional gasoline engine, combustion begins at the spark plug; in a diesel, it begins at the fuel injector; and in an HCCI engine it happens in all parts of the combustion chamber at once. That makes for an intense explosive reaction, one that puts more downward force on the piston during the engine's power stroke than the other two engine types do. Gasoline and diesel engines both must light the fuel while the piston is still moving upward on the compression stroke, achieving peak cylinder pressure while the piston is close to the top of its stroke.

"That means the piston is still moving up, already building pressure," says Chen. "The piston has to fight against the current, if you will, of the pressure."

"If we did compression ignition, it happens over such a short period of time, we can actually target the peak of the pressure right after top dead center of the piston," Chen continues, using the industry term for the point when the volume of the cylinder is at an absolute minimum. That way, "all the energy is released immediately, and bam!—the piston just pushes down with the greatest amount of force. For the same amount of fuel, we can get a much higher pressure out of our combustion process through compression ignition than we can through traditional spark ignition."

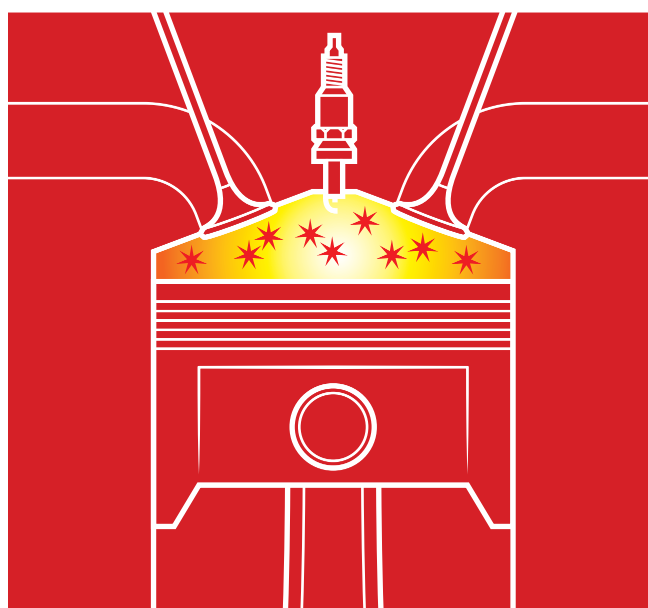
To make it work, HCCI engines need to run at a very high compression ratio, just as diesel engines do. According to Sandia National Laboratories, one of the few outside sources that gives numbers, HCCI engines typically run at compression ratios as high as 14:1. Conventional turbocharged gasoline engines commonly run at around 10:1, while diesels, such as

A tiny, local fire raises the pressure, making the fuel-air mixture detonate all at once.



LIGHT THE FIRE

The spark plug ignites a merely local fire. The expanding gas raises the pressure throughout the entire combustion chamber, finally pushing it beyond the threshold of ignition.



CONTROLLED EXPLOSION

Now that the fuel-air mixture is under ignition pressure at every point, the entire charge blows up all at once, without a propagating wave front. Result: an efficient combustion that produces very little noxious exhaust.

the familiar Cummins 5.9-L turbo diesel installed in Ram pickups, run at 17.2:1.

However, HCCI engines can't always time that spontaneous explosion so that it happens just after the piston passes top dead center in its stroke and begins moving downward on its power stroke. They simply can't be designed to exert such precise control, because they're harnessing highly exothermic chemical reactions that behave chaotically, in a fast-changing environment.

As Chen puts it, "Whenever the air and the fuel inside the cylinder reaches a critical temperature and pressure, it's just going to go boom."

THE BEATING HEART: This Mazda prototype incorporates a Skyactiv-X engine within the body of a Mazda3, but the only way you'd know it is by the high fuel economy and the low tailpipe emissions.

MAZDA

* * *

BECAUSE HCCI combustion is possible under only the right conditions of load and engine speed, HCCI engines need spark plugs to let them run in conventional, spark-ignition mode as well. And here is where the challenges begin. In an HCCI engine, compression ignition is spontaneous, so it is difficult to know exactly when the cylinder's air and fuel mixture will ignite. If that rapid, forceful combustion that we prize so much during the power stroke occurs too early, while the piston is still rising for the compression stroke, catastrophic engine damage could occur. But variations in engine load, throttle position, and temperature make it difficult to rule out such premature ignition if some combination of those factors suddenly creates a compression ratio high enough for compression ignition.

Mazda finesses the problem by having the engine initially give just a very small squirt of fuel. That trick ensures that the mixture is so lean, regardless of conditions, that it will never preignite. "Then, during the compression stroke, we give a larger injection of fuel, under higher pressures. That atomizes, but it doesn't have the same amount of time to heat up. In that way, it doesn't have enough time to reach the autoignition temperature threshold," explains Chen.

How, then, to get this lean mixture to light at the most opportune moment in the cycle? Mazda's creative solution to this problem is to build its SPCCI engines with a compression ratio of about 16:1—just below the threshold for compression ignition in this engine.

The earlier, HCCI engines needed a spark plug for conventional operation when the temperature, engine load, throttle position, and rpms were unsuitable for compression ignition. But Mazda's engineers realized that by manipulating conditions within the compression chamber, they could use that spark plug to ignite a local fire within the chamber. The expanding flame front increases pressure throughout the combustion chamber, effectively raising the compression ratio high enough to trigger ignition in all parts of the chamber at once.

That left the lighter-fluid problem: How do you light that compression-enhancing fireball in a fuel mixture that's too lean to catch fire? Mazda's solution is to create a region near the spark plug that's just a bit too lean to catch fire by compression alone. The spark can then set off a fireball whose expansion will boost pressure throughout the cylinder and cause compression ignition. In other words, the spark doesn't so much light the fire as help the fire to light itself.

Creating such a local less-lean zone isn't easy. "We can't just put fuel in and make it slightly less lean, because it will just mix with [everything else in the chamber]," Chen notes. "In order to cordon off this region of slightly less lean, and very lean outside of that, we introduce cylinder swirl."

Just as baristas create artistic images in espresso foam, it is possible to induce the air-fuel mixture inside the cylinder to swirl in a very carefully designed pattern. But rather than drawing a whimsical heart shape, Mazda engineers induce the flowing air to swirl like a hurricane, with a placid eye centered on the spark plug.

"We create this swirl inside the cylinder through our port design in the cylinder head and also because we have a lean supercharger that helps deliver a high amount of flow," Chen says. "The more flow, or the harder it is blowing, the more turbulence and vortex we have." It is into this walled-off vortex that the Skyactiv-X engine injects a little extra fuel, just enough extra to let the spark plug set off the fireball that triggers the cylinder-wide spontaneous compression ignition at the correct instant.

Other carmakers that have pursued HCCI engines—notably General Motors and Mercedes-Benz—have had some problems in smoothly switching the engine from HCCI mode to conventional spark-ignition mode. Basically, the vehicle would lose some power for about a second as the transition took place. This hiccup was quite noticeable if some combination of driving conditions meant the engine was switching back and forth between modes frequently.

General Motors insists the problems were mere teething pains. "As we showed with the public demonstration of the GM HCCI development vehicles in 2007-2008, drivability and mode transitions are not a major barrier to commercial implementation," says Paul Najt, GM engine systems group manager. In his view, the main challenge for commercialization is in economically combining HCCI with other technologies, like the selective deactivation of cylinders, to achieve even greater fuel economies.

Mazda's Chen explains that SPCCI doesn't have any problem switching from HCCI to conventional spark ignition because it doesn't turn the spark plug on and off. It simply adjusts how its spark is used–to ignite the fuel mixture or to pump up the pressure so that the mixture ignites itself.

"Because we are running the spark plug all the time, in both compression-ignition mode and spark-ignition mode, we can drastically expand the range of compression ignition throughout most engine rpm and engine loads," Chen says. "Only at very high engine speeds do we switch back to a spark-ignition mode."

This is where SPCCI differs from HCCI. "In a traditional HCCI engine, every time it switches modes, there's a momentary pause," Chen says. "And that pause causes a stumble in drivability. So every time you step on the gas, you might get one stumble, then another stumble as it transitions modes. And you have this drivability problem, which is why a traditional HCCI engine never made it to the market. It was good in the labs, it was good maybe as a concept, but customers wouldn't accept it."

For the SPCCI, Mazda managed to overcome these problems by equipping its engines with fast electronic valve-timing actuators. Mazda also adds sensors that directly measure combustion pressures in each cylinder every time it fires. This high-speed monitoring lets the engine-management computer make adjustments on the next-to-fire cylinder stroke to ensure that it is running optimally.

Overcoming the drivability problems of earlier incarnations of HCCI may have been the most crucial accomplishment to making SPCCI feasible for production. But Chen says he is most proud of the fact that Mazda was able to advance the state of the art in combustion technology while relying almost entirely on existing, off-the-shelf parts.

✶ ✶ ✶

MAZDA IS ON THE SMALL END of car companies. Its sales of about 1.56 million cars a year is dwarfed by Toyota's 10 million. So Mazda may seem an unlikely candidate to advance the state of the art in internal combustion. But the company has a history of doing exactly this sort of thing. In the 1970s it became the first (and still only) manufacturer to put the Wankel rotary engine into mass production. In the 1990s, it developed supercharged Miller cycle engines, which are relevant to the Skyactiv-X because each engine design employs an engine-driven supercharger to pump a high volume of air into the cylinder. Typical performance-oriented supercharged engines, such as the 527-kilowatt (707-horsepower) Dodge Challenger Hellcat Hemi V8, use the compressor to pack air into the cylinders and so to boost power output.

This air-supply scheme employs an intercooler to help cool the intake charge, just as conventional superchargers do. Much of the incoming air is recirculated exhaust gas. Cooling the air raises its density, which puts that much more oxygen in the combustion chamber.

Skyactiv-X also features a hallmark of economy-focused engines, a hybrid-electric assist motor. The engine is incorporated within a "mild" hybrid power train, which means the electric motor can't propel the car on its own. A belt from the engine drives the car's rather small alternator, which is smaller than a "strong" hybrid's alternator but a bit larger than what you'd find in a conventional car with an ordinary 12-volt battery. In the Mazda, the alternator allows the car to recover a bit of energy during deceleration, store it in the battery and later use it to seamlessly stop and restart the gasoline engine. (Cold starts are performed by a regular starter motor.)

✶ ✶ ✶

THE SAME ADVANCES in digital technology that are boosting the fortunes of EVs are also extending the life span of combustion engines. True, the basic moving parts, such as pistons, crankshafts, and valves, remain largely unchanged, but everything else about the process of capturing energy from burning gasoline is in flux.

Computers are providing modeling and analysis that lend insight into combustion that never existed previously. Indeed, MIT's Green Research Group has developed a combustion model that can run on PCs. The MIT Engine Simulator (MITES) follows 4,000 chemical reactions that can take place in combustion; this analysis enables it to characterize the operating range of HCCI engines. Other engine-development tricks include using engines with clear quartz cylinders fitted with laser sensors that peer into the fiery cauldron. Of course, carmakers like Mazda have enough computing resources to model complex combustion events before building a test engine, but having a modeling tool that runs on a PC can give others the ability to look into this developing area at much lower cost.

"HCCI engines are more sensitive to the details of the combustion chemistry than [spark-ignition] and diesel engines," note the MITES developers in a paper describing their tool. "Hence, without a solid understanding of the physical and chemical processes taking place in HCCI engines, it is difficult to develop practical, efficient, and robust engines."

Other than the cylinder-pressure sensors, all of the Skyactiv-X's components are substantially the same as those in today's engines "We did it without reinventing the engine, hardware-wise," Chen says. "Everything in the engine is a component that existed somewhere on the market before Skyactiv-X."

That continuity with the past explains a bit of the magic that Mazda has invoked. Internal combustion is no desiccated relic of the past but a living, developing technology. As the heir to untold investments and ingenuity, the gasoline power plant continues to fend off challenges from electric propulsion. It will be in a lot of cars for the next generation of motorists. And for the one after that, too. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/mazda0818

WITH ELECTRIC PROPULSION AND LOTS OF PROPELLERS, PLANES CAN

Reinventing

the Wing

USE SMALLER WINGS TO FLY EFFICIENTLY

BY ALEX STOLL

I REMEMBER DISTINCTLY THE COOL DECEMBER DAY IN 2013 AT my company's headquarters in the Santa Cruz mountains when we met with researchers from NASA to plan tests for a novel propeller configuration for electric aircraft. Somehow, our Joby Aviation team, the NASA researchers, and colleagues from another small California business brainstormed our way into a much more ambitious program than any of us had expected when the meeting began.

Instead of building and testing a scale model, we decided to construct a full-scale wing–one large enough to lift a four-passenger aircraft. And it would have not two or four, but a dozen or more separate motors and propellers arrayed along the leading edge. We could have tested a smaller wing by mounting it on a pickup truck. A full-scale wing would require something a lot more elaborate. And the project would need to be completed in less than a year, on a budget small enough to make most companies turn tail. But we were committed.

Our novel configuration was based on an old concept: The idea–known as a "blown wing"–was to propel air at high speed over the wing using many motors and propellers mounted along the leading edge. Usually, the speed of this airflow is about the same as the speed the aircraft is moving; that's why airplanes need to pick up speed before they can take off. But with many propellers blowing air over it at high speed, the wing behaves as though it's traveling faster than it actually is, providing greater lift.

That's a key advantage, because with greater lift, you can use a smaller wing, one that would otherwise require inordinately long runways so that the plane could take off and land at high speed. The situation is different in flight, when the plane is traveling fast and only a small wing is needed to provide the requisite lift. During that phase of flight, a larger wing is a disadvantage, because drag forces act over the whole area of the wing, reducing efficiency.

So what's an airplane designer to choose: a big wing or a small one? Takeoff and landing considerations usually rule the day, so aircraft end up with wings that are too large for efficient cruising. A larger wing also means that the aircraft will be tossed around more when it encounters turbulence.

PREVIOUS PAGES: CURT MASON/PROJECT HABU; ABOVE: TOM TSCHIDA/NASA

WINGING IT: NASA engineers Sean Clarke [top left], Kurt Papathakis [top right], and Anthony Cash [foreground] prepare the experimental LEAPTech wing for ground-based tests.

With many propellers blowing air over it at high speed, the wing behaves as though it's traveling faster than it actually is, providing greater lift

The blown wing provides a solution to this conundrum. During takeoff and landing, air can be blown over the wing at higher speeds, providing additional lift without sacrificing cruise performance. Although a few aircraft have been developed in the past with blown wings, the use of combustion engines for propulsion limited how far their designers could go. They had to use relatively few, large propellers, which aren't well suited to pushing air at high speed.

It would be more effective to distribute a large number of small propellers across the span of the wing, but for most of aviation history, that arrangement has been impractical.

The problem is that the efficiency and specific power (the ratio of power output to weight) of combustion engines plummet as they're scaled down. So using a large number of smaller engines results in a less efficient and heavier aircraft.

What's more, combustion engines are complex beasts. So placing a large number of them on the wing would create a maintenance nightmare. True, a series of propellers could instead be driven by a system of driveshafts and gearboxes connected to a single engine or perhaps a small number of them. But that approach, too, would create additional maintenance concerns and force various design compromises, as the French firm Breguet Aviation discovered in the 1960s with its short-lived 941 model, which used a blown wing.

What has changed the picture, of course, are recent advances in electric propulsion. Electric motors don't give up much efficiency or specific power as they're scaled down. And they're extremely simple—often having just one moving part—so they require very little maintenance. As a result, there is little disadvantage to using a large number of small electric motors, which can be placed at locations on the aircraft where a combustion engine would be impractically bulky or heavy, such as near the wingtips.

Although electric motors can be driven by a combustion-powered generator, the benefits are even greater if the aircraft is battery powered. Indeed, battery-electric propulsion is about three times as efficient as a typical combustion-engine power train. It's also a lot quieter. And because electricity costs much less than aviation fuel, this two-pronged attack—adding a more efficient power train, plus a more efficient airframe due to the smaller wing—promises to slash operating costs, especially considering the reduced need for maintenance.

So why aren't all aircraft battery powered? Because, of course, batteries aren't yet up to the task. Even today's best are very heavy for their energy content, which severely limits the range of electric aircraft. And they are sometimes prone to catching fire, which some commentators speculate may have been the cause of a fatal crash of an electric airplane in Hungary this past May. But battery technology will no doubt improve with time. So NASA, Joby Aviation, and many other companies are busy exploring various strategies for designing electric aircraft. And reviving the blown wing is one of them.

FIVE YEARS AGO, engineers at NASA started to think about using a large number of electric motors to create a blown wing, later naming the project LEAPTech, for Leading Edge

Asynchronous Propeller Technology. (The "Asynchronous" part of that moniker refers to the possibility that the propellers would not necessarily all be spinning at the same speed.)

Joby Aviation, a startup formed in 2009 to develop personal electric aircraft, had already been collaborating with NASA. When my Joby colleagues and I learned about LEAPTech, we jumped at a chance to get involved. Rounding out the LEAPTech collaboration was Empirical Systems Aerospace (ESAero), another small business that had worked with NASA to investigate how electric propulsion can improve aircraft performance.

NASA hoped to vet the idea with an actual test of a wing and propellers, in part because the relevant aerodynamic effects are very complex, and so computational fluid dynamics, or CFD, simulations of them would perhaps not be completely trustworthy. Another concern was that this distributed propulsion system might turn out to be too complicated to operate reliably in a real-world environment.

The test NASA was envisioning would show whether a smaller-than-normal wing with electrically powered leading-edge propellers could produce enough lift to allow a four-passenger airplane to take off at a reasonable speed. Typically, such a test would be done in a wind tunnel. But leasing such a wind tunnel would have exceeded NASA's small budget for the project. Besides, the waiting lists for appropriately sized wind tunnels were just too long.

So we decided that we would test a prototype LEAPTech wing by mounting it on a truck and driving at a high enough speed to analyze takeoff and landing performance. Such a test is not without precedent. Perhaps most famously, Scaled Composites performed a similar test of the tail of its SpaceShipOne space plane, a method its engineers jokingly also dubbed CFD—for Creative Ford Driving. And Joby had been conducting similar testing for years, with a Ford F-150 Lightning pickup.

Shortly after the fateful 2013 meeting when we decided to build and test a full-scale LEAPTech wing, we divvied up the labor. Joby would work with NASA on the design, also building the wing, motors, and propellers, and it would modify a suitable truck for testing. ESAero would do the wiring, configure the needed instrumentation, and troubleshoot the test setup.

NASA's initial design sketches featured a wing with 10 leading-edge propellers for takeoff and landing, plus two separate propellers mounted on each wingtip to power the aircraft after takeoff. Putting propellers on the wingtips—where they can reduce drag by counteracting the wingtip vortices—is another old idea that would rarely be practical without electric propulsion. Combustion engines are just too large and heavy to build into a wingtip, and using driveshafts and gearboxes in a wing to turn propellers at the tips creates engineering headaches, just as it does for leading-edge propellers.

After a few months analyzing the problem, we arrived at a design for a wing with a span of about 9 meters and an area of about 5 square meters. It would have a series of 18 propellers, each about a half meter in diameter, distributed along the length of the wing. Altogether, the 18 motors offered some 225 kilowatts, or 300 horsepower.

Although this wing would be used only for ground tests, we designed it with a particular application in mind: an experimental aircraft based on the Tecnam P2006T four-seat twin-engine propeller aircraft. We chose the P2006T because it was a good size, because it had wing-mounted engines (meaning replacing them with electric motors would be straightforward), and because the management at Tecnam was excited about the project.

The experimental aircraft we envisioned would weigh about 1,400 kilograms and take off at a speed of 61 knots (113 kilometers per hour) while cruising at 174 knots (322 km/h). Only the wingtip propellers would be used after the aircraft was up and away. And the leading-edge propellers would be needed just during takeoff and landing. We therefore designed the latter so that their blades could fold flush against their nacelles during the remainder of the flight, making them similar to the folding propellers used in some modern motor gliders. But because our testing would be limited to measuring takeoff and landing performance, the test wing would include neither the wingtip propellers nor the folding mechanism.

These specifications make our design comparable to that of four-seat propeller planes, but with a much smaller wing. Indeed, our wing would be only about a third the size of those on conventional aircraft. On paper, anyway, it would still provide enough lift for normal-speed landings and takeoffs. Our charge was to prove that this surmise matched reality.

For that, we purchased a Peterbilt truck—the kind of thing you might see barreling down the highway with a trailer in tow. On it we constructed supports to mount the wing high enough to minimize the aerodynamic effects of the ground below. To reduce vibration, we attached the wing to the truck using four beefy airbags. The giant winged truck looked distinctly odd, but it was exactly what this job required.

After the design and construction work was complete, we began our tests on the dry lake bed at NASA's premier flight-testing facility, the Neil A. Armstrong Flight Research Center, at Edwards Air Force Base in California's Mojave Desert. Tom Wolfe's 1974 book *The Right Stuff* and the 1983 movie of the same name made this locale famous. It's where Chuck Yeager first broke the sound barrier in 1947, and it was the original landing site for the space shuttle.

We were using carefully groomed sections of the lake bed that are maintained as backup runways for the flight test programs currently under way at Edwards. Although it would never leave the ground, we had to treat our unconventional test platform like an aircraft and take all the same precautions to minimize the chance that we'd harm the lake bed or leave behind debris that could later damage an aircraft making an emergency landing there.

Once we had all the batteries and power cables secured and our instrumentation system logging data, we began our tests, which entailed driving the truck at speeds up to about

130 km/h (80 mph) with the wing canted at different angles and with the propellers set to spin at various speeds. A wind tunnel would have offered carefully controlled conditions, whereas we had to estimate our airspeed based on the ground speed of the test vehicle and the wind speed as measured by several weather stations we had placed around the dry lake. To minimize errors and variations, we began at daybreak when the winds were calmest. We also had to find days when other aircraft were not likely to need our runway for an emergency landing, which meant a lot of waiting while NASA tested its X-56A drone and the Air Force tested the Lockheed Martin F-35 Lightning II fighter.

After two months in the desert, we had collected enough data to fully check our computer simulations. We were happy to see the expected performance boost. Indeed, the tests indicated that our predictions for the lift force that could be generated were somewhat conservative. Our electrically blown wing indeed worked!

Based on those encouraging results, NASA decided to further explore the blown-wing concept with a new experimental aircraft, one based on the same aircraft we'd investigated during the LEAPTech project, the Tecnam P2006T. It would be dubbed the X-57 Maxwell, the first piloted NASA X-Plane in more than a decade.

For the X-57, we modified the design in various ways. For one, the X-57 will be using a slightly larger wing. That change would provide enough interior volume for installing the wiring. But a more significant motivation was to improve "loiter" performance: Although the energy required to travel a given distance increases with a larger wing, the energy required to stay in the air for a given amount of time actually goes down. This is important when, for example, the aircraft must circle an airport while waiting for the weather to improve to land.

We also decided to reduce the number of leading-edge propellers from 18 to 12, which we felt would be a better compromise between simplicity and performance. Also, the takeoff speed was decreased slightly to 58 knots (107 km/h), which is more like that of comparable aircraft. And the two wingtip propellers, which we had designed for a "pusher" configuration, were moved from behind the wing to ahead of it, to provide additional ground clearance on landing, when the nose of the plane comes up.

Construction on the X-57 Maxwell is now under way. The original Tecnam P2006T will be modified in stages. For its first flight, probably less than a year away, the two wing-mounted engines will be replaced with two electric motors, without otherwise modifying the wing. The next phase will swap out the original wing for a much smaller one, with the two electric motors moved outboard to the wingtips for greater efficiency. (After this modification, the plane will require longer runways to take off and land.) The final phase will add 12 smaller electric motors spaced along the leading edge, to allow it to take off and land on typical runways while retaining the efficiency gained with the smaller wing.

Flight tests of the X-57 will help NASA engineers gauge the performance and practicality of this configuration. Those tests will also help guide designs for the next generation of distributed electric propulsion, which is soon to arrive. My Joby colleagues and I have already completed a study that examines the possibility of applying similar principles to an 11-seat airliner.

Wingtip propellers and blown wings are not the only strategies newly made practical by advances in electric propulsion. As another example, my colleagues at Joby and I are developing a five-seat electric aircraft that uses tilting propellers to take off vertically and then transition to normal airplane flight, allowing it to cruise much faster and more efficiently than a helicopter.

Most of today's airplanes and helicopters look very similar to models from many decades ago, but as this work demonstrates, that's about to change. Thanks to the flexibility of electric propulsion, aviation is about to experience the greatest renaissance in design since the advent of the jet engine. So be prepared, and don't forget to fasten your seat belt. ■

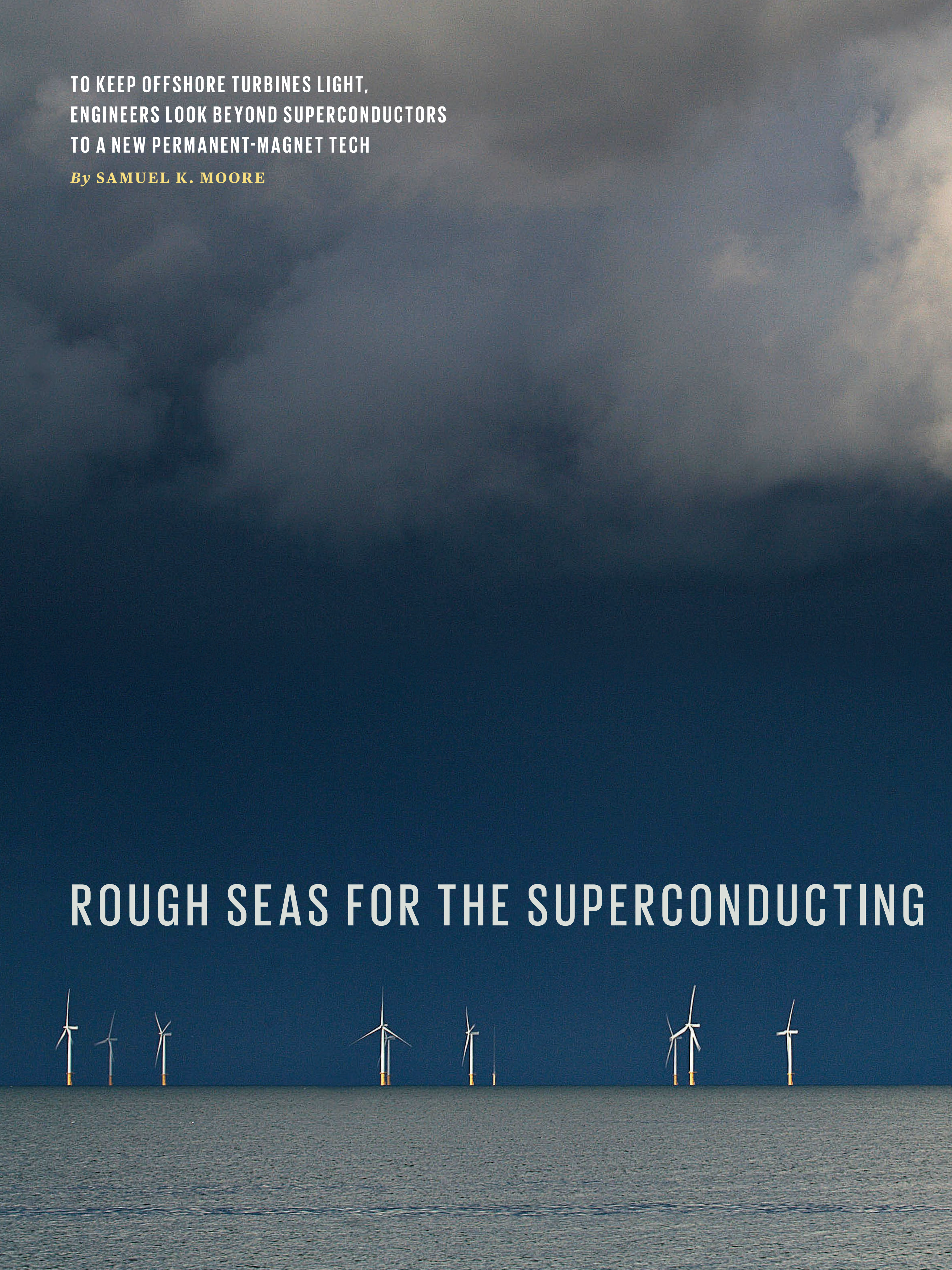
↗ **POST YOUR COMMENTS** at http://spectrum.ieee.org/wing0818

FUTURE X-PLANE: A special stand [top] is used to test the wingtip cruise motors for the upcoming X-57 Maxwell, which is depicted in this computer rendering [bottom].

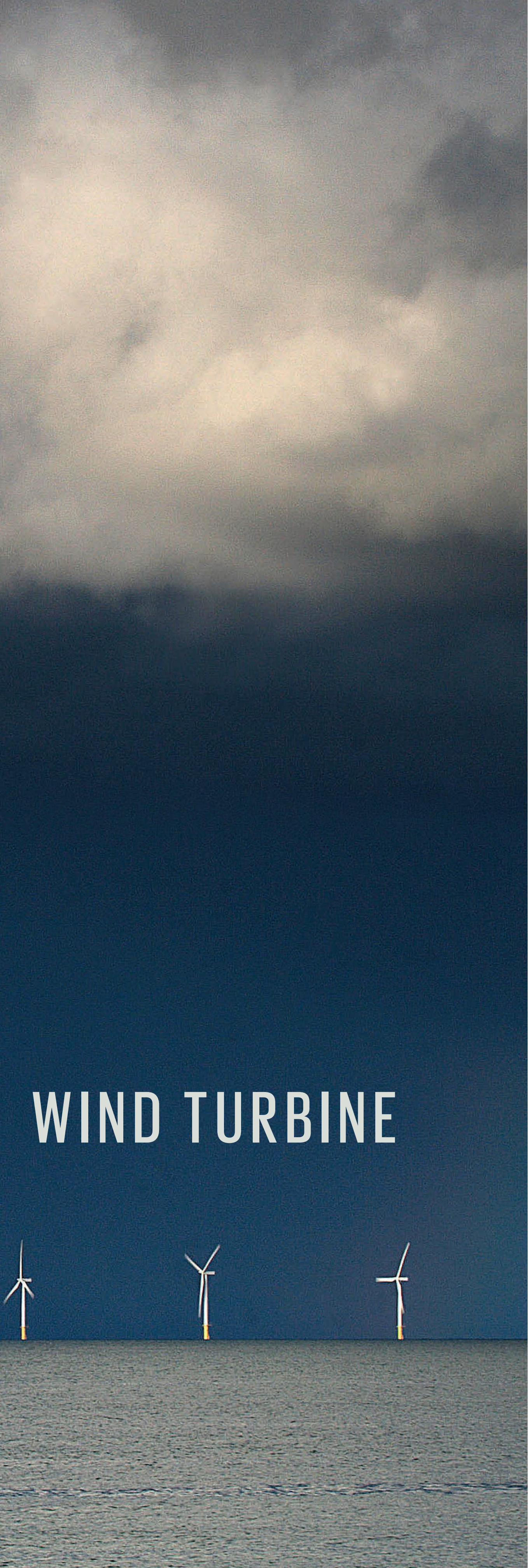
TOP: LAUREN HUGHES/NASA; BOTTOM: ADVANCED CONCEPT LAB/AMA/NASA LANGLEY

TO KEEP OFFSHORE TURBINES LIGHT, ENGINEERS LOOK BEYOND SUPERCONDUCTORS TO A NEW PERMANENT-MAGNET TECH

By SAMUEL K. MOORE



ROUGH SEAS FOR THE SUPERCONDUCTING



WIND TURBINE

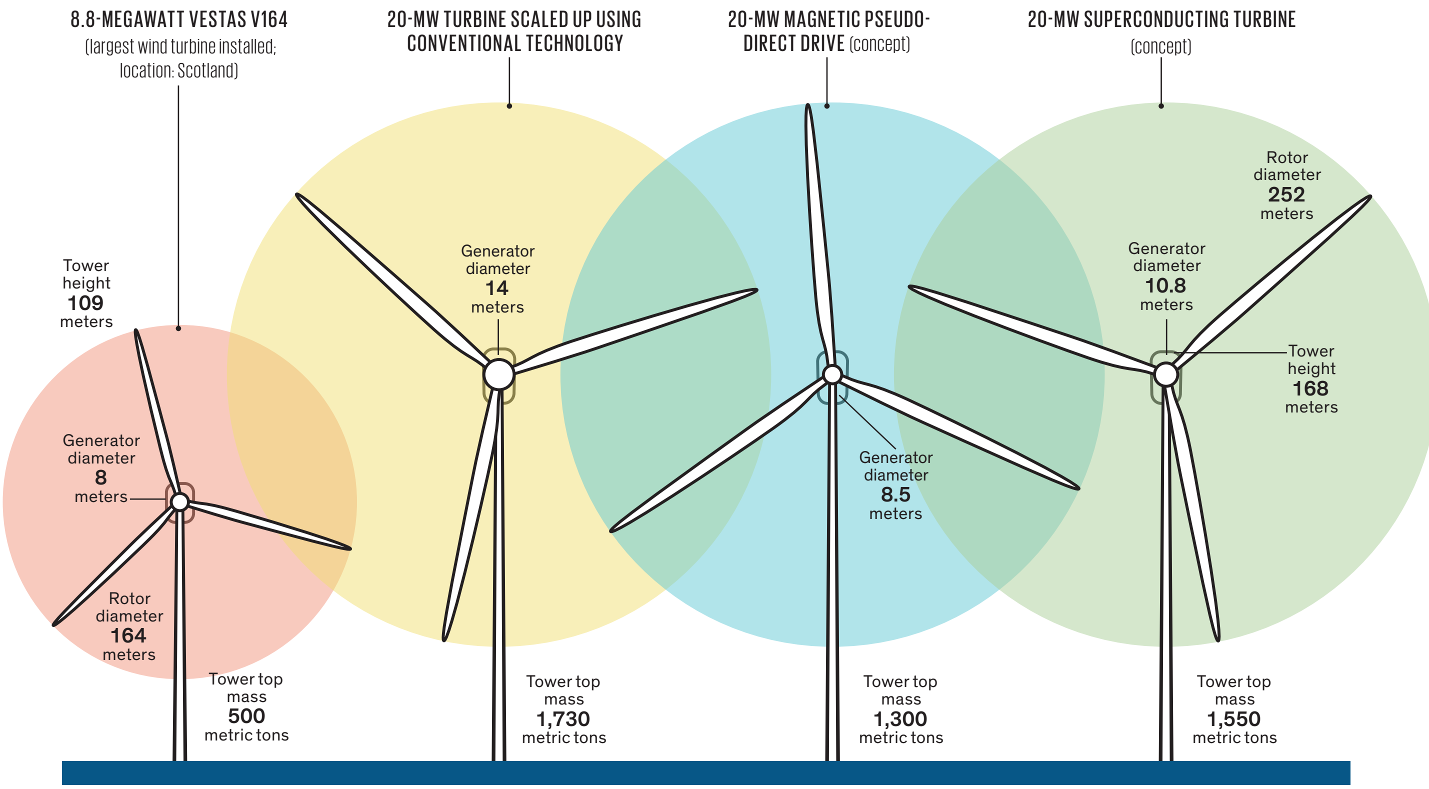
TRY TO WRAP YOUR HEAD AROUND THIS: A slender tower stretches 100 meters above the waves. Blades, each one of them nearly 60 meters long, face down the briny spray as they turn about a 250-metric-ton nacelle at the top of the tower, which houses the turbine generator and everything else needed to produce electricity.

Now double the size of everything, and make it five times as heavy.

That's the problem that will eventually face builders of offshore wind farms. In general, bigger—more megawatts per turbine—is better. So wind farm operators have been demanding higher-power offshore turbines, and manufacturers have been delivering. The most powerful turbine yet installed, an 8.8-megawatt machine from Vestas Wind Systems, went up off the coast of Scotland in April, and bids for some upcoming North Sea wind farms were made with the expectation that 13- to 15-MW turbines would be available by the middle of the next decade. Such turbines could power about 9,000 homes while the wind is blowing. But though bigger might be better, without some equally big changes in the wind turbine's core technologies, bigger quickly becomes ludicrous.

Massive Machines

Today's biggest offshore turbine is dwarfed by proposed 20-megawatt turbines. Low-cost systems designed by the InnWind consortium show superconductors [far right] making for a less-massive system. But an upstart permanent-magnet technology [second from right] is lightest.



A European Union project called InnWind calculated that if a 20-MW wind turbine were to be built with today's technology, its nacelle alone would weigh nearly 1,100 metric tons (the mass of 11 blue whales). The turbine's three blades themselves would weigh nearly 40 metric tons each and span a diameter of more than 250 meters (8 blue whales in length). The tower beneath this monster of megawatts would need to weigh nearly 1,800 metric tons to hold up all of these structures some 170 meters above the waves. To complete the picture: That's 18 blue whales holding up 11 others with 8 more spinning like a cetacean pinwheel. (You're welcome.)

"The problem is that there is a limit for constructing with current technology," says Iker Marino, an electrical engineer in the renewable energy and storage systems group at the Spanish applied-research organization Tecnalia Corporación Tecnológica and coordinator of an EU superconducting turbine project called Suprapower. "The weight of the top of the machine is too huge."

So how do you remove hundreds of tons from the mass of a machine made of magnets, gears, iron cores, and kilometers of copper winding? Exchange the magnets and maybe even the copper winding for coils of superconductors.

Simple, right? Actually, no. Years-long multinational research efforts have recently concluded that, while feasible, building such a turbine would be a monumental tech challenge. And the case for doing so is weakening as permanent magnets get better and cheaper. In fact, a dark-horse competitor whose technology is based on permanent magnets is on track to nudge superconductors aside in the 10-MW realm. And unless either the economics or the attributes of superconductors greatly improve—and, actually, both things are indeed possible—even future 20-MW titans of the sea might be superconductor-free.

WIND TURBINES ARE COMPLICATED. They operate as a result of an interplay of mechanical, magnetic, and electrical processes that change in complex ways with every tweak of a parameter. Nevertheless, they all have essentially the same set of basic conditions and components. The blades turn at a pretty stately pace, though with a great deal of torque. That slow speed is far from ideal for generating electricity, so in geared turbines—the majority, particularly onshore—a gearbox steps up the speed hundreds of times, devoting that rapid rotation to the spinning of the generator.

PREVIOUS PAGES: HOWARD LITHERLAND/ALAMY

ILLUSTRATION BY James Provost

But in an effort to reduce maintenance costs, some manufacturers are turning to an alternative offshore turbine technology called direct drive, which requires no gearbox. Here, the rotor is a gigantic ring holding many permanent magnets with alternating polarity. The generator's other key component—the stator—surrounds the rotor. It contains coils of copper wire where voltage is induced by the rotor's magnetic field.

Basically, superconductors can reduce the weight of a generator because they can replace the direct drive's permanent magnets with lighter electromagnets made from coils of superconducting wire. These electromagnets are comparatively light because superconductors can carry an enormous amount of current—that is, they have a high current density. Copper conductors in such machines top out in the single digits of amperes per square millimeter cross section. In the experimental superconducting turbine winding built for the Suprapower 10-MW turbine project, current density leaps to an astounding 58 A/mm^2.

Much has been made of the potential of high-temperature superconductors, such as yttrium barium copper oxide (YBCO), because they become superconductive at temperatures below 90 kelvins—warm enough for cooling with cheap liquid nitrogen instead of very costly liquid helium. And a leading YBCO maker, AMSC, produced a rough turbine design several years ago. (The company did not respond to requests for comment on this article.) But most of the recent European superconducting wind turbine projects have independently settled on a different superconductor: magnesium diboride.

Magnesium diboride's superconductivity was discovered only in 2001, and although it doesn't lose its resistance until it dips below 40 K, it's so much less expensive that it beat YBCO in every cost analysis. At about €4 (US $4.63) per meter of tape, MgB_2 is "maybe not the material that gives the best performance, but it gives the best cost performance," says Marino.

Columbus Superconductors, based in Genoa, Italy, is a leading MgB_2 wire supplier and was a partner in Suprapower and in an earlier U.S. Department of Energy project. The company has also contributed to InnWind and a recent French project called EolSupra20.

Of these, Suprapower most recently produced something tangible. The project, which ended in May 2017, was a €5.4 million ($6.25 million), five-year affair intended not only to design a 10-MW direct-drive superconducting turbine generator but also to build a critical part of the design—two of the 48 superconducting electromagnet coils that would make up a full rotor. The design calls for a 163-metric-ton generator, a mass reduction of 26 percent over what the thing would weigh if constructed with today's permanent-magnet technology.

The rotor coils are made from a flattened copper wire in which an MgB_2 wire has been embedded. The copper reinforces the comparatively brittle MgB_2 and conducts heat away from it. For Columbus, the geometry of the coils was the difficult part, says Gianni Grasso, the company's managing director during the project. These "racetrack" coils are roughly rectangular in shape, and the sharp corners produce stress on the wires that could crack the superconductor. "We had to develop a specific tool to do the winding," he says.

Finding a way to keep the windings at 20 K—and do that out at sea—was an even greater challenge. "All the engineering around heat extraction is feasible but complex," says Marino. "Offshore conditions are a problem for complexity."

Usually superconductors, such as those in MRI machines, are cooled by bathing them in a cryogenic fluid like liquid helium. But Suprapower ruled that option out. During any kind of maintenance at sea, that fluid would have to be removed to warm up the generator's innards and then replaced. Handling such a fluid at the top of a wind-buffeted tower and hauling around the equipment needed to reliquefy the gas just didn't seem practical.

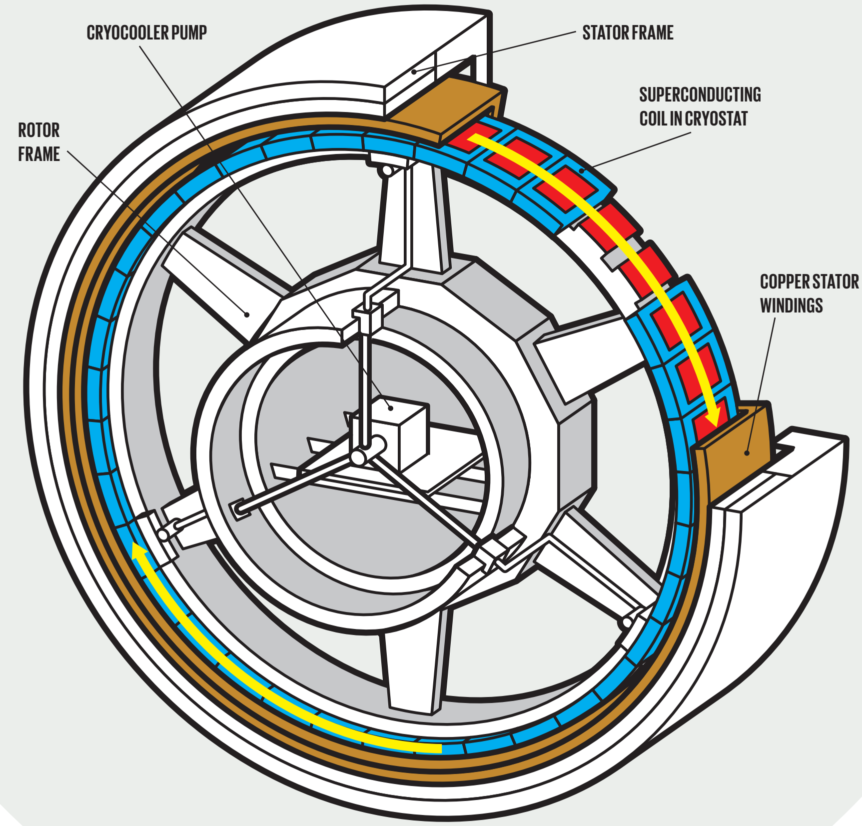
Instead, Suprapower's engineers chose to cool the coils by conduction. Gifford-McMahon cryocoolers would provide the cooling power to a distributed set of modular cryostats—enclosures that maintain the temperature of what's inside them. Each superconducting coil in this modular system has its own cryostat, which was designed to keep the coil in a vacuum.

The hope, Marino says, is that the modular nature of these cryostats will make maintenance easier. In the event that it or the coil it encloses needs replacing, a technician would have to bring only that particular segment up to room temperature and then cool its replacement back down. That convenience could speed repairs, though Marino expects that maintenance would still take longer than on a conventional machine.

THOUGH SUPRAPOWER was able to build a critical piece of a superconducting wind turbine, it didn't answer the question of whether it, or even bigger superconducting turbines, should be built at all. That was the goal of InnWind. The €20 million ($23.2 million) project, begun in 2012, developed several designs based on a variety of new technologies, including MgB_2 superconductors. It aimed to design complete 10- and 20-MW wind turbines for use in 50 meters of water at the lowest cost possible, thereby pointing the way toward the future. A funny thing happened on the way to the future, however: It got more complicated.

In the last five years, the price of the kinds of permanent magnets needed for advanced turbines has fallen by more than a factor of four, to about €25 ($29) per kilogram. Asger Bech Abrahamsen, the senior researcher at Technical University of Denmark's wind energy department who led the drivetrain design efforts for InnWind, says, "With that kind of input price level, superconducting machines can't compete."

InnWind researchers sought systems that resulted in the lowest levelized cost



Superconducting Wind Turbine
A 10-megawatt turbine generator designed as part of the Suprapower project uses magnesium diboride superconductors as the rotor's electromagnets. Each of the 48 magnets is cooled to below 40 kelvins and sits in its own cryostat.

of electricity (LCOE) for the whole turbine, including the foundation, tower, and blades. LCOE is basically the price a turbine needs to get for its electricity, over its lifetime, to break even. That figure takes into account manufacture, construction, maintenance, efficiency, decommissioning, and other factors and is among the key metrics that wind farm investors use to decide what to build—and where.

In InnWind's quest for the lowest LCOE, the fall of permanent-magnet prices forced it to reduce the amount of superconductor in its 10-MW superconducting turbine designs and to add magnetic steel to help concentrate the remaining superconductor's magnetic field. InnWind then had to add even more steel because of an unexpected resonance in the structure. This problem resulted from the mass at the top of the tower being so light that when the 41.7-metric-ton blades swung past the tower, they strained the structure at a frequency that was too close to its natural frequency. Eventually, that strain would have shortened the substructure's required 25-year lifetime. Also—and most unfortunately—simulations showed that the resonance was stronger the *lighter* the turbine generator became, explains Abrahamsen. Faced with a situation in which making the generator lighter would lead to a more costly substructure, the InnWind designers allowed the mass of the 10-MW superconducting drivetrain to balloon to 286 metric tons, compared with the 215 to 237 metric tons for scaled-up versions of permanent-magnet-based direct-drive tech.

Though InnWind's 20-MW MgB_2 design didn't have the resonance problem, it still needed a lot of steel to make up for the design's reduced amount of superconductor. With superconductors, the instinct is to make the lightest, smallest turbine generator possible, says Abrahamsen, but from the perspective of low LCOE, "we had to conclude that a lightweight generator as always beneficial is not quite always true."

THE PRICE COLLAPSE OF PERMANENT MAGNETS also opened an opportunity for a dark-horse competitor to superconductors. Called the magnetic pseudodirect drive (PDD), it's a kind of magnetic gearing system in development at Magnomatics, based in Sheffield, England.

The system is hard to fully grasp unless you see it in motion, but here goes: A PDD is a set of three concentric cylinders. The inner and outer rings are each made up of stripes of permanent magnet with alternating polarities. The outer cylinder has many stripes, the inner just a few. The central cylinder consists of alternating stripes of steel and nonmagnetic support material. In operation, the outer ring is held stationary, while the turbine's low-speed input from the blades spins the central steel cylinder. That cylinder manipulates the magnetic lines of force of the outer cylinder's permanent magnets so that they form a magnetic field that rotates quickly and in the opposite direction of the steel cylinder. This field couples with the permanent magnets of the inner cylinder to produce high-speed rotation. To turn this gear into a generator, coils of copper wire are set around the outer ring, where they experience the same fast-moving magnetic

ILLUSTRATION BY James Provost

field that the inner ring does. That fast-moving field induces a voltage in the coils of copper wire.

In InnWind's analysis, this setup beat the superconducting design on efficiency. PDD "gained most by having high efficiency even at low wind speeds," says Abrahamsen. "A superconducting machine can also reach a pretty high efficiency, but it needs a cooling system," which is a constant drain on energy even when the wind is barely blowing, he notes. While other factors, such as construction cost, are spread over the turbine's 25-year life, efficiency has a much more direct effect on cost.

"It doesn't sound like much, but 2 percent more efficiency means 2 percent on LCOE," says David Powell, principal engineer for drive technology at Magnomatics. And in the wind industry, he adds, "2 percent is a big deal."

The PDD gets that relatively high efficiency by adopting the smaller size of geared turbines without suffering from energy losses in mechanical gears. These losses can be 1 to 2 percent per stage, and many turbines have three gear stages, explains Powell. In the PDD, however, there are no mechanical connections; the cylinders float within each other separated by an air gap, so the system doesn't even need lubricant.

Though the main selling point in the wind industry is the PDD system's efficiency, it is also considerably smaller and requires much less copper winding than existing technology. The 10-MW PDD design's drivetrain mass was more than 100 metric tons lighter than the superconducting MgB_2 design. And the turbine was only 6 meters in diameter versus the reference design's 10 meters. That size difference may offer an advantage in manufacturing, Powell says, because it would give turbine makers the option of building new high-megawatt turbines in older, smaller factories.

Magnomatics plans to capitalize on this victory. But it has a lot to do to scale up to 10 MW or beyond. With conventional technology already in the water, little more than 1 MW away from that mark, "we need to get there very soon," Powell notes. "It's all happening for us now. We just have to catch the right people."

RAPHAËL PASQUET/CEA SACLAY/IEEE

MAGNESIUM DIBORIDE MASH: Filaments of the superconductor magnesium diboride are encased in ribbonlike support structures of copper and other elements. The ribbons are then carefully wound into a "racetrack" shape to form the turbine's high-power electromagnets.

THOUGH a nonsuperconductor technology won InnWind on cost, that consortium's analysis isn't the only one around. The smaller, French project called EolSupra20 aimed straight for the 20-MW mark with its LCOE exploration and came up with very different results.

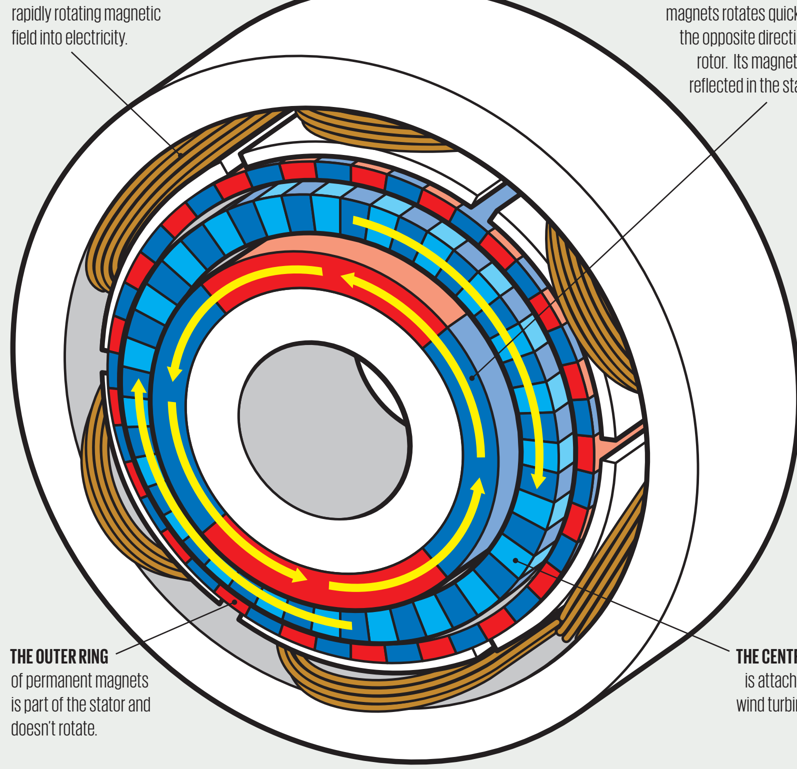
Unlike those of others, EolSupra20's design includes MgB_2 superconductors in both the rotor and the stator. "What you want for the rotor is to create a really large magnetic field," says Loïc Quéval, assistant professor at the University of Paris-Saclay. So all you need is DC current, which in a superconductor flows without loss and generates no heat.

"The stator is something different," he says. As the rotor's magnetic field cuts through it, the current in the stator's windings changes directions. Amazing as they are, superconductors do experience some loss when carrying AC current. This had two effects on the design. First, it required a different form of superconducting wire to do the job. An alternating magnetic field causes loss-inducing loops of current in the surface of a superconductor. Unfortunately, superconductors—especially the high-temperature variety—are usually produced as tapes rather than wire, so they have lots of surface area on which these loops can form. "It's almost impossible to produce a low-AC-loss, high-temperature superconductor," says Columbus Superconductor's Grasso, whose company also produces such materials. "But it's possible with MgB_2."

Instead of the tape, Columbus has been working on an MgB_2 format with a smaller surface area. It's producing wires in which many round filaments of MgB_2 with diameters of 10 micrometers are embedded. These filaments have too small a surface area for many current loops to form, explains Grasso. In one format, 91 such filaments are embedded in a copper-and-nickel hexagonal wire. These wires would then be packed into a flat format called a Rutherford cable, although this has yet to be achieved at useful lengths.

Magnetic Pseudodirect Drive

A peculiar arrangement of permanent magnets turns a wind turbine's high torque into the quickly rotating magnetic field needed for a generator.



The second consequence of having a superconducting stator is that it must be cooled, and those cooling demands will be steeper than what the rotor needs. The EolSupra20 design uses a set of cryocoolers to keep the rotor at 10 K, a temperature that maximizes the superconductor's current-carrying ability. The stator is on a separate group of cryocoolers set to keep it at 20 K, because it would take too much power to maintain a lower temperature than that.

To meet these needs, the design calls for no less than 85 cryocoolers in total. "We put cryocoolers everywhere," says Quéval. Sourcing powerful cryocoolers was a problem, so EolSupra20 used multiple smaller ones. The Sumitomo Heavy Industries RDK-0408S2 two-stage cryocoolers that EolSupra20 used in its design weigh just 18 kilograms and can pull mere watts to tens of watts of heat from the coils–but at the expense of about 100 times that amount of energy. "Right now, efficiency is really low," Quéval says.

EolSupra20's superconducting design did manage to beat its version of a turbine built using conventional technology with respect to LCOE. It chimed in at €119 per megawatt-hour ($140/MWh) compared with €129/MWh ($152/MWh) for the conventional turbine. The difference, according to Quéval and the EolSupra20 team, was the substantially lower generator mass enabled by the superconductors. At 178 metric tons, the fully superconducting generator was barely more than one-third of the conventional generator's bulk.

EolSupra20's LCOE is quite noticeably higher than that of InnWind's reference 20-MW turbine, which is €93 ($108)/MWh. Quéval points out that LCOE is, to some extent, a local affair. InnWind's aim was the deeper waters of the North Sea, where competition is fierce and grid connections are planned, if not yet plentiful. Future wind farms have already been promised there at less than €100 ($116)/MWh. The Atlantic coast of France is a different environment, both economically and geographically. France currently has no offshore wind farms, despite having a long, windy coast. But since 2012, the country has awarded tenders for 3,000 MW of offshore capacity, at the lofty price of about €200 ($232)/MWh. That number could change–and soon. Seeing the unexpectedly rapid fall in prices in the North Sea, the French government began signaling a desire to renegotiate in March.

SO, GIVEN THE MIXED SIGNALS, which technology will rule the sea in the future, superconductors or PDDs? InnWind's is surely a comprehensive study, with five years of work by some 27 industrial and research entities. That said, even its reports admit to a lot of uncertainty. And InnWind judges both drivetrain technologies at the same level of readiness: "Test in laboratory."

A better question, and one that InnWind tries to answer, might be: What would it take for superconductors to match the PDD drive? According to Abrahamsen and his InnWind colleagues, a price reduction in MgB_2 similar to what happened to permanent magnets would go a long way. If MgB_2 tape cost €1 ($1.16) per meter instead of €4 ($4.64), a 20-MW design could add much more of it, making stronger magnets that need less cumbersome amounts of magnetic steel. But such a design would also require a tenfold reduction in the estimated cost of cryostats and cooling equipment to make it competitive. It's

ILLUSTRATION BY James Provost

an open question whether the commercialization of massive superconducting wind turbines would create enough demand to lead to prices that low in either technology.

But price isn't the only thing that could change. The critical temperature at which a superconductor starts superconducting is what most people focus on, but it's really a triumvirate of conditions that leads to superconductivity. There is a critical current density above which the phenomenon collapses, as well as a maximum magnetic field. A fourfold boost in the critical current value, say, would have a similar effect as a price reduction, because you could produce a stronger field with one-quarter the amount of superconductor. Even better, it would allow for different drivetrain designs. "The better the wire, the more simple the rest of the system is," sums up Suprapower's Marino.

It's also possible that these LCOE analyses for extremely massive turbines are all a bit premature. Another EU project called EcoSwing aims to prove that a superconducting generator can compete at more modest scales, and its engineers have nearly done it. By March 2019, the €14 million ($16.3 million) project plans to have installed such a superconducting generator inside a modified 3.6-MW turbine on land, where the installation and maintenance are easier.

Unlike the high-megawatt offshore projects, EcoSwing is aiming for the middle of today's onshore market. Superconductor technology has let the designers double the turbine's power density, allowing for a 40 percent smaller turbine generator and a 15 percent cost reduction over those of market leaders, says Jürgen Kellers, EcoSwing's director at ECO 5, an engineering company that's one of the nine contributors to the project.

Apart from its size, the EcoSwing generator differs from the InnWind and other offshore designs in that EcoSwing uses a single large cryostat instead of many modular ones. It also relies on a high-temperature superconductor—yttrium barium copper oxide—instead of MgB_2. The company chose the former despite the cost, because it's easier to cool YBCO. "You might say MgB_2 is already at a cost that YBCO wants to be in the future," says Kellers. "On the other hand, cryogenics is not as straightforward and rugged as with YBCO."

On 22 May, the consortium completed testing of its generator at the Fraunhofer Institute for Wind Energy Systems' DynaLab, a facility that can provide the torque and other conditions to test full-scale wind turbine generators. It's the first superconducting machine ever to undergo such tests.

From the DynaLab, the machine will stop at the University of Twente, in the Netherlands, for some final assembly and then move by ship to Denmark for installation in the turbine. "Then we have the lift and see how the EcoSwing generator performs in the harsh conditions of the North Sea coast," says Kellers.

Magnomatics isn't too far behind with its magnetic pseudodirect drive. Its next stage is a 500-kilowatt generator, which it will test on a dynamometer at the National Renewable Energy Centre, in Blyth, England. From there "we're going to try to put a 2- to 3-MW machine in a nacelle and get real data," says Magnomatics' Powell.

The battle for future designs may have gone to the PDD, but the fight to prove whether either technology really works is just beginning. ■

DOCKING MANEUVER: Workers prepare to link a 3.6-megawatt superconducting generator [blue] to a machine that simulates the torque and other aspects of a wind turbine [gray].

FRAUNHOFER INSTITUTE FOR WIND ENERGY SYSTEMS

↗ **POST YOUR COMMENTS** at http://spectrum.ieee.org/windturbines0818

A VIEW TO THE CLOUD

What really happens when your data is stored on far-off servers in distant data centers

By Barry M. Lunt

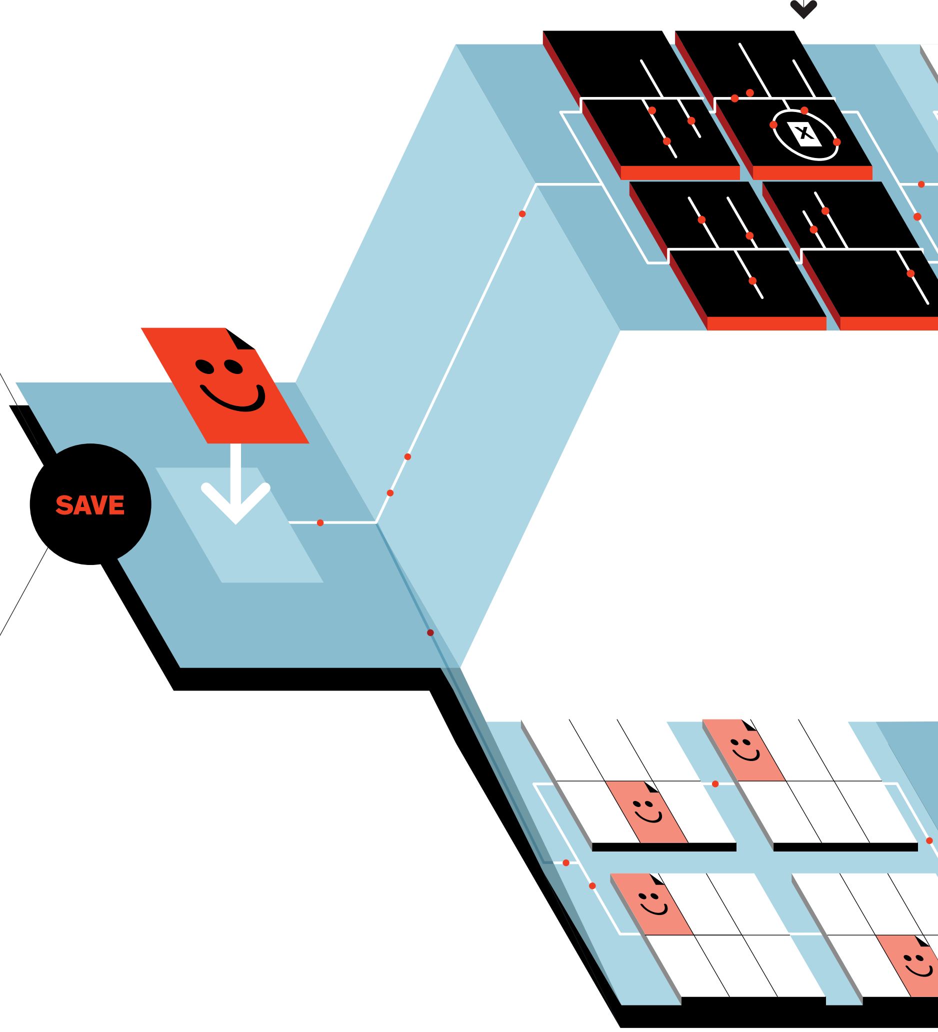
We live in a world that's awash in information. Way back in 2011, an IBM study estimated that nearly 3 quintillion—that's a 3 with 18 zeros after it—bytes of data were being generated every single day. We're well past that mark now, given the doubling in the number of Internet users since 2011, the powerful rise of social media and machine learning, and the explosive growth in mobile computing, streaming services, and Internet of Things devices. Indeed, according to the latest Cisco Global Cloud Index, some 220,000 quintillion bytes—or if you prefer, 220 zettabytes—were generated "by all people, machines, and things" in 2016, on track to reach nearly 850 ZB in 2021.

Much of that data is considered ephemeral, and so it isn't stored. But even a tiny fraction of a huge number

THE BASICS OF DATA STORAGE

Storing Locally on a Solid-State Drive

Step 1: Clicking on the "Save" icon in a program invokes firmware that locates where the data is to be stored on the drive.



Storing Remotely in the Cloud

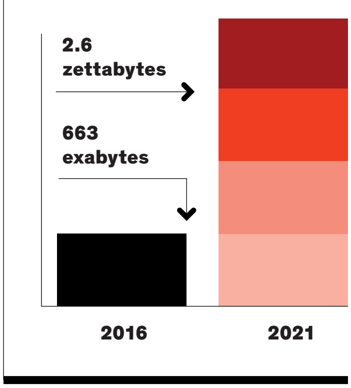
Step 1: Data is saved locally, in the form of blocks.

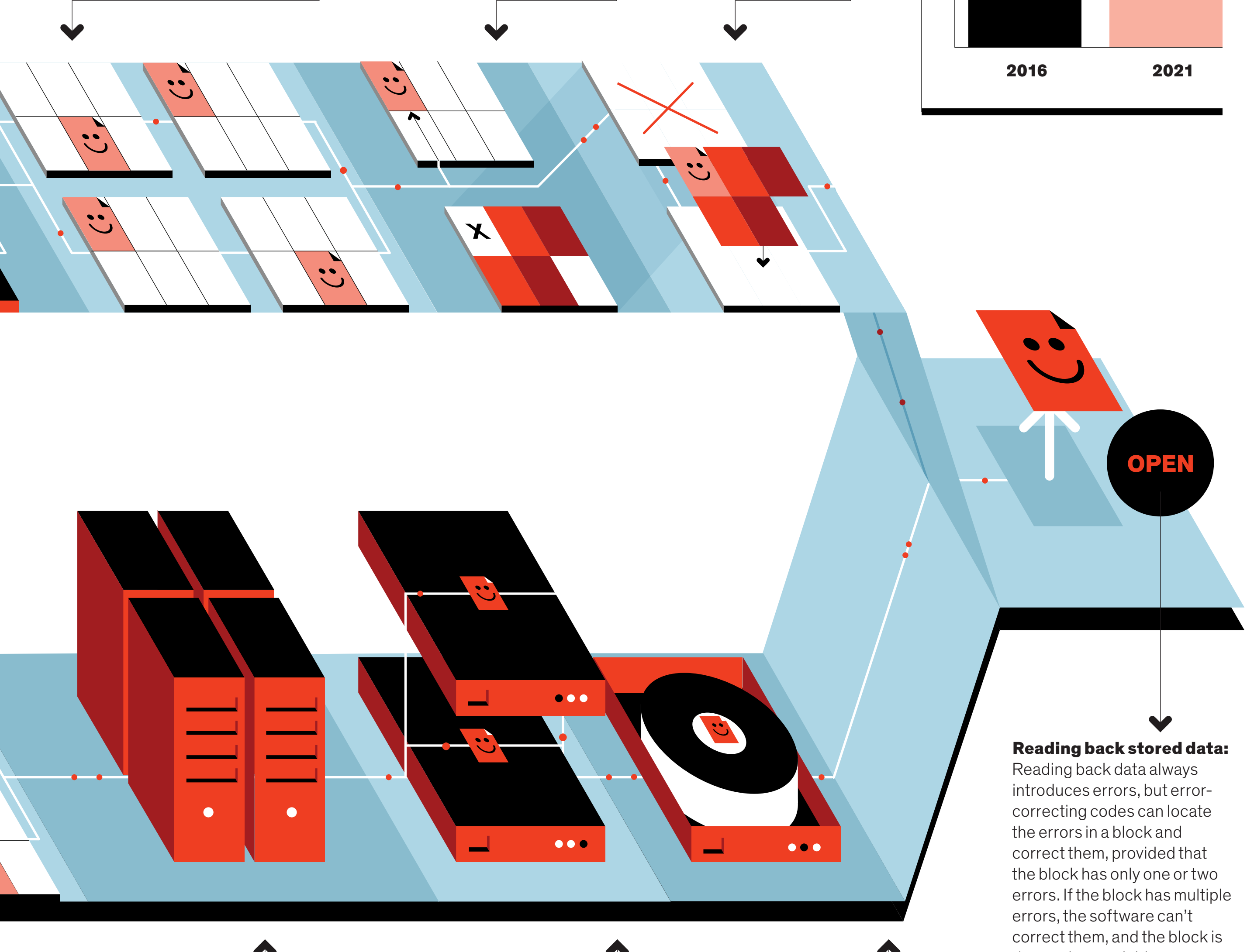
Step 2: Inside the drive, data is physically located in different blocks. A quirk of the flash memory used in solid-state drives is that when data is being written, individual bits can only be changed from 1 to 0, never from 0 to 1. So when data is written to a block, all of the bits are first set to 1, erasing any previous data. Then the 0s are written, creating the correct pattern of 1s and 0s.

Step 3: Another quirk of flash memory is that it's prone to corrupting stored bits, and this corruption tends to affect clusters of bits that are located close together. Error-correcting codes can compensate for only a certain number of corrupted bits per byte, so each bit in a byte of data is stored in a different block, to minimize the likelihood of multiple bits in a given byte being corrupted.

Step 4: Because erasing a block is slow, each time a portion of the data on a block is updated, the updated data is written to an empty part of the block, if possible, and the original data is marked as invalid. Eventually, though, the block must be erased to allow new data to be written to it.

Projected global data-center storage capacity, 2016 to 2021





Step 2: Data is transmitted over the Internet to a data center.

Step 3: For redundancy, data is stored on at least two hard-disk drives or two solid-state drives (which may not be in the same data center), following the same basic method described above for local storage.

Step 4: Later that day, if the data center follows best practices, the data is backed up onto magnetic tape. However, not all data centers use tape backup.

Reading back stored data: Reading back data always introduces errors, but error-correcting codes can locate the errors in a block and correct them, provided that the block has only one or two errors. If the block has multiple errors, the software can't correct them, and the block is deemed unreadable.

Errors tend to occur in bursts and may be caused by stray electromagnetic fields—for example, a phone ringing or a motor turning on. Errors also arise from imperfections in the storage medium.

INFOGRAPHIC BY **Francesco Muzzi/Story TK**

A DEEPER DIVE INTO THE CLOUD

Though most data that gets stored is still retained locally, a growing number of people and devices are sending an ever-greater share of their data to remote data centers.

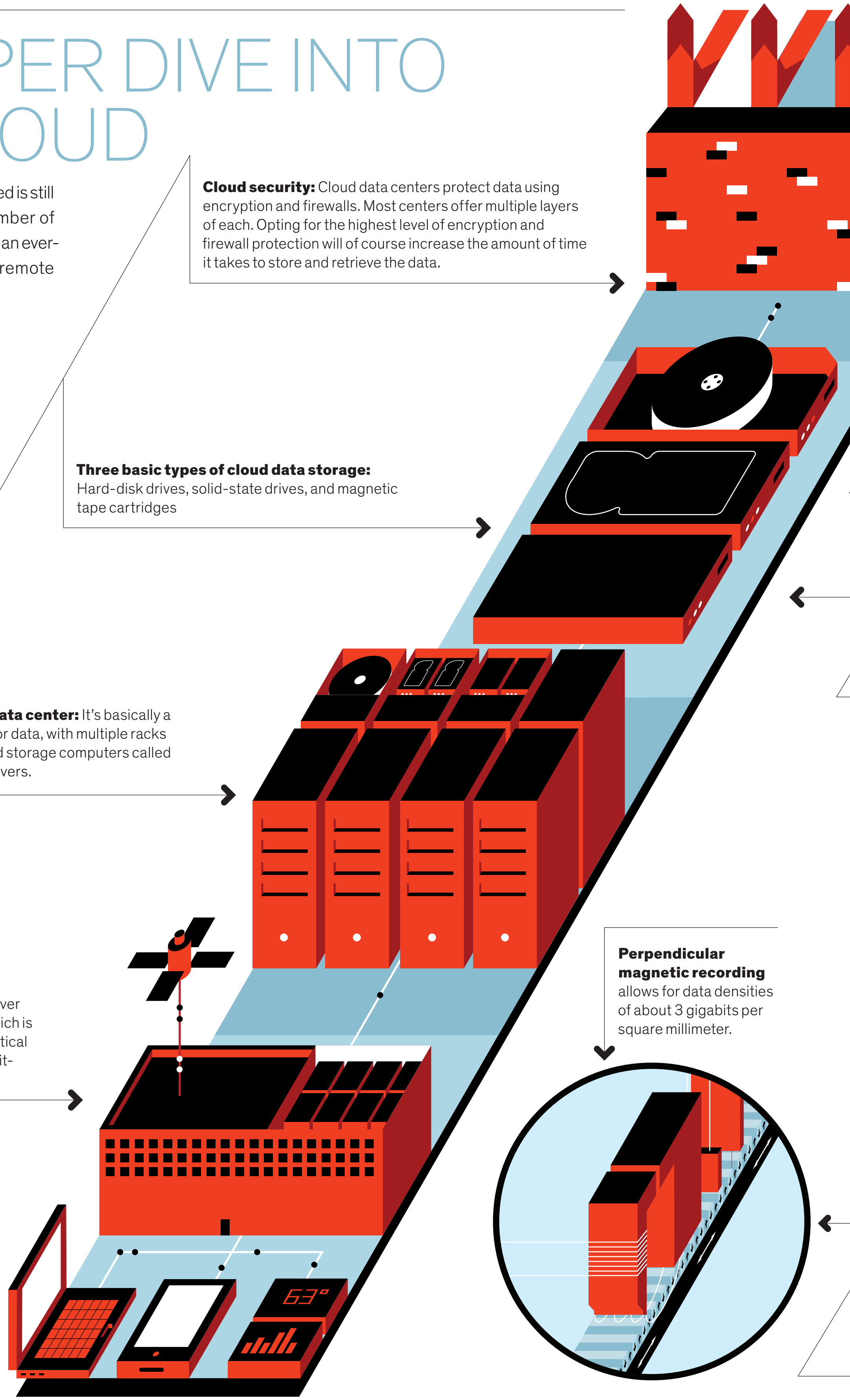
Cloud security: Cloud data centers protect data using encryption and firewalls. Most centers offer multiple layers of each. Opting for the highest level of encryption and firewall protection will of course increase the amount of time it takes to store and retrieve the data.

Three basic types of cloud data storage: Hard-disk drives, solid-state drives, and magnetic tape cartridges

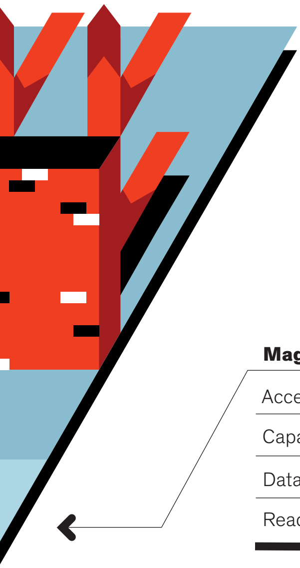
The cloud data center: It's basically a warehouse for data, with multiple racks of specialized storage computers called database servers.

Data from multiple users moves over the Internet to a cloud data center, which is connected to the outside world via optical fiber or, in some cases, satellite gigabit-per-second links.

Perpendicular magnetic recording allows for data densities of about 3 gigabits per square millimeter.



INFOGRAPHIC BY Francesco Muzzi/Story TK



Magnetic Tape

Access time, read/write	10–60 seconds
Capacity	12 terabytes
Data persistence	10–30 years
Read/write cycles	Indefinite

Hard-Disk Drive

Access time, read/write	7 milliseconds
Capacity	8 terabytes
Data persistence	3–6 years
Read/write cycles	Indefinite

Solid-State Drive

Access time, read/write	50/1,000 nanoseconds
Capacity	2 terabytes
Data persistence	8–10 years
Read/write cycles	1,000

Magnetic storage vs. solid state: Hard-disk drives and magnetic tape store data by magnetizing particles that coat their surfaces. The amount of data that can be stored in a given space—the density, that is—is a function of the size of the smallest magnetized area that the recording head can create. Perpendicular recording [left] can store about 3 gigabits per square millimeter. Newer drives based on heat-assisted magnetic recording and microwave-assisted magnetic recording boast even higher densities. Flash memory in solid-state drives uses a single transistor for each bit. Data centers are replacing HDDs with SDDs, which cost four to five times as much but are several orders of magnitude faster. On the outside, a solid-state drive may look similar to an HDD, but inside you'll find a printed circuit board studded with flash memory chips.

can still be impressively large. When it comes to data, Cisco estimates that 1.8 ZB was stored in 2016, a volume that will quadruple to 7.2 ZB in 2021.

Our brains can't really comprehend something as large as a zettabyte, but maybe this mental image will help: If each megabyte occupied the space of the period at the end of this sentence, then 1.8 ZB would cover about 460 square kilometers, or an area about eight times the size of Manhattan.

Of course, an actual zettabyte of data doesn't occupy any space at all–data is an abstract concept. Storing data, on the other hand, does take space, as well as materials, energy, and sophisticated hardware and software. We need a reliable way to store those many 0s and 1s of data so that we can retrieve them later on, whether that's an hour from now or five years. And if the information is in some way valuable–whether it's a digitized family history of interest mainly to a small circle of people, or a film library of great cultural significance–the data may need to be archived more or less indefinitely.

The grand challenge of data storage was hard enough when the rate of accumulation was much lower and nearly all of the data was stored on our own devices. These days, however, we're sending off more data to "the cloud"–that (forgive the pun) nebulous term for the remote data centers operated by the likes of Amazon Web Services, Google Cloud, IBM Cloud, and Microsoft Azure. Businesses and government agencies are increasingly transferring more of their workloads–not just peripheral functions but also mission-critical work–to the cloud. Consumers, who make up a growing segment of cloud users, are turning to the cloud because it allows them to access content and services on any device wherever they go.

And yet, despite our growing reliance on the cloud, how many of us have a clear picture of how the cloud operates or, perhaps more important, how our data is stored? Even if it isn't your job to understand such things, the fact remains that your life in more ways than you probably know relies on the very basic process of storing 0s and 1s. ■

↗ **POST YOUR COMMENTS** online at https://spectrum.ieee.org/clouddatastorage0818

Penn Engineering

The School of Engineering and Applied Science at the University of Pennsylvania is growing its faculty by 33% over a five-year period. As part of this initiative, the Department of Mechanical Engineering and Applied Mechanics is engaged in an aggressive, multi-year hiring effort for multiple faculty positions.

For this search, we seek applicants for appointments at the rank of Associate or Full Professor in the areas of robotics and controls. Candidates who enrich the diversity of our community are strongly encouraged to apply.

Candidates must have exceptional research accomplishments leading to international leadership in their field. Applicants' training and future research should be strongly rooted in mechanical engineering. Candidates must have a demonstrated commitment to excellence in undergraduate and graduate education in mechanical engineering, and a track record of service and collegiality.

Successful candidates will conduct innovative research programs benefiting from Penn's robust interdisciplinary tradition. The Department maintains close collaborations with all other engineering departments and other Schools at Penn including the School of Arts and Sciences, the Perelman School of Medicine, the Wharton School of Business, and the School of Design. Our faculty engage with leading centers and initiatives including the General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory, the Penn Institute for Computational Science (PICS), the Laboratory for Research on the Structure of Matter (LRSM), the Penn Center for Health, Devices & Technology, the Center for Engineering Mechanobiology, the Engineering Entrepreneurship Program, and the Singh Center for Nanotechnology. Thus, candidates should articulate ways they will leverage or add to any of these relationships in their application. Candidates should also describe ways their research aligns with the School's strategic plan (**http://www.seas.upenn.edu/PennEngineering2020**).

Applicants should supply a cover letter (up to 2 pages), CV, teaching statement (up to 2 pages), research statement (up to 3 pages, with a 300-word abstract), names and contact information of 4 references, and 3 to 4 representative publications. The link to apply for the search can be found below. For full consideration, candidates must apply by **Oct. 1 2018**.

http://facultysearches.provost.upenn.edu/postings/1384

The University of Pennsylvania is an affirmative action/equal opportunity employer. All qualified applicants will receive consideration for employment and will not be discriminated against on the basis of race, color, religion, sex, sexual orientation, gender identity, creed, national or ethnic origin, citizenship status, disability, veteran status, or any other characteristic protected by law.

上海科技大学
ShanghaiTech University

TENURE-TRACK AND TENURED POSITIONS

ShanghaiTech University invites highly qualified candidates to fill multiple tenure-track/tenured faculty positions as its core founding team in the School of Information Science and Technology (SIST). We seek candidates with exceptional academic records or demonstrated strong potentials in all cutting-edge research areas of information science and technology. They must be fluent in English. English-based overseas academic training or background is highly desired. ShanghaiTech is founded as a world-class research university for training future generations of scientists, entrepreneurs, and technical leaders. Boasting a new modern campus in Zhangjiang Hightech Park of cosmopolitan Shanghai, ShanghaiTech shall trail-blaze a new education system in China. Besides establishing and maintaining a world-class research profile, faculty candidates are also expected to contribute substantially to both graduate and undergraduate educations.

Academic Disciplines: Candidates in all areas of information science and technology shall be considered. Our recruitment focus includes, but is not limited to: computer architecture, software engineering, database, computer security, VLSI, solid state and nano electronics, RF electronics, information and signal processing, networking, security, computational foundations, big data analytics, data mining, visualization, computer vision, bio-inspired computing systems, power electronics, power systems, machine and motor drive, power management IC as well as inter-disciplinary areas involving information science and technology.

Compensation and Benefits: Salary and startup funds are highly competitive, commensurate with experience and academic accomplishment. We also offer a comprehensive benefit package to employees and eligible dependents, including on-campus housing. All regular ShanghaiTech faculty members will join its new tenure-track system in accordance with international practice for progress evaluation and promotion.

Qualifications:
-Strong research productivity and demonstrated potentials;
-Ph.D. (Electrical Engineering, Computer Engineering, Computer Science, Statistics, Applied Math, or related field);
-A minimum relevant (including PhD) research experience of 4 years.

Applications: Submit (in English, PDF version) a cover letter, a 2-page research plan, a CV plus copies of 3 most significant publications, and names of three referees to: sist@shanghaitech.edu.cn. ***For more information, visit*** http://sist.shanghaitech.edu.cn/NewsDetail.asp?id=373

Deadline: The positions will be open until they are filled by appropriate candidates.

TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF INFORMATION TECHNOLOGIES

3 Tenure Track Professorships and several post-doc positions in the areas of

- **Trustworthy Software Technologies**
- **Hardware Security and Trust**
- **Internet of Intelligent Things**

Estonia is the homeland of pioneering ICT solutions, which include Skype, e-identity, e-health, and e-governance. Building on these successes, the Estonian ICT industry and academia are establishing **three new research groups** in the named areas.

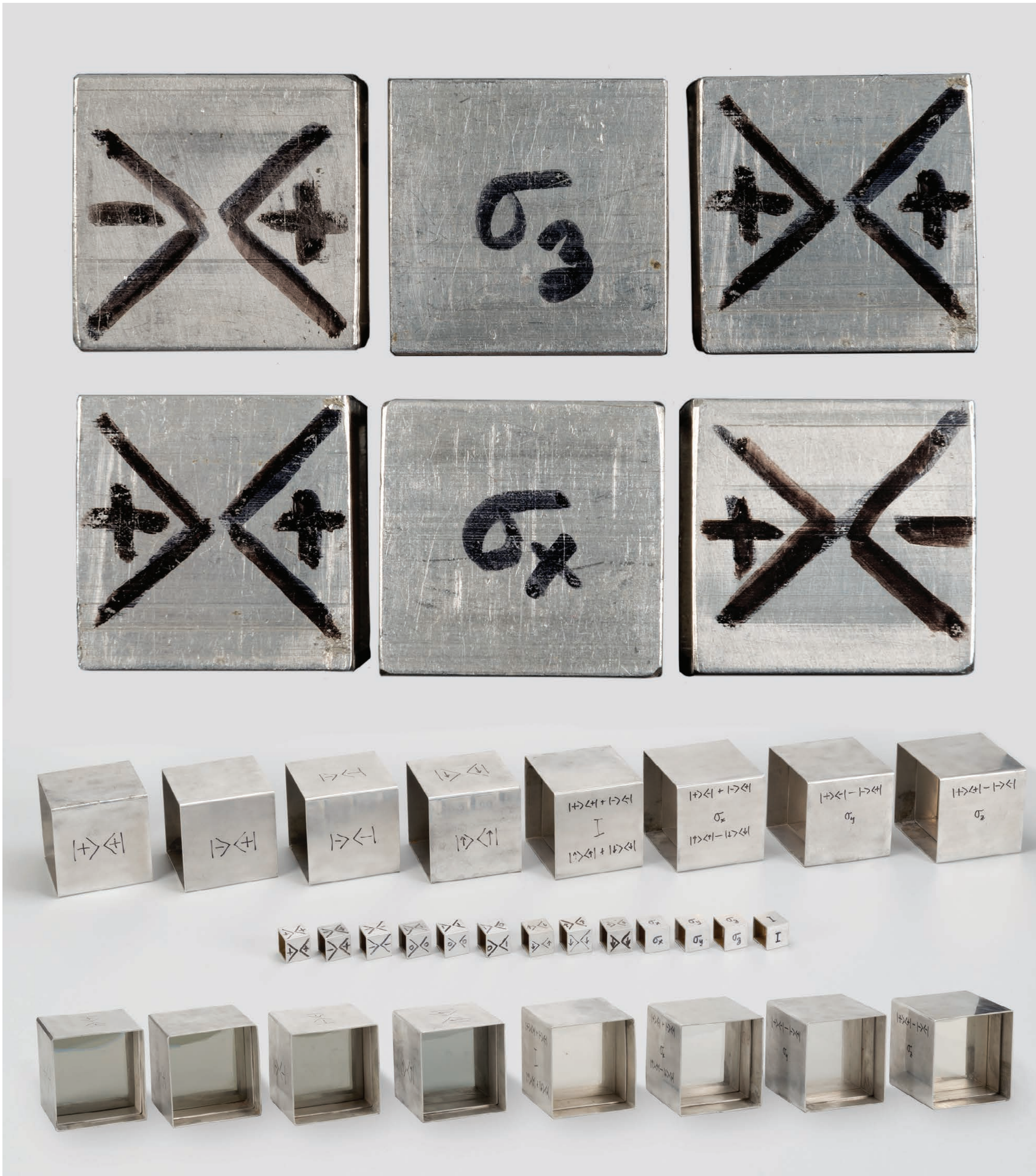
Tallinn University of Technology is looking for candidates for **tenure track positions** with a proven research track record, leadership capabilities, ability to acquire competitive funding, ability and interest to collaborate across disciplines, experience in developing an academic curriculum in English, willingness to cooperate with industry and the public sector. Successful candidates are expected to perform basic and applied research and teaching.

For **tenure track professors** the university offers:

- A competitive **net salary** in a range of 45,000 - 60,000 EUR per year
- **Dedicated funding for establishing a research group**
- Location in Tallinn, which is one of the fastest-growing IT hubs in Europe and home to The European Agency for the operational management of large-scale IT systems (eu-LISA) as well as the NATO Cyber Defence Centre of Excellence
- A young and internationally active faculty with rapid and efficient university e-management, allowing you to concentrate on the essential

Within the same call the university is looking for candidates for **20 new post-doc/researcher positions** with a proven research track record, ability and interest to collaborate across disciplines, willingness to cooperate with industry and the public sector. For **post-doc/researcher positions** the university offers a competitive **net salary** in a range of 20,000 - 30,000 EUR per year.

More information and directions how to apply: **https://ttu.ee/itpositions**



COLLECTION OF HISTORICAL SCIENTIFIC INSTRUMENTS/HARVARD UNIVERSITY

A QUANTUM OF PLAY

Quantum mechanics is hard. Can a toy make the subject any easier? Costas Papaliolios thought so. As a graduate student at Harvard in the early 1960s, he created these aluminum blocks marked with variations of Paul Dirac's bra-ket notation for describing quantum states. He made 4-inch blocks and 1-inch blocks. (The upper photos are enlargements of the 1-inch, or 2.54-centimeter, blocks.) A polarized filter fit inside each open-ended block. Shining a light through a block, or a series of blocks, yielded one of two results: The light passed through or it didn't. Papaliolios hoped his toys would help students grasp abstract concepts like linear operators and matrix representation. For most people, though, quantum mechanics remains as puzzling as ever. ■ ↗ **For more on Papaliolios's quantum toys, see http://spectrum.ieee.org/pastforward0818**